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space research institute in times of change

glimpses of the past and visions of the future

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space science: yesterday, today and tomorrow
30 september – 2 october 2015, Moscow
selected papers

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Space Research Institute in Times of Change. Glimpses of the Past and Visions of the Future

International Forum
"Space Science: Yesterday, Today and Tomorrow"
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Selected Papers from the Session

This collection of essays gives a very brief overview into the history of Space Research Institute of the Russian Academy of Sciences (IKI RAN) and some of its most prominent events. The book is based on selected talks given at International Forum "Space Science: Yesterday, Today, and Tomorrow" (Moscow, 2015) dedicated to the 50th anniversary of IKI RAN.

Keywords: space research, space exploration, space, history, Space Research Institute, Academy of Sciences, history, international collaboration, proceedings.

ALONG THE THORNY PASS OF SPACE SCIENCE. 50-YEARS-JOURNEY*

Lev M. Zelenyi, Moscow, Russia

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My task is to tell you the very brief history of Space Research Institute, which turned 50 in 2015, and, thus, was established as far back in time as 1965. The date itself *est nomen*. The second half of 1950s was the very start of political and cultural *ottepel* (literally, "thaw") in the USSR, which brought to life new generation of poets, artists, musicians, and — not to the least extent — scientists. The main change was perhaps that the "iron curtain" was gradually lifted, which had been separating the country from the most of the outer world during the cold war. The spirit of international friendship permeated or started to permeate all spheres of life. The 6th World Festival of Youth and Students in Moscow in 1957 designated these changes in the foreign and inner policy, and paved the way for future international projects, scientific among others.

It is true that science was largely dependent on military goals; and even more so for rocketry, which was considered by many — luckily, not by all — to be merely the weapon to deliver special missiles to potential targets. However, those who drove the development of rockets saw farther and were able to persuade the leaders of the nations that entering outer space can be a goal in itself, a matter of national pride, and a way to new discoveries and inevitably technologies.

October 4, 1957, Sputnik was launched, the first man-made object to enter space. The international response was immense, and outside the USSR even larger than within. The newspapers praised Soviet designers and nation leaders, and mocked at their political rivals, the USA.

> Oh, little Sputnik, flying high
> With made-in-Moscow beep,
> You tell the world it's a Commie sky
> and Uncle Sam's asleep.
>
> *G. Mennen Williams*, the Democratic governor
> of Michigan, published in *The Washington Post*

Sputnik was, however, obviously not merely the nine-day wonder. The main outcome for science was that space age truly began, which meant new opportunities to study the outer space and other planets *in situ*, to see the Earth from outside, and perceive the sky beyond the thick veil of terrestrial atmosphere.

Going back to the USSR, one should be glad that by that time strong cooperation and friendship bound two key figures in rocket industry and science: Sergey Pavlovich Korolev and Mstislav Vsevolodovich Keldysh. An interesting twist of history is that now the name of Korolev is acclaimed all around the world, while that of Keldysh stays somewhat in shadow even in Russia. Back then, in 1950 and 1960s it was vice versa. Sergey Korolev, totally classified person, was referred to as anonymous "Chief Designer" in media, and Mstislav Keldysh was a brilliant academic star, the member of the Academy of Sciences of the USSR, its vice-president (1960–61), and then president from 1961 to 1975 (he passed away in 1978). But some part of his scientific life was also "top secret". Few knew that he and his colleagues worked on mathematical

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* The paper is based on the talk given at plenary session on October 2, 2015, in the Russian Academy of Sciences. Necessary supplements and amendments were made to reflect the latest events and changes in Russian space program, adopted in March 2016 — *ed.*

theory for jet aviation, and later for rocket engineers. Later, Keldysh headed a special commission in the Academy of Sciences, which coordinated the works on the instruments for the first full-fledged scientific satellite (launched as *Sputnik 3* in May, 1958).

Shortly afterwards he became the leader of space research in the USSR, which meant that under his leadership a consistent and progressive program was formed, which included in the first place the exploration of the Moon and other planets, accompanied by studies of the space itself and distant objects (we leave out manned space flights, albeit they too were the matter for academic science, but that is another story, so to say).

Sputnik, space and the First Secretary
of the Communist Party — Nikita Khruschev in media

The First Sputnik

Mstislav Keldysh and Sergey Korolev

Keldysh headed the Interdepartmental Scientific and Technical Council for Space Research at the Academy of Sciences of the USSR, established in 1958.

Space exploration began with *Sturm und Drang*, but soon it was clear that real exploration requires some system, and some coordinating center. On July 5, 1963, Mstislav Keldysh sent a letter to the Central Committee of the Communist Party, suggesting a special Joint Space Research Institute to be established within the Academy of Sciences. Such an institute would be entitled to develop the program of space research and exploration for the sake of fundamental science, and coordinate the works on its implementation, as well as develop and build dedicated instruments for space experiments, test them, and install aboard scientific spacecraft. The institute would be "combined" from the groups and institutions already involved in space science, hence the word "joint" in its name.

In the letter Keldysh properly mentioned the international space race: "Such institute will provide and ensure the leading position of the Soviet Union in space exploration in the nearest years and set off its achievements against many specialized space science centres of the USA".

The proposal was approved and accepted, to a large extent thanks to Nikita Sergeevich Khruschev, the First Secretary of Central Committee of the USSR Communist Party. Space in the late 1950s became his favourite child. It is hard to overestimate the role Khruschev played for rapid launch of the national space program. However, while the grand success of *Apollo's* program is justly tributed to the US president Kennedy, in Russia the memory of Khruschev was meticulously erased from public awareness, after he was succeeded by Leonid Brezhnev.

Classified Decree of the USSR Council of Ministers No. 392-147 «On the establishment of the Space Research Institute» was issued on May 5, 1965 (declassified in 2010). It stated that the Institute "is the head organization for science research in space studies, exploration of the Moon and planets of the Solar System, and constitutes the scientific and methodological base for Interdepartmental Scientific and Technical Council for Space Research at the Academy of Sciences of the USSR" (this Council was dismissed in 1992, but revived as Council on Space of the Russian Academy of Sciences, which I am privileged to head today since 2013).

The site for the future Institute was chosen in the outskirts of Moscow, near the highway to Kaluga. Now it's the intersection of two large streets, and — what an irony — bears the name "Keldysh's Square". The actual construction of the Institute's building lasted for many years, and those who work in IKI from its inception remember first "temporary" two-floor houses, which copied standard design of Soviet barber shops. They are still in use, by the way, proving an old wisdom that nothing is more stable than temporary structures.

The staff of Space Research Institute of Russian Academy of Sciences, or IKI RAN (IKI is Russian abbreviation of the full name and in English it is also used as is), in accordance with the initial plan, was completed with scientists and engineers from many other institutes, universities, and design bureaus. Namely, from the Academy there were people from the Interdepartmental Council, who provided organizational backbone for the newborn Institute, and laboratories from Institute for Applied Mathematics (again, the child of Keldysh), the Institute for the Physics of the Atmosphere, Lebedev Institute of Physics, Institute for Computing Technics, Institute for Nuclear Physics (Novosibirsk), Vernadsky Institute for Geochemistry and Analytical Chemistry, Institute for Radioelectronics.

Постановление Совета Министров СССР
«О создании Института космических исследований Академии наук СССР»

№ 392-147 15 мая 1965 г.

СОВ. СЕКРЕТНО

В целях обеспечения дальнейшего развития в Советском Союзе исследований космического пространства, накопления и обобщения научных знаний о космосе Совет Министров Союза ССР ПОСТАНОВЛЯЕТ:

1. Принять предложение Академии наук СССР о создании в 1965 году в г. Москве Института космических исследований Академии наук СССР.

2. Установить, что Институт космических исследований Академии наук СССР является головной организацией по научным исследованиям в области изучения космоса, разработке и изучению научных проблем по исследованию Луны и планет солнечной системы, связанных с космическими полётами, и является научно-методической базой Междуведомственного научно-технического совета по космическим исследованиям при Академии наук СССР.

3. Возложить на Институт космических исследований Академии наук СССР:

– научно-методическое руководство и обобщение результатов работ, проводимых организациями Академии наук СССР, государственных комитетов, министерств и ведомств СССР по исследованию верхних слоёв атмосферы, космического пространства, Луны и планет солнечной системы;
– разработку перспективных комплексных планов исследований космического пространства, Луны и планет солнечной системы, изыскание путей и методов их выполнения в короткие сроки и с наименьшими затратами средств.

4. Академии наук СССР в двухмесячный срок разработать и представить согласованное с Министерством общего машиностроения и Министерством обороны СССР Положение об Институте космических исследований Академии наук СССР, а Комиссии Высшего совета народного хозяйства СССР по военно-промышленным вопросам рассмотреть и утвердить это Положение.

5. Разрешить Академии наук СССР построить в 1965-1967 годах, в виде исключения, в г. Москве для размещения Института космических исследований лабораторные корпуса общей рабочей площадью основного назначения до 30 тыс. кв. метров.

Мосгорисполкому отвести Академии наук СССР для строительства указанных корпусов земельный участок. Строительство корпусов Института космических исследований возложить на Главспецстрой при Государственном производственном комитете по монтажным и специальным строительным работам СССР.

6. Разрешить Академии наук СССР и Госплану СССР, в виде исключения, включить в план капитальных работ на 1965-1966 годы строительство лабораторно-производственных корпусов Института космических исследований без наличия утверждённой в установленном порядке проектно-сметной документации.

Госбанку СССР впредь до утверждения проектно-сметной документации финансировать строительство указанных объектов по проектам и сметно-финансовым расчётам, составленным по рабочим чертежам.

Председатель Совета Министров Союза ССР А. Косыгин

Управляющий Делами Совета Министров СССР М. Смиртюков

АП РФ. Ф.93. Коллекция постановлений и распоряжений СМ СССР за 1965 г. Заверенная копия на бланке.
Советская космическая инициатива в государственных документах. 1946–1964 гг. / Под ред. Ю. М. Батурина. М.: Изд-во «РТСофт», 2008.

Decree of the USSR Council of Ministers establishing IKI

A bulk of scientists came from Lomonosov Moscow State University (MSU). They were extremely active in the very first experiments in space, including Sternberg Astronomical Institute and Skobeltsyn Institute for Nuclear Physics, which belong to MSU. Then there were a number of Moscow educational institutes: Moscow Institute for Physics and Technology, Aviation Institute, Energy Institute, State Pedagogical Institute, Institute for Geodesy and Cartography, Institute for Telecommunications.

From industry came colleagues of S. P. Korolev from Special Design Bureau 1 (OKB-1, future *Energia* Rocket and Space Corporation), Russian Scientific and Research Institute for Space Instrumentation, and other. There were also people from Institute for Atomic Energy (Kurchatov Institute), Meteorological Agency, and some other institutions.

Such a list meant that the Institute was comprised of people with very different mentalities and approaches to science and space research, who were put into a kind of "melting pot". Getting them all together was a challenge, and this challenge was aggravated by the fact, that the nation's leaders very soon lose interest in space research, so that great efforts were needed to bring the missions from design to launch. So, one may say that the Institute has never known easy times, and its leaders just the more so.

Academician Georgy I. Petrov was appointed the first director of the Institute. He was a prominent expert in mechanics, and originated a new branch of physics — space gas dynamics. He also authored an interesting explanation of Tunguska event. He suggested that it was an old nucleus of a comet, consisting from dirty water ice, which entered the Earth's atmosphere. After it disintegrated, no leftovers of the space body itself could be found on Earth other than the traces of the shock wave of the explosion.

Georgy Petrov headed IKI in 1965–73, and was succeeded by Roald Z. Sagdeev, brilliant expert in plasma physics and the youngest academician in that time. Prof. Sagdeev started the age of international collaboration in IKI and, moreover, opened it not only for the exchange of ideas, but for exchange of instruments. That meant that foreign instruments could be installed aboard Soviet spacecraft, which provided and excellent basis for collaboration between people and nations.

Academician Georgy I. Petrov,
the first director of IKI (1965–73)

Academician Roald Z. Sagdeev,
director of IKI (1973–88)

Academician Albert A. Galeev,
director of IKI (1988–2002)

Academician Lev M. Zelenyi,
director of IKI since 2002

The apex of this "golden age" of IKI's history was VEGA project. It included the expedition to Venus, with two landers and two balloons, the first and until now the only atmospheric probes to drift in the alien atmosphere. The second part was Comet Halley encounter with two probes. They flew by the comet nucleus on March 6 and 9, 1986, and were a part of a large space flotilla, which included two Japanese probes *Sakigake* and *Suisei* and European *Giotto* spacecraft. Besides *Vega*'s own scientific tasks, they provided key data on the comet location for European probe *Giotto* (project *Vega Pathfinder*). Thanks to it, ESA's experts were able to bring *Giotto* as close to comet nucleus as 596 km. To coordinate these efforts, InterAgency Consulting Group (IACG) was established. Nine countries participated in scientific instrumentation of *Vega* spacecraft, which made it truly international. VEGA accomplishment was acknowledged by the nation leaders, and in 1986 IKI was awarded Lenin Prize.

An unexpected interest to the project and its results came from the Catholic Church. At that time they discussed the idea if Halley Comet could be the Star of Bethlehem. It turned out in the very end to be not the case, but IKI's director and other involved scientists were invited to visit the Pope Saint John Paul II.

Sagdeev's successor, academician Albert A. Galeev, became IKI's director in 1988. "The wind of change" had already been blowing through the USSR in the end of 1980s, but changes were painful and sometimes the effect was devastating, as it was for Russian science. From 1988 to 2002, the years when Albert Galeev headed IKI, much was lost, and only few successful missions were launched: *Granat* astrophysical observatory and *Interball* multiprobe mission to study the Earth's magnetosphere. Still, despite the difficulties, space science in Russia and IKI survived, and full tribute should be paid to Albert Galeev.

He is a remarkable scientists, student of Sagdeev, and also an expert in plasma physics. He started working at IKI in 1973, where he headed Space Plasma Department. He elaborated a theory of explosive reconnection of force lines in the tail

of the magnetosphere, the theory of weak wave interactions in plasma, and, together with Sagdeev, neoclassical theory of transfer in tokamaks. He suggested a theory, explaining solar wind acceleration from coronal holes by Alfven waves.

His greatest achievement as a director (since 1988) was probably the fact that the Institute not only survived, but managed to keep its "backbone", which are scientific traditions and experience in space engineering. We did not escape brain drain, which was and is a plague of Russian science, but somehow it did not affect IKI to the point of no return. The people who worked then at the Institute, might remember that there were no arrears of salaries — a rare case in that-days Russia.

Moreover, the Institute managed to bring into space two international projects: *Granat* astrophysical observatory and four *Interball* spacecraft to study the near-Earth plasma. Both were successful and yielded a lot of scientific information to work with.

Unfortunately, the large planetary mission *Mars 96*, also an international project, was lost because of the booster failure. This was a bitter blow for the planetary program, and damped its further development for many years. Even now we feel the aftermath of this tragedy.

Albert Galeev decided to step down because of health, and in 2002 I was elected director of the Institute.

I graduated from the Moscow Institute of Physics and Technology (Department of Aerophysics and Space Research) in 1972 and ever since I work at IKI. I became interested in space plasma physics, and namely the theory of collisionless plasma, magnetic fields reconnection, charged particle dynamics, magnetosphere physics. I also was a PhD student under Galeev's supervision.

The beginning of 2000s was the end of the toughest times (so far), but still far from tranquility. What was the most grievous is the fact that one-and-a-half-decade-long hiatus sorely injured the industry and the damaged could not be amended at once. The first successful full-fledged scientific spacecraft was launched in 2011, *Spektr-R* radio observatory, I will speak about below.

In 2005 the Federal Space Program for 2006–2015 was adopted, which prescribed the sequence of missions in various areas of space research and exploration. It has not been fully implemented, and today (the end of 2015) we are on the verge of new space program to be adopted in the near future*. IKI is principal organization for many space missions to be included in the program and prime contractor for Roscosmos, that's why Federal Space Program, along with the Academy of Sciences, plays an important part in the life of the Institute.

Today, IKI's expertise includes several areas of space research, both in their experimental and theoretical aspects: planetary exploration, plasma physics, astrophysics, Earth observations from space, space dynamics and celestial mechanics, space instruments design and development. The Institute works closely with many universities and educational institutes, as well as with high school students, who are already interested in space physics.

To give even a brief overview of all accomplishments made in these 50 years, one would have to write a book comparable with the whole volume. I will concentrate on the present day and the most important future projects, which, as we hope, will be the beginning of a new era of space exploration.

* Finally adopted in March, 2016 — *ed*.

PLANETARY RESEARCH IN IKI

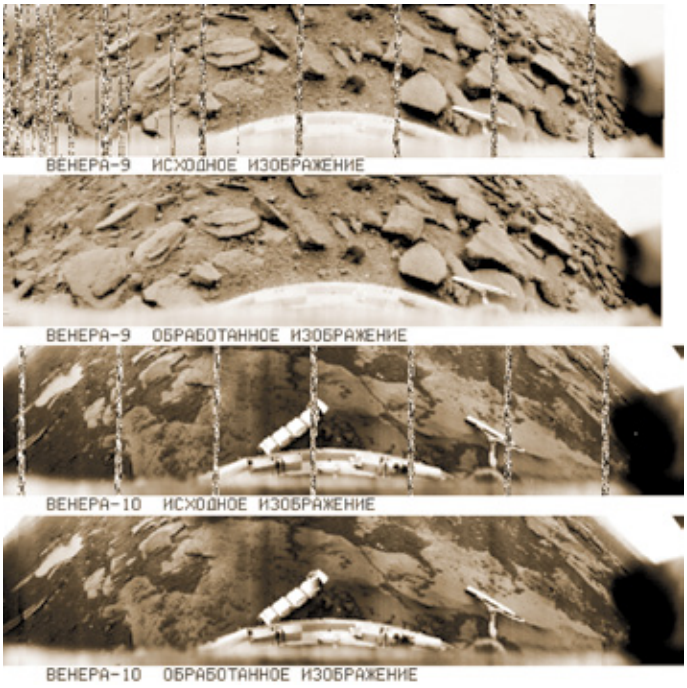
Just after its founding IKI started working for planetary program of the USSR. It included at that time studies of the three nearest objects (if we do not account for asteroids): the Moon, Venus, and Mars. The most successful was, of course, Venusian and Lunar programs. For different reasons, IKI did not play significant role in Soviet lunar program, even though there was a special department dedicated to Moon research. It was headed by Kirill P. Florensky, the son of Russian philosopher Pavel Florensky (those interested in Russian religious philosophy would certainly remember his name). Professor Florensky was talented as a scientist and a leader of a department. He did not try to rival such "lunar experts", as engineers, who made the spacecraft and most of instruments for Moon, but developed its own niche instead. The role of IKI was to provide scientific premises for further exploration. However, because of several sometimes personal reasons the department was transferred to another institute (Vernadsky Institute for Geochemistry and Analytical Chemistry) soon after *Luna 24* mission, the last in Soviet *Luna* series.

The most important for IKI were Martian and especially Venusian programs, i.e. the planets with atmospheres.

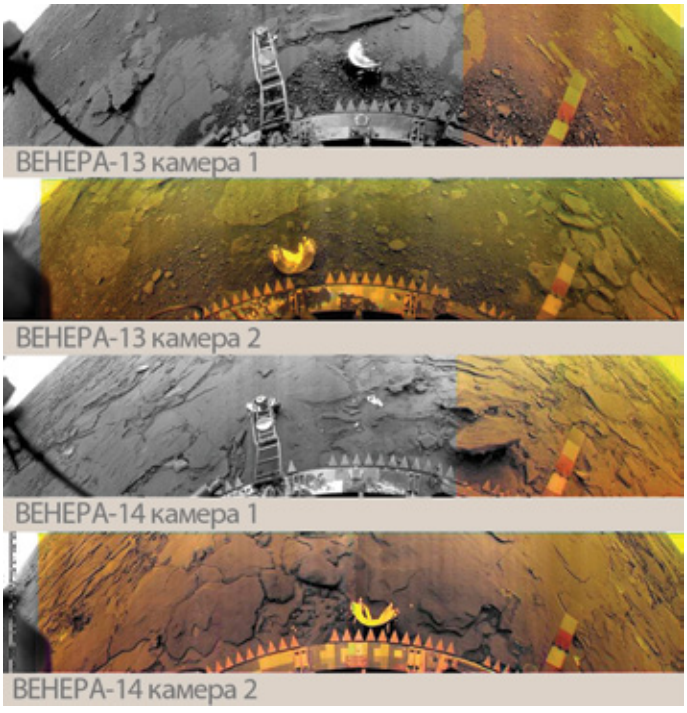
The person, who founded the school of planetary science in IKI was Professor Dr. Vasiliy I. Moroz, the first head of the planetary department. He was also the founder of the scientific school on planetary atmospheres and the originator of the infrared spectrometry in Russia.

Dr. Kirill P. Florensky
(1915–82)

Professor Dr. Vasiliy I. Moroz
(1931–2004)



Venus panoramas by *Venera 9*, *10* (1975)



Venus panoramas by *Venera 13*, *14* (1981)

VEGA spacecraft before the launch

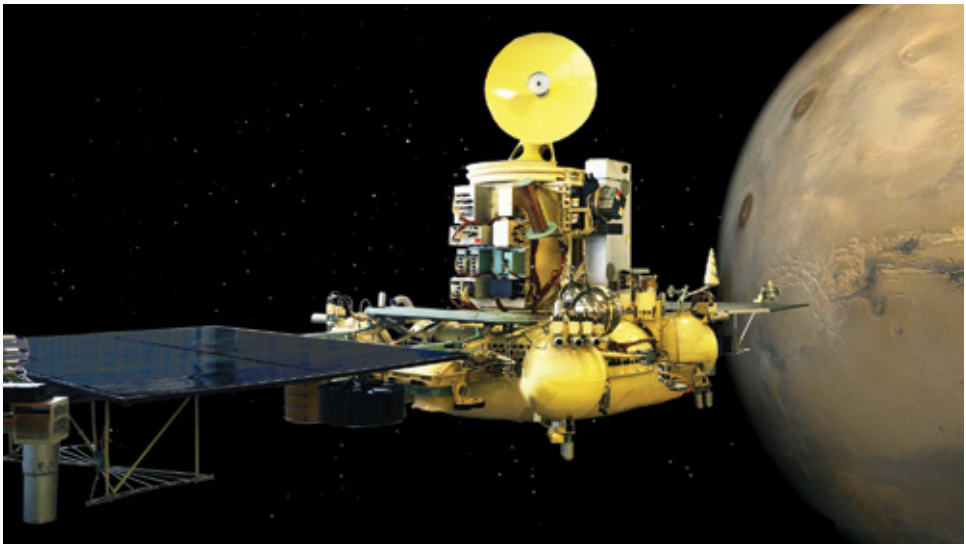
The IR-spectrometer on orbit is an effective tool of planetary exploration, since the planetary IR-spectrum contains distinctive bands of gases in the atmosphere, information of its temperature vertical profile, and surface composition, of the composition and distribution of the aerosol component. The obtained information enables to estimate the conditions on the planet, particularly its dynamics, and is used to constrain atmospheric models.

For IKI Venus missions started with participation in *Venera 9* and *10* (1974–86). Venusian program included landers, orbiters, remote sensing of the planet, and *in situ* experiments, crowned with VEGA project. After this comprehensive studies we knew that Venus is indeed a planet of storms (the title of science fiction movie by Pavel Klushantsev), with recent and probably ongoing volcanism, very strong greenhouse effect, clouds made of sulphuric acid, and most likely never inhabited even by the post primitive microorganisms.

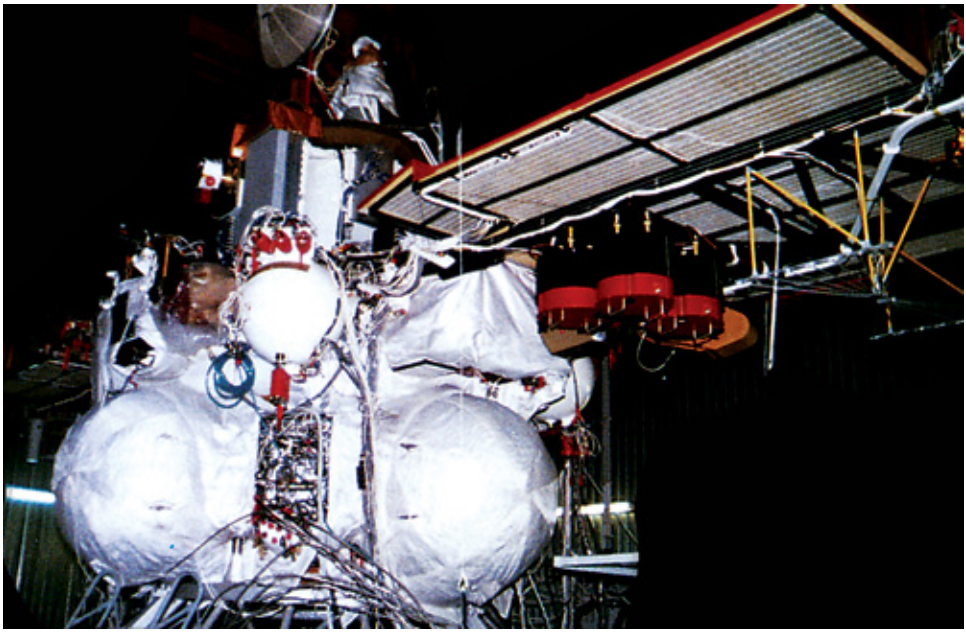
Martian missions were much less successful. IKI immersed into this topic in 1965. There was a large gap between the *Mars 4*, *5*, *6*, and *7* launch in 1973 and "return" to the Red planet in 1986 with the spacecraft *Phobos 1* and *2*. The initial experiments yielded important results, such as the great role of ionosphere in the interaction with the solar wind, since Mars had been found to lack intrinsic magnetic field. *Mars 2*, *3*, and *5* discovered that plasma envelope of Mars resembles that of the Earth, consisting of a bow shock, magnetopause with a boundary layer, and magnetic tail with heavy ions of ionospheric origin.

VEGA lander on the Venus surface.
Artistic impression

VEGA flyby module near comet Halley.
Artistic impression

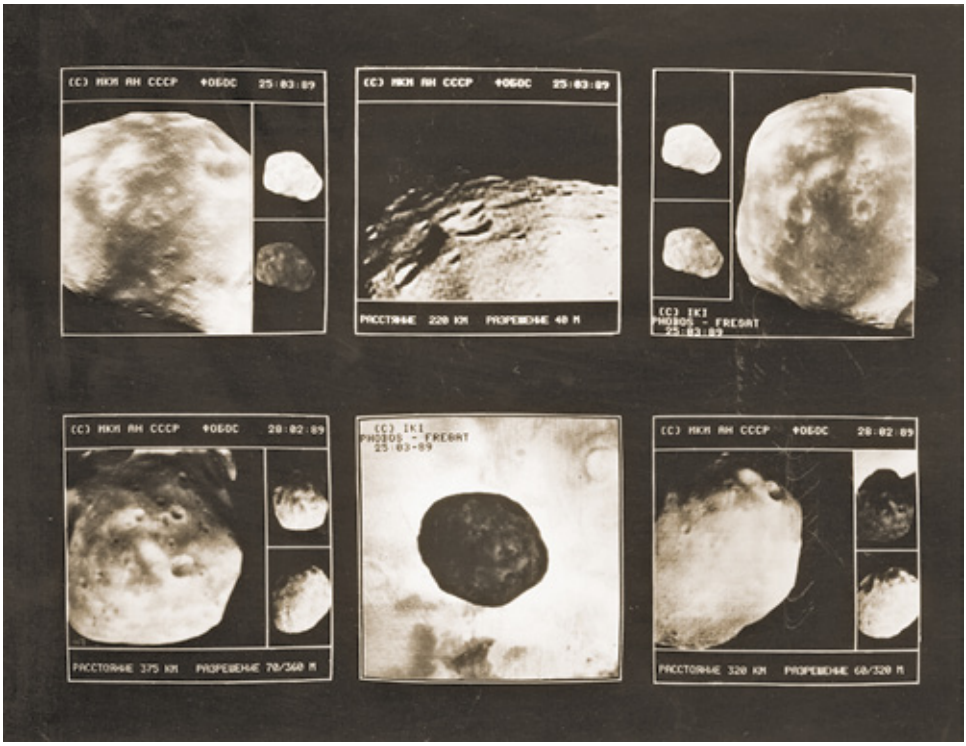


Phobos spacecraft near Mars. Artistic impression



Phobos spacecraft at the assembly workshop

Still, these results were not so impressive, if compared with the achievements of the USA. *Phobos 1* and *2* (1986–87) were partial success, we measured the plasma parameters near Mars and found, in particular, that the pick-up of planetary ions by the solar wind and their outflow through the magnetotail were the main mechanism of atmospheric loss. Also, this project gave first reliable estimated of this outflow.



Mars and Phobos images acquired during *Phobos* mission (1988)

Unfortunately, later missions to Mars ended with tragedies: *Mars 96* and *Phobos Sample Return* projects (1996 and 2011 respectively) in post-Soviet Russia were bitter blows, because spacecraft did not even leave the low-Earth orbit.

These two projects were in the same time the only national planetary missions after 1988. Still, IKI was able to continue scientific research with its own instruments, which now were installed aboard foreign missions. Federal Space Agency, Roscosmos, made it possible for Russian scientists to participate in the scientific payloads of missions, the instruments for which are usually selected through open and severe competition.

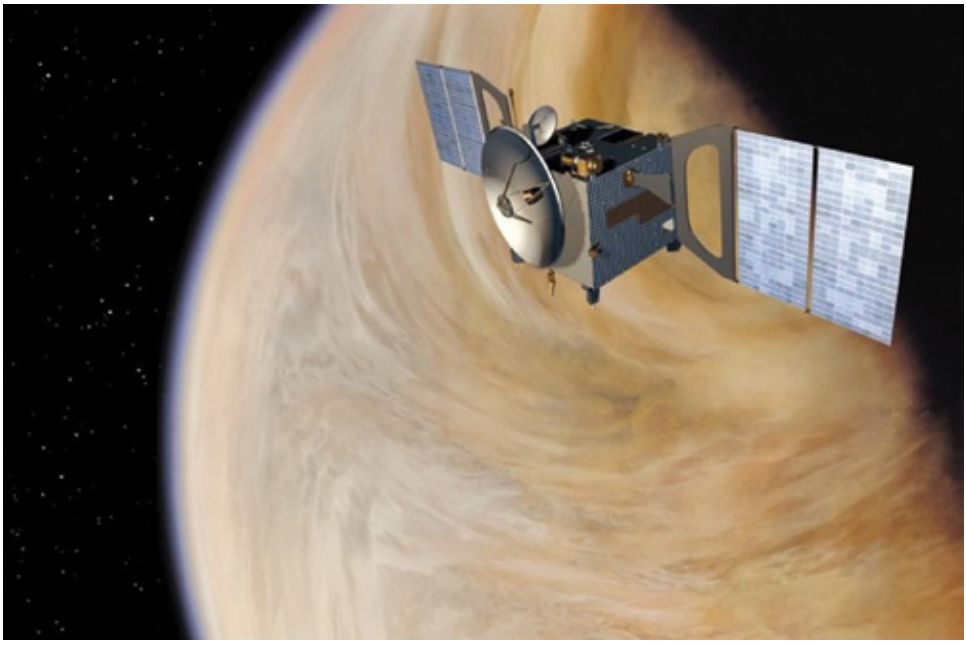
Joint missions with NASA were aimed at Mars. The first were two spacecraft of *Mars Surveyour* program, but, unfortunately, the missions itself were failures. Mars is indeed a hard nut to crack. However, we went on, and the outcome was rewarding. IKI participated in *Mars Exploration Rovers* program with two Moessbauer spectrometers, but for us more significant was *Mars Odyssey* (NASA, 2001), where High Energy Neutron Detector, or HEND (also known as part of GRS experiment) was installed. It provided the most convincing evidence that the upper layer of Martian surface contains water in the form of ice (permafrost) or hydrated minerals. HEND maps are used now to pinpoint the most interesting areas for further exploration of the planet. It was succeeded by DAN experiment, now working onboard *Curiosity* rover, which studies the distribution of hydrogen in the shallow subsurface of Gale crater. According to DAN, the crater is rather dry place, with weight content of water almost never higher than 6 %, but in May, 2015 it managed to find an anomaly — a region with relatively high water content.

Close collaboration with European colleagues included orbital missions to Mars and Venus: *Mars Express* (bearing the legacy of *Mars 96*) and *Venus Express*. The latter was the first dedicated mission to Venus in more than 10 years, and it highlighted many important questions for further studies. IKI contributed to two instruments aboard the spacecraft: SPICAV/SOIR (UV- and IR-spectrometer) and PFS (Planetary Fourier Spectrometer, which, unfortunately, was not able to provide scientific information, because the mechanism, which should have pointed it to the planet, did not work properly). IKI also participated in three science teams of the spacecraft.

HEND neutron detector aboard Mars Odyssey spacecraft

Venus Express was able to detect ozone (for the first time) in Venusian atmosphere, to register "glory" — kind of glow in the upper cloud layer, and give new D/H ratio, which turned out to be 240 times higher than that on Earth. Moreover, it continued the measurements of atmospheric composition made earlier by Soviet and American spacecraft, providing new reference data for modeling and studies.

Venus Express ended its mission in the late 2014. Now, the one spacecraft working near the planet is Japanese *Akatsuki*, which was brilliantly inserted into the orbit around Venus after it missed the target for the first time in 2010.



Venus Express near Venus, artistic concept © ESA

We too think about going back to Venus. For a long time we have been developing a project of a lander, which will be able to survive on the surface for much longer time that its predecessors, and was named *Venera-D*. This project experienced many difficulties, because of the scarce financing, and most likely it will be implemented in the late 2020s. Now we are considering a to invite our American colleagues to participate in it, which could bring together our mutual interest to the planet. A joint Venus mission Science Definition Team was formed, to formulate specific goals of such mission and search for a way to bring it to life.

While Venus is now a faraway project, Mars becomes nearer, since Russia entered *ExoMars* project. It is a cooperation between ESA and Roscosmos (since March 2013), and it envisages at least two missions to be launched in 2016 and 2020.

Main goals of *ExoMars* is to search for signs of past and present life on Mars, to study atmospheric trace gases and their sources, Martian climate from orbit and from the surface, and to investigate the water and geochemistry of shallow surface.

The first mission was already launched on March 14, 2016. The *Proton* rocket for the launch was provided by Roscosmos. It consists of the *Trace Gas Orbiter* (TGO) and *Schiaparelli*, an entry, descent and landing demonstrator module. TGO will perform a very complete study of Martian atmospheric trace gases, some of which may inform us about possible ongoing biological or geological processes, map shallow subsurface water deposits, and obtain stereo images of the surface. Its payload includes two instruments made under IKI's lead. The first one is Atmospheric Chemistry Suite (ACS) — a set of spectrometers designed to study minor atmospheric species, and first of all methane, which may be a sign of present biological activity. The second is Fine-REsolution Neutron Detector (FREND), which will continue exploration of Martian subsurface water deposits with spatial resolution much higher than that of its predecessor HEND.

Both instruments were successfully switched on during first flight tests, and now wait for the arrival to Mars (scheduled for October, 2016). Several detectors of FREND were working during the cruise phase to monitor radiation environment during the flight.

The second *ExoMars* mission, being prepared for launch in 2020, comprises a European rover and a Russian stationary surface platform. The rover combines the capabilities to move on the Martian surface and to drill to a maximum depth of 2 meters. The rover's objective is to search for signs of past or present life by collecting and analysing subsurface samples. It bears two instruments, which are built in IKI. The descent module to land on Mars is provided by Roscosmos. After landing and rover egress, the Russian surface platform will investigate the environment in great detail. Scientific payload of the platform are developed under the lead of IKI and consists of 13 instruments, including two European. The *Proton* launcher for this mission is also provided by Roscosmos.

We also dream about going back to Phobos. Unfortunately, we did not manage to reach it in 1986 and 2011, but it is still an interesting target and probably a key to the history of the early Solar System. The ultimate goal is to bring back a sample of Phobos regolith to be able to study it in the Earth's laboratory. The mission was nicknamed *Boomerang*, and it can be implemented in the second half of 2020s.

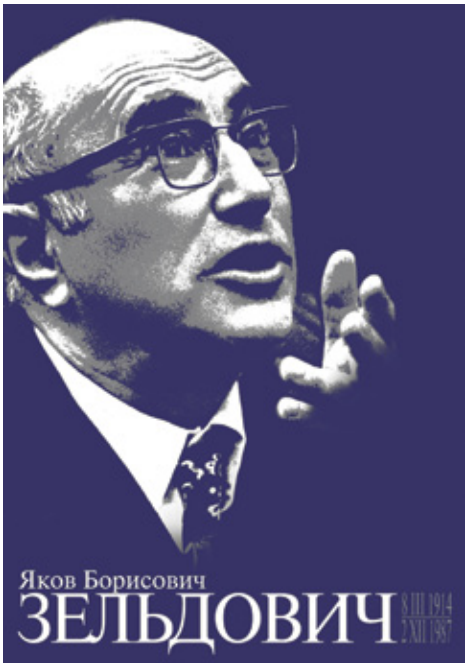
Meanwhile, we are also participating in joint ESA-JAXA's *BepiColombo* mission to Mercury, scheduled to 2017, and IKI contributed to several instruments aboard two spacecraft.

ASTROPHYSICS

Astrophysics is extremely vast branch of space science, and IKI has its own specialization, which are radioastronomy and radio interferometry, high energy and microwave astrophysics, and, last, but not the least, theory and modeling.

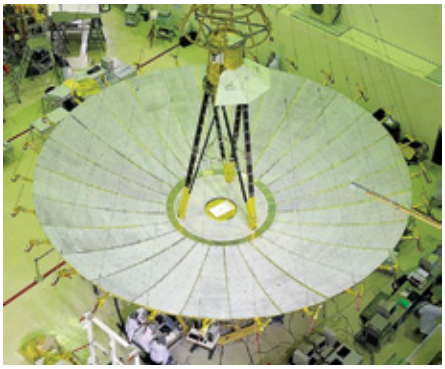
Two great scientists originated astrophysics in IKI: Yakov B. Zeldovich and Iosif S. Shklovsky. In the very beginninng dedicated astrophysical experiments were a piggyback payload aboard planetary missions. Gradually, however, studies of stars, galaxies, and interstellar and intergalactic medium, observations of distant objects separated and grew into a branch of science totally in it's own right.

Several experimental milestones are to be mentioned. The first one, ironically, is not a space mission, *sensu stricto*, but the method, which, first, began a new age in radioastronomy, then, second, opened new era in international collaboration, and, third, provided an impetus for a new generation of space missions. I am speaking about very long baseline interferometry, or VLBI. The idea that two radio telescopes sufficiently far from each other can provide much better angular resolution was first proposed by Leonid I. Matveenko, then in the Lebedev Institute of Physics (FIAN), in 1962. I won't go into details, but because of different reasons first observations using VLBI technique were made not in the USSR, but between Canada and the USA. However, Prof. Matveenko managed to persuade many authorities to give green light to the first experiment with Green Bank Observatory, the USA, in 1969. In the same year this experiment was transferred to IKI, and in 1971 first observations of selected quasars (also with Goldstone radio observatory) were run, and the method fully justified itself.



Dr. Yakov B. Zeldovich (1914–87)

Dr. Iosif S. Shklovsky (1916–85)



Spektr-R mirror deployed at Lavochkin Association during tests

The next step was quite logically to place one of the radio telescopes outside the Earth, to make the baseline longer than the Earth's diameter. The idea was developed first in IKI, then, after some of IKI's staff transferred to FIAN, by FIAN's AstroSpace Center. It matured during the most difficult times for all space science, and finally we got *RadioAstron*, aka *Spektr-R*.

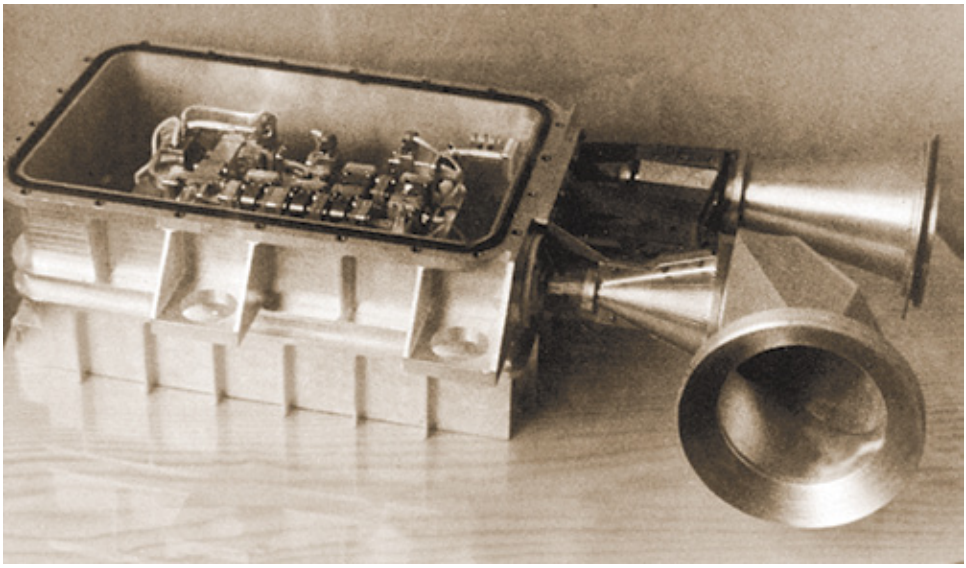
Launched in 2011, it is essentially a space-based radio telescope in a high elliptical orbit, sometimes going farther away from the Earth, than the Moon. It works with many ground-based radio facilities, and by now its collaboration has already published several very interesting results. In IKI we are still very much engaged in ground-based radio observations. Moreover, IKI installed a small set of plasma instruments aboard the spacecraft, *Plasma-F* experiment, I will talk about in the relevant section.

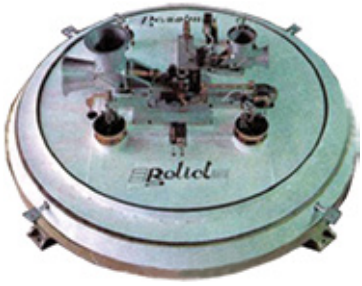
The second milestone was first observations of cosmic microwave background radiation, CMB, and its anisotropy. The experiment, called *Relikt*, was placed aboard *Prognoz 9* spacecraft, whose primary aim was plasma studies (as I said, some astrophysical experiments were an additional payload). *Relikt* as an instrument was quite simple, consisting of microwave radiometer, low-sidelobes antennae, radiation cooling system.

Project *RadioAstron* — 10 m radio observatory in space

But it managed to get first radio map of the Universe at 36 MHz frequency. CMB anisotropy was estimated and the excess radio brightness of the Galaxy plane at 36 GHz was discovered. We wanted to continue the experiment with more sophisticated instruments, but political and inevitable financial changes of *Perestroika* did not allow us to bring *Relikt 2* into space. The discovery of CMB anisotropy was duly acknowledged by Nobel committee: John Smoot and George Mather, the scientists who made COBE missions (1989, NASA), were awarded Nobel Prize for Physics in 2006.

The third milestone, or rather a sequence of milestones, which, we hope, will continue in the nearest future, is X-ray astronomy. It is associated with the name of one of the greatest physicists, triple hero of socialist labor, academician Ya. B. Zeldovich.

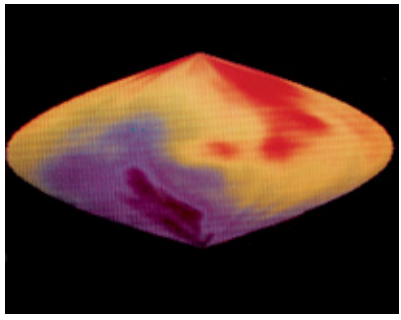




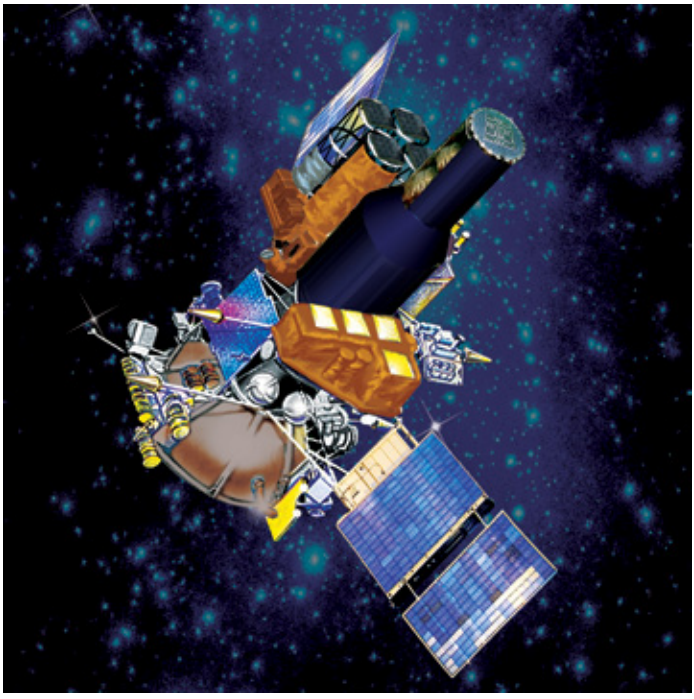
Relikt instrument set aboard *Prognoz 9* spacecraft

In the early 1960s he established a department of theoretical astrophysics within the Institute for Applied Mathematics of the Academy of Sciences of the USSR. In 1974 by invitation from Roald Sagdeev, Yakov Zeldovich arranged and took the lead of the theoretical astrophysics department in the relatively young IKI of the Soviet Academy of Sciences. Several years later it included two experimental laboratories and was named "High-Energy Astrophysics Department".

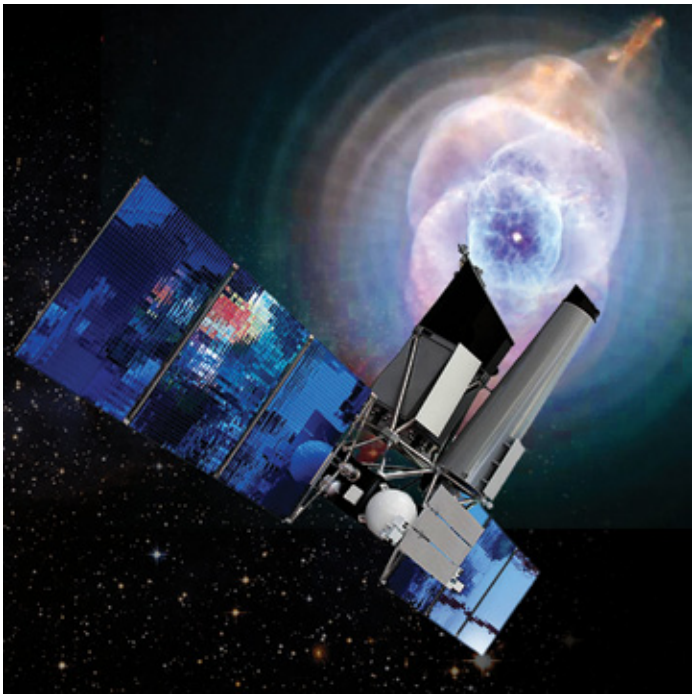
The first experimental results related to the Soviet-French experiment SNEG-2MP9 on the *Prognoz 9* satellite (1983–1984), but the true start was *Rentgen* observatory onboard *Kvant* module of *Mir* space station. It was a unique observatory with four instruments, three of them were manufactured in the Western European institutes, and one in the USSR, a hard X-ray instrument *Pulsar X-1*. It worked in 1987–2001, but its first years were the most fruitful.



The map of Cosmic Microwave Background on the basis of Relikt data



Granat international observatory. Artistic concept



Spektr-Rentgen-Gamma X-ray observatory. Artistic concept

Thanks to *Kvant*, IKI's astrophysicists were able to observe a unique very close supernova in the Large Magellanic Cloud, the brightest one over the last 400 years, named SN1987A. *Kvant* telescopes immediately started observations. At the same time, theoreticians in the IKI High-Energy Astrophysics department calculated and predicted the emission spectrum resulting from the radioactive decay of nickel-56 synthesized during the collapse, which was later confirmed by the actual data.

Virtually at the same time with preparation for the *Rentgen* observatory launch, IKI was conducting works on establishing a space observatory on an independent satellite for detailed research of astrophysical objects within energy range of 2 keV through 100 MeV. The observatory was named *Granat*, it was an international project involving Soviet, French, Danish, and Bulgarian scientists. It worked in 1989–99, and was extremely successful, not to mention that it operated throughout the most difficult years for all our science.

Now IKI is participating in the international *Integral* astrophysical project (led by ESA, in orbit since 2002). Russian scientists dispose of 25 % of its observational time, and several interesting projects were done using this quota, such as discovery of electron-positron annihilation line in the Galactic Center and observations of radioactive ^{56}Co after supernova explosion in galaxy M82.

Scientific data obtained within the Russian observation time quota are transferred to the International Scientific Data Center of the *Integral* observatory (Switzerland) and then become available for Russian scientists via Russian Scientific Data Center (RSDC) of the *Integral* observatory hosted at IKI's High Energy Astrophysics Department.

The flagship mission to be implemented, hopefully, in the nearest future, is *Spektr-RG* observatory, now joint Russian-German project bearing two X-ray telescopes: *eRosita* (Germany) and ART-XC (Russia).

Its aim is to provide the most minute census of massive galaxy clusters and supermassive black holes in the observable Universe. These data are directly connected with the Universe properties and evolution, and nature of the dark energy and dark matter. The observatory will be launched to the outer Lagrangian point of the Sun-Earth system and shall operate there for seven years at least. The main goal is all-sky observation in the X-rays with the sensitivity surpassing all previous surveys. It is expected that during the sky observation *Spektr-RG* will discover all massive galactic clusters in the observable Universe (around 100 000), around 3 million of accreting supermassive black holes, hundreds of thousands of stars with active coronae and accreting white dwarfs, tens of thousands of star-forming galaxies, and many other objects including those of unknown nature.

PLASMA PHYSICS

Up until the discovery of dark energy in the very end of 20th century plasma was deemed to be the most common state of matter in the Universe. The statement, however, still holds true, if we limit the discussion with baryonic matter. Plasma is indeed ubiquitous. It envelopes the Earth as the ionosphere, it fills the near-Earth space within the boundaries of our magnetosphere; outside it, we meet solar wind — once again, a flux of plasma; and, following it we sometimes meet some plasma bubbles, created by other planets in the Solar System, and farther away, with the solar wind we crush into interstellar medium, which is again essentially plasma.

Dr. Konstantin I. Gringauz
(1918–93)

All these plasma objects interact and influence each other in a way and in a scope, that we cannot model elsewhere but in space. So, space is a natural plasma lab, and from the very first missions plasma instruments were included in scientific payloads. Then, there were and are many dedicated plasma missions, and this field of space science is one of the major for IKI.

Just to remind what we started from, I say, that first plasma experiments were run aboard *Luna 1*, *2*, *3* and *Venera 1* spacecraft, which confirmed many theoretical predictions made earlier, and experimentally discovered solar wind (rather unexpected) and the Earth's plasmasphere and it's sharp boundary — the plasmapause.

The pioneer of these researches was Konstantin I. Gringauz (1918–93), the radio engineer and researcher. His team made the famous radio transmitter onboard *Sputnik 1*, whose *Beep... Beep... Beep* heralded the Space Age. Later, when IKI was created, Konstantin Gringauz and his team joined the newly founded IKI. His second major discovery was made during VEGA mission. *Vegas*' instruments brought back experimental evidences of cometary bow shock existence and of the solar wind pre-shock deceleration by picked-up cometary ions. Moreover, previously unknown cometary plasma structures — the "cometosheath" and "cometopause" — were discovered, in some respect similar to the structures near the Earth, and in some respect different, because, contrary to the Earth, comets do not have intrinsic magnetic field.

Another founder of plasma physics in IKI was its second director, academician Roald Sagdeev, who came to space research from theoretical plasma physics. By the time he was invited to join IKI, Sagdeev had already developed a totally new theory of collisionless shocks in plasma, and that phenomenon turned out to be one of the most important in space, where the density of plasma particles is extremely low.

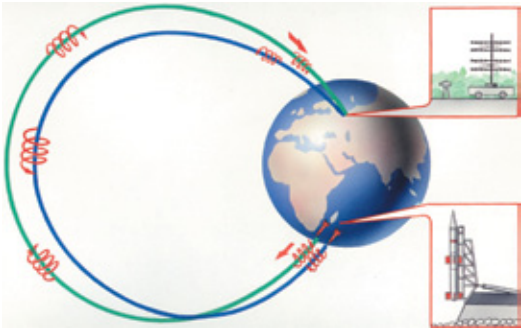
During 1970s and 1980s numerous space and Earth experiments were run, the most notable of which were ARAKS, ARCAD, and *Prognoz* series (I omit many others, and I beg my colleagues to pardon me for this voluntary decision). During Russian-French ARAKS experiment (1975) electron flux was injected from sounding rockets, launched from Kerguelen (France). Simultaneously, plasma parameters with the help of optical and radar instruments were measured and electromagnetic waves were detected in the region near Arkhangelsk (the USSR), which is located on the other end of the flux tube of the Earth's magnetic field (so called magnetic conjugation). In the frame of ARCAD-3 project (again Soviet-French collaboration) on 21 September 1981 a satellite was launched equipped with 9 scientific instruments.

It measured plasma parameters, energetic particles, and electromagnetic waves as well as DC magnetic and electric fields throughout six years.

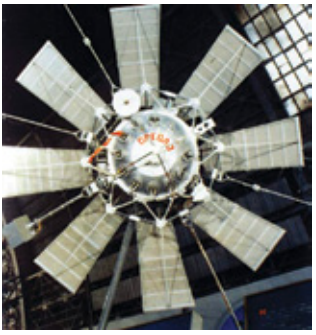
ARCAD-3 was headed from French side by H. Reme, and from Russian side by Yuri I. Galperin, prominent magnetospheric physicist, whose interests were mainly connected with the physics of auroras.

Slightly deviating from the main topic, I would like to say that Russian-French collaboration and personal contacts, which originated then, overcame the difficulties of *Perestroika*. In 2000s IKI participated in a joint Russian-French laboratory "Space Physics" (COSMOPHYSIQUE). From French side it was headed by J.-A. Sauvaud and now by B. Laurand, from the Russian side — L. M. Zelenyi. Recently it was expanded to International Research Network «Helio-Plasmas (H-P).

ARAKS experiment

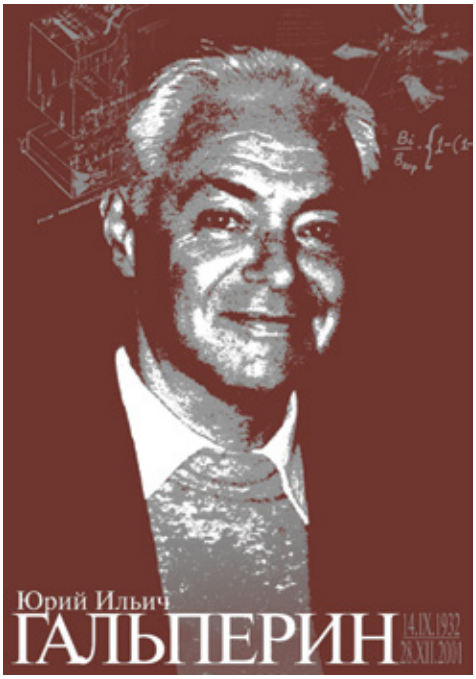


Scheme of the ARCAD experiment



Aureole satellite for ARCAD-3 project

Yuri I. Galperin during ARCAD experiment



Dr. Yuri I. Galperin
(1932–2001)

General Gennady M. Tamkovich
(1936–2006)

The laboratory is supported by French CNRS and Russian Foundation for Basic Research, and runs several working groups in the studies of heliosphere, planetary atmospheres and magnetospheres, plasma acceleration in planetary magnetospheres, wave-particle interactions, and magnetosphere-ionosphere-atmosphere interactions.

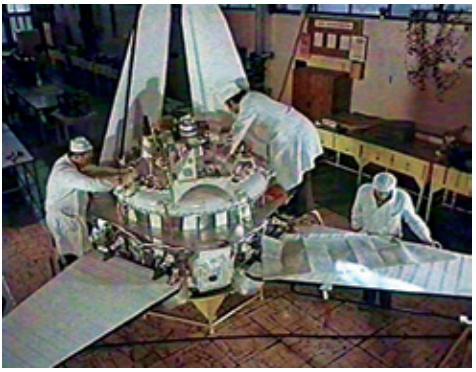
Extremely fruitful were *Prognoz* series, which included 12 spacecraft launched from 1972 to 1996. Most of them were mainly dedicated to solar wind and magnetosphere studies (the only one, which also carried astrophysical experiment, was *Prognoz 9*, aka *Relikt*, see before). The last two of them were launched in 1995 and 1996 as a part of one INTERBALL project, for which I acted as a Principal Investigator. INTERBALL was to my mind indeed a miracle, because we managed to bring it into space during the harshest years for science in gloomy Yeltsin times.

The person, who made it possible, was General Gennady M. Tamkovich, deputy director of IKI and the head of State Commissions, which tested and launched several scientific spacecraft. He used all his influence and contacts in the industry to bring this mission to space.

Moreover, we coped to keep scientific collaboration. Eighteen countries participated in the project. It was one of the very first multiprobe missions, because it included four spacecraft (two satellites and two subsatellites, made in Czech Republic), which were launched into different orbits. One pair studied the tail of the Earth's magnetosphere, the other circled in auroral regions. This project was a part of International Solar-Terrestrial Physics (ISTP) program, and contributed a lot into our understanding of plasma processes in the Earth's magnetosphere. Among

other results, *Interball* spacecraft happened to register precise time of substorm onset in the middle tail ~15R_E because of magnetic reconnection in the magnetotail.

Now multiprobe missions become more and more common, since scientific community agree that simultaneous measurements in different regions of space give us far more information about plasma dynamics. European CLUSTER (also comprised of four spacecraft), NASA's THEMIS and MMS succeed the idea, and we are very grateful to our European and American colleagues for the opportunity to participate in data analysis, provided by these missions.



Interball satellite at assembling facility

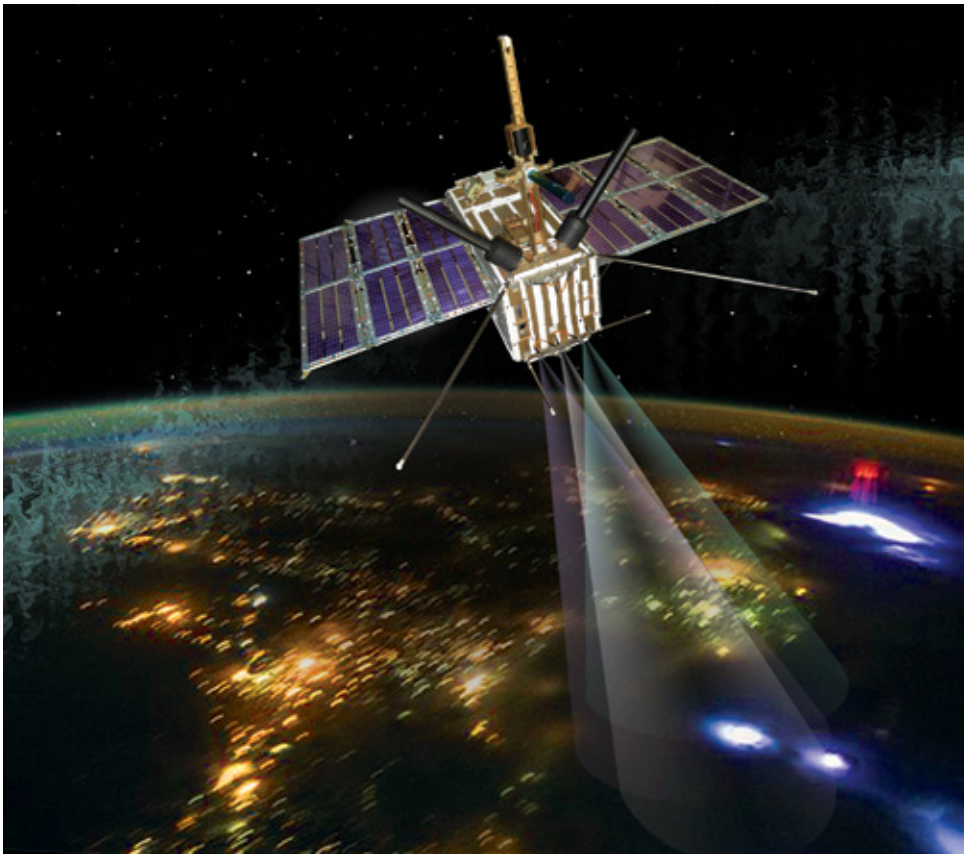
Interball satellite in the orbit. Artistic impression

As for Russian plasma experiments in space, I would say that the first ten years of the century were not total loss, since there were CORONAS solar observatories (under the leadership of FIAN and Pushkov Institute for Earth Magnetosphere, Ionosphere, and Radiowave Propagation, or IZMIRAN). To our great sorrow, the last of them, *Coronas-Foton*, did not complete its nominal mission, and now Russia has a number of more or less separate experiments, one of which is IKI's *Plasma-F* aboard *Spektr-R* spacecraft, described above. *Plasma-F* is rather modest (with respect to its mass) set of instruments, which study solar wind outside the magnetosphere and Earth's plasma inside it. Since the orbit of the spacecraft brings it sometimes farther than the orbit of the Moon, we have a chance to study vast regions of near-Earth space. Slovakia, Czech Republik, Greece, Ukraine, and China participates in the experiments of *Spektr-R*.

Plasma-F has been working since its launch in 2011, and found some interesting details about solar wind. It's very high temporal resolution provides new important data on the fine structure and properties of the solar wind, unavailable in the previous experiments. For example, it was discovered that the solar wind flux is comprised of many beams of smaller scale, whose direction reflects the magnetic structures in the photosphere. Brake of spectral slope was found at the frequency of 1–2 μHz, which reflects the differences between inertial and dissipative scales. In inertial region we observe Kolmogorov spectrum, while on higher frequencies the slope increases.

One of the two instruments within *Plasma-F* suite: Energetic Particles Monitor (MEP)

Another interesting experiment of the recent times was *Chibis-M* microsatellite, which studied electromagnetic phenomena in the Earth's upper atmosphere associated with lightnings. The craft was rather small, just 42 kg with the payload (hence the name *Chibis*, or 'Lapwing'), but it was the first one to be built entirely or almost entirely in IKI on the funds supplied by the Academy of Sciences. We did have strong collaboration with other Russian and foreign institutes, but the platform, i.e. service and housekeeping systems were designed and built in Special Design Bureau of IKI, which is located in a small town of Tarusa, in Kaluga region (the very Kaluga, which was home for Konstantin Tsiolkovsky).



Chibis-M microsatellite in the flight. Artistic impression

Chibis-M microsatellite in the transportation/launch container to be installed in *Progress-M* cargo ship

Chibis-M deployed from the container

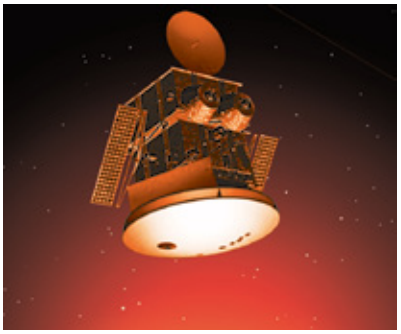
Another peculiar feature of the mission was the orbit insertion scheme. Having no thrusters to maintain the orbit, *Chibis* was bound to last as long as his orbit would allow him. To increase the lifetime, *Progress* cargo ship was used after it had fulfilled its initial mission on ISS supply. Having undocked from the ISS, *Progress* used the fuel leftovers to go higher, where *Chibis-M* was released at 550 km from the special transportation/launch container, also developed and built in IKI. Total lifetime of the satellite in this orbit two times exceeded the initial mission plan for 1 year: it operated in orbit from January 25, 2012 until October 15, 2014.

It was our second microsatellite, since the very first one was Russian-Australian spacecraft *Kolibri*, which worked in 2002 and measured the parameters of magnetic field and particles in the low-Earth orbit. *Chibis-M* was however far more advanced, proving the suggestion that low-cost miniature spacecraft are capable to yield very interesting results, that was fine structure of lightning discharge. More specifically, lightnings, known to generate electromagnetic waves in a very wide energy range, turned out to be more complex phenomena to be described with the help of fractal mathematics. Now we are thinking about the next "small bird", *Chibis-AI*, which will be targeted at studies of atmospheric electricity and discharges between the clouds.

The closest future missions within the Federal Space Program are *Resonance* multisatellite mission and dual *Interhelioprobe* system. Both have a long history, and their current schemes differ very much from what was initially suggested before, in the Federal Space Program 2006–2015.

Resonance mission is still aimed at the inner magnetosphere of the Earth. We want to put several identical spacecraft in orbits that will allow to study ring current, outer radiation belt, plasmasphere, electron-wave interactions, and phenomena in auroral regions. The program envisages that one satellite is launched in 2021, to be followed later by the others, hopefully prior to 2025.

The aim is to put several spacecraft into one magnetic flux tube, so that they are skimming the latter and study interactions between particles and waves in this region. Observations at magnetosynchronous orbits can provide data on many phenomena, such as ring current and small-scale active zones, particle precipitation, give an insight into outer radiation belt and auroral region acceleration, i.e. to those regions, which are called "the kitchen of" space weather.



Interheliprobe. Artistic impression

Interhelioprobe is a very ambitious mission to send two spacecraft with the same payload to the Sun's close proximity (60 solar radii) and on the orbit out of the ecliptic plane. I need not say the benefits of such a mission, since no spacecraft has ever operated in these regions. The mission is included in the plan as it is now, but its launch is scheduled after the program ends, i.e. after 2025. Still, we are determined to implement it and will look for every possibility to do it as soon as possible.

EARTH OBSERVATIONS FROM SPACE

IKI was initiated to study space and space bodies, but the Earth is, strictly speaking, also the planet of the Solar System, albeit in many respects very different from its closest neighbours. Earth's observations as a separate field of activity in IKI are associated with the names of Valentin S. Etkin and Yan L. Ziman. They developed the theory, instruments, and methods of Earth's remote sensing in microwave and optical ranges.

Valentin Etkin, the pioneer of the IKI new research area, promoted radiophysical methods in the Earth's remote sensing. Special focus was on the exploration of the ocean and development of the methods that enable to tell what is going on in the deep waters by the processes observed from above. Such an approach to application of the remote radiophysical methods of research of the processes both in the deep and on the ocean surface resulted in creation of a new research area — the radio fluid physics. Later the interest of the department, which he headed, shifted to the field of Earth exploration as a single ecological system of, primarily, climatic interaction of the ocean and the atmosphere.

The research programs, the department was involved in, stipulated annual field experiments in various regions of the world ocean: from the Black and Barents Seas to the Pacific Ocean. The experimental works were conducted together with the theoretical researches aimed, first of all, at the development of the radiophysical and hydrophysical models of the phenomena observed in the ocean and the atmosphere, as well as towards snow and ice covers, the degree of anthropogenic impact on the environment.

Professor Yan Ziman was a veteran of the Great Patriotic War, four time cavalier of military awards and 14 medals, a laureate of the USSR State Prize. He was the first head of Optico-Physical Department, which, among many things, initiated a new international team for Earth remote sensing as a part of the *Intercosmos* Council. In the 1970–1980s the Department conducted a series of experiments on multispectral photography of the Earth surface – this technique consisted in imaging conducted separately in several spectral bands. The experiments were carried out from four manned *Salyut* stations and the spaceship *Soyuz 22*.

Today IKI RAN managed to maintain both fundamental and applied approaches to Earth remote sensing data. There are those who use satellite information to understand the complex interactions of Earth's ocean and atmosphere, for instance, the role

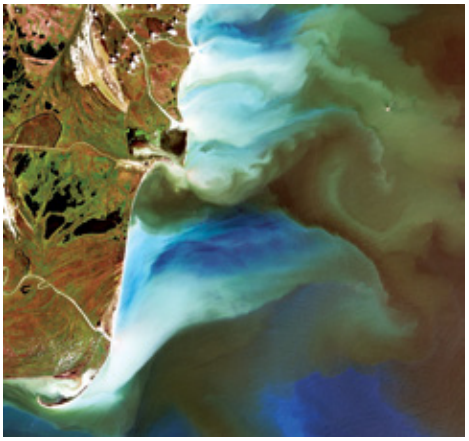
of tropical cyclones in the climatic system. On the other hand, special methods and techniques are developed to monitor the ecological situation on the Earth. Just one example of the works is development of oil spill monitoring system based on complex analysis of satellite data. The system was used to assess the scope of oil spills in Black Sea, Baltic Sea, in the Gulf of Mexico. Based on the whole body of circumstance of the available satellite data the daily monitoring of the oil film distribution was conducted, the area of the polluted aquatic zone was estimated, the hydrodynamic situation in the disaster area was studied and further pollution distribution was predicted.

Another branch of research in the same field are technologies for automated maintenance of super large satellite databases, which are continuously updated. By now, the depth of the archives exceeds ten years, so one can trace the dynamics of many processes, such as forest fires, the evolution of land cover and forests, melting of glaciers, etc.

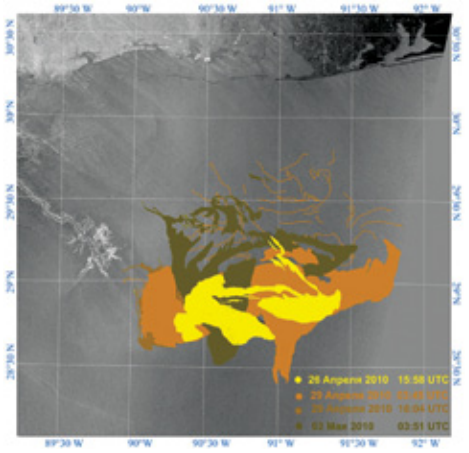
Over 20 scientific and applied systems for remote monitoring were developed in IKI, including the Center for Collective Use of Satellite Data Archiving, which now stores over 1 Petabyte of data (the sixth in the world). One of the latest developments is *VEGA Science* project. Its aim is to use a unified technological platform of information services and supply the users with an opportunity to work remotely with the satellite observation data, results of their processing, and relevant information to resolve the problems of renewable biological resources monitoring. VEGA implements the concept of a geospatial web-service collecting satellite and other geographical information from different sources and providing the access to all users worldwide virtually real-time.

Dr. Valentin S. Etkin
(1931–95)

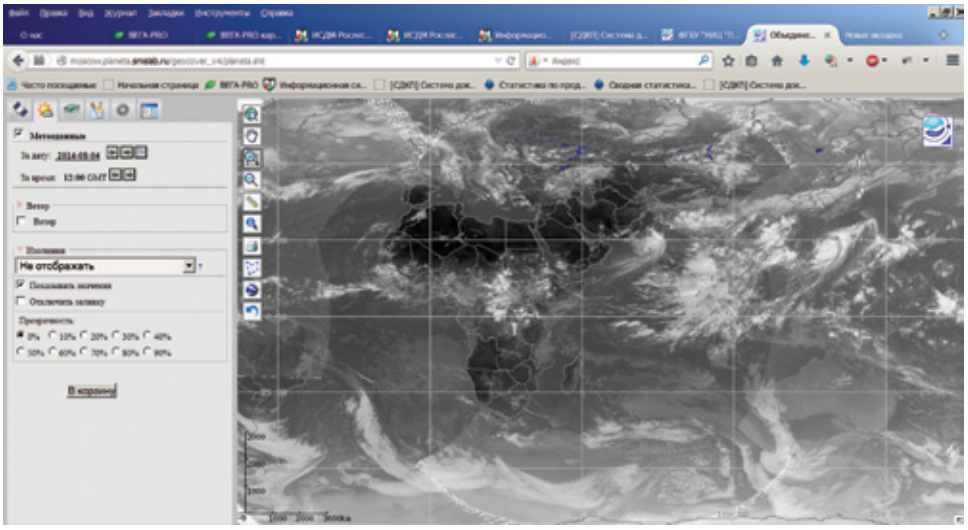
Prof. Dr. Yan L. Ziman
(1922–2009)



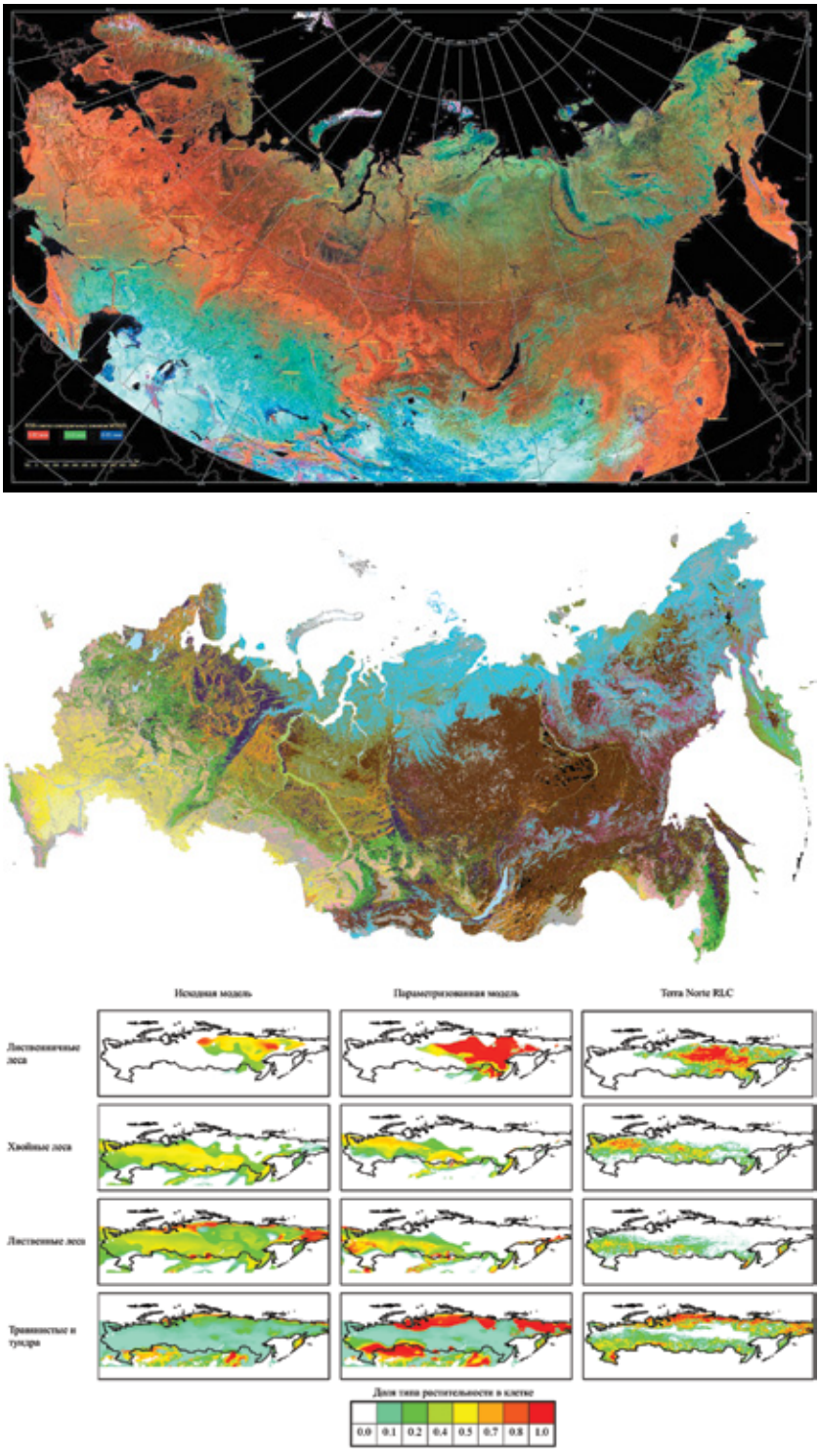
Danube flow into the Black Sea



Oil spill in Mexico Bay



VEGA Science information system



Some examples of the maps acquired using Earth remote sensing data processed in IKI

BOKZ star trackers

This service helps to analyze the state and dynamics of the vegetation cover within the whole territory of the North Eurasia starting from the beginning of the 21st century.

An interesting offshoot of the works on the Earth remote sensing, which eventually became a separate field of study, is the development of star and Sun trackers for navigation purposes. Interestingly, they were "born" in the same group that was engaged with Earth remote sensing under the leadership of Yan L. Ziman. More than 100 BOKZ (short for Russian "Module to Define Star Coordinates) star trackers were launched since 1998. In particular, the one installed aboard the ISS has been already working in space for more than 15 years. It may seem far from space research *per se*, but it is the very thing which NASA calls 'spin-off' of space technologies, the application of our instruments and knowledge for civil benefits.

LUNAR PROGRAM

Why do I want the wrap it up with the lunar program? The answer is that lunar program is not merely 'lunar' and not merely 'program', meaning that if it succeeds, we indeed will have stepped beyond research and started real exploration of space and its bodies. Moreover, it is the project that involves to a certain extent most of the Institute's departments. And, finally, it is not the separate mission for the studies of the Moon, but the whole sequence of missions, which can open new opportunities of space exploration both for robots and people.

Space Research Institute was initiated to run fundamental research, and when we think about Mars and Venus, they are indeed objects for purely scientific inquiry. The case of Moon is different, because it is the closest body and it offers some interesting possibilities. For a "classic researcher", the Moon is the Earth's neighbour sharing common history and probably the clue to the evolution of Solar System. However, it is also a very promising place to build a crewed scientific station outside the Earth and the low-Earth orbit. It is close enough to be safe (remember *Apollo 13*) and it is still a real space, outside the Earth's magnetosphere and atmosphere and man-made radio signals, which interfere with many astronomical observations. I believe that establishing a lunar observatory is a goal, which could be achieved in close future, but I do not wish to limit the imagination of engineers.

Such lunar base is by no means a new idea, but it seems that only today we really have necessary technologies and vision to build it. Not the least, the station is most likely to be international, because of its cost and because of the appeal of the idea. The success of the ISS as a joint project makes lunar base looks more viable.

So, one may say that the lunar program as it is developed now, combine all the elements of space research and exploration to achieve a new quality of research. The missions, which are now envisaged within this program, are still automated and

scientific: we plan to return to the Moon with two landers, one orbiter, one sample return mission (before 2025) and one rover (after that). These missions will pave the way for crewed expeditions, and eventually we plan to finish with a full-fledged lunar base with shift workers and all kind of scientific facilities.

The two first landers will explore the polar regions of the Moon, which turned out to contain unexpectedly large quantities of the water ice — up to 4 % by weight (the discovery was made by LEND neutron detector, built in IKI and working aboard NASA's *Lunar Reconnaissance Orbiter*). These regions are promising sites for lunar base, since water is very important resource, which human beings will certainly need. So, one of the questions to be addressed during the missions is to explore the regions for its potential ability to host a habitable base.

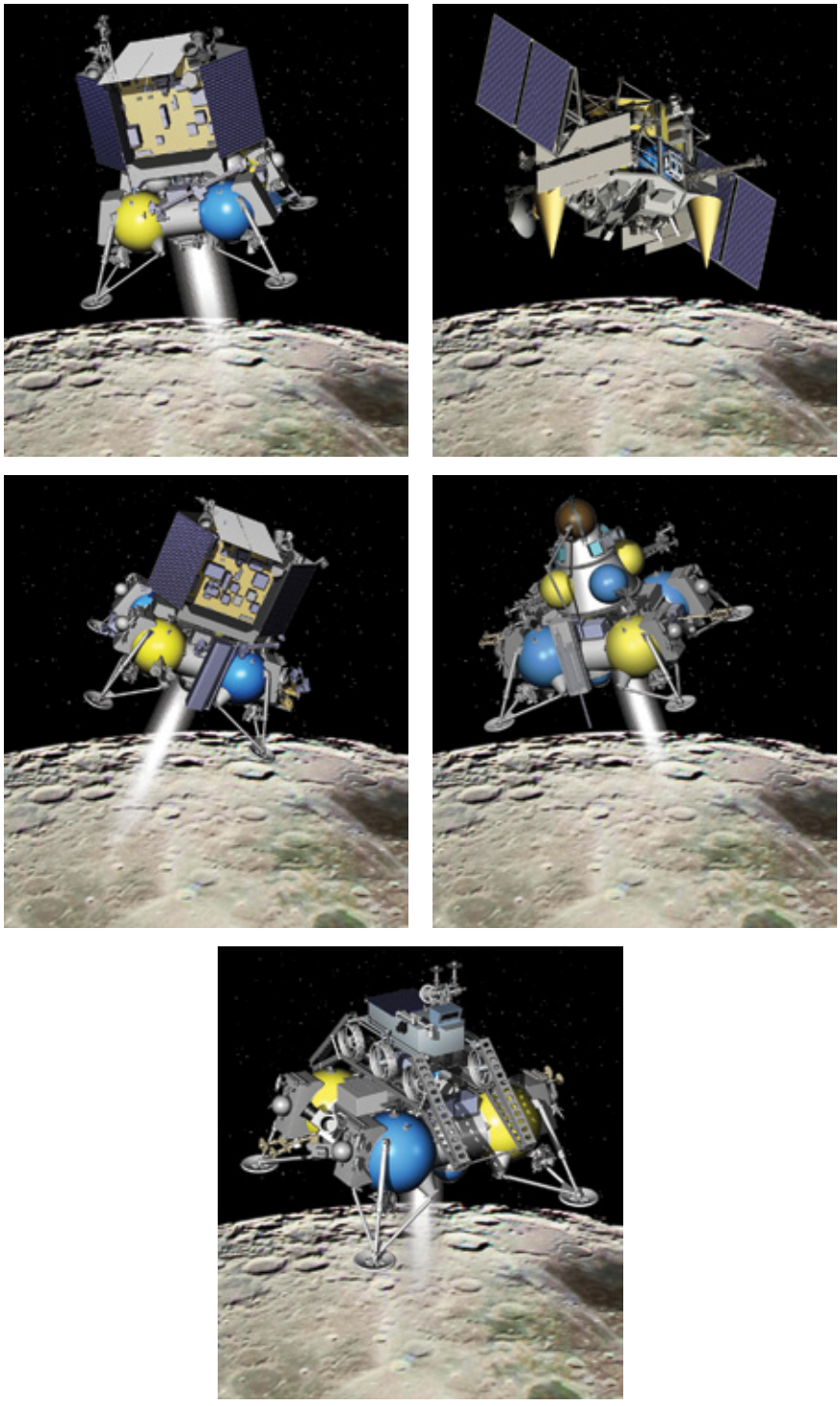
Now, briefly about the missions. I will refer to them as *Luna 25*, *Luna 26*, and *Luna 27*, following the Soviet sequence of *Lunas*, ended in 1976 with successful *Luna 24* sample return mission. *Luna 25* is a lander to investigate the immediate vicinity of the landing site. It is, *par excellence*, a technological mission with quite modest scientific payload. Then comes *Luna 26* orbiter, which will test pole-orbit UHF radio link and orbital operations. The plan for the mission is rather extended. It is supposed to work for three years and perform observations from several orbits, including the one, as low as 50 km and as high as 500 km (for the sake of cosmic rays researches). Its scientific payload include several spectrometers, dust analyzer, neutron detectors and plasma experiments, to give us a comprehensive view of the Moon and the space near it. *Luna 26* will also search for landing sites candidates for the next *Luna 27* landing mission.

It is possible, that some elements of these missions will already be contributed by the European Space Agency, but we expect that true international will be *Luna 27* lander. During the mission it is supposed to test systems for high precision landing and hazard avoidance, and perform cryogenic drill testing, which was never done before (with regard to restrictions on keeping volatiles frozen into the lunar regolith intact). This is a key task, because we know relatively well the composition of regolith per se after Apollos' and Lunas' sample return missions, but we know close to nothing about abundancies of volatiles there, so we need to preserve them during sampling. *Luna 27* will also study mechanical, thermal properties, and composition of polar regolith down to 2 meters, assess water content and elements abundance in the shallow subsurface of the polar regolith, study plasma, neutral, and dust exosphere at the pole, perform seismometry and high accuracy ranging.

ESA's participation in *Luna 27* is planned now to include high accuracy landing system, radio link Moon-Orbit, cryogenic drilling, and some scientific instruments. We hope very much that by that time we will already have successful *ExoMars* experience, which is also joint European-Russian mission, under implementation now.

Luna 28 is a mission to deliver samples of lunar regolith with untouched volatiles back to the Earth where it can be studied more thoroughly and with more sophisticated instruments in terrestrial laboratories. Then, *Luna 29*, which will be probably launched after 2025, is supposed to deliver a new rover — lunokhod — to the Moon, which will collect the most interesting samples from outside of the immediate vicinity of the lander.

I have briefly outlined the first five missions to the Moon and said that the ultimate goal of this program is to build a base on the Moon, most likely an international endeavour. Will it bear the name of International Moon Station? I hope so; and I will be very glad to know that some time Space Research Institute includes a special extraterrestrial branch office — Moon Laboratory Station.



Lunar Program for the nearest decade, from *Luna 25* to *Luna 29* and new Moon rover — Lunokhod

Today IKI RAN is somewhat more than an Institute or a working place for many of its scientists and engineers, it is a place to live and grow your ideas until they are mature enough to fly as high as space — I beg for pardon for this rather clumsy comparison. It is great that this spirit lives not only in the elder generation, but very soon captures young scientists who come to IKI RAN as undergrads or graduate students. IKI RAN collaborates with many Moscow universities and provides PhD programs for undergraduate students in several fields. I am glad, that space science is still attractive for young scientists, those, who already succeed us in space research. May the future 50 years be none the less fascinating than the years I just finished speaking about!

50 YEARS OF VISION, SCIENCE, AND INTERNATIONAL FRIENDSHIP

Roget-Maurice Bonnet

International Space Science Institute, Bern, Switzerland

INTRODUCTION

Dear friends and colleagues,

Let me first address all my warmest thanks to my dear friend Lev Zelenyi for inviting me to this important and historical celebration of one of the most famous space research institutes in the world.

One cannot address and remember 50 years of space research and the history of IKI without replacing these remembrances within the political and geopolitical context that framed these difficult, though very glorious 70 years following the end of the Second World War. While preparing that talk, in early May, 2016, the French TV was nearly every night showing unbearable pictures and movies of the War after Germany invaded Russia. Difficult scenes, hard to see! the fight for Stalingrad reached an apex of violence, wildness, and death. That madness ended after Berlin's fall on May 2, 1945 when the Red Army defeated what was left of the 3rd Reich (Fig. 1). That was just 20 years before IKI would be created. I cannot think of these 20 years without stressing the incredible determination of those who put an end to the most unthinkable barbarism of all times. I am sure that many of you today in this audience have had a father, an uncle, or a relative falling victim of that most ferocious war.

Fig. 1. On 2nd May 1945 the Red Army reaches Berlin and raises the Soviet Flag on the Reichstag, bringing to an end the most unthinkable barbarism of all times

Fig. 2. The famous Boris Polevoi's book celebrated war pilot Alexey Meressiev who was shut down by the Nazis. He survived 3 weeks in the woods and the snow, crawling to the nearby villages. The partisans retrieved him. Soon later he decided to become a war pilot again and a national hero who eventually participated in the final victory

The Story of these Real Men similar to the war pilot Alexey Meressiev, hero of the famous Soviet writer Boris Polevoi (Fig. 2), often came back to my mind while reflecting on the story of these 70 years and on the 50 years of IKI. As a child, whose house located in the suburbs of Paris was bombed and destroyed, I had sympathy for the victims and gratitude for the winners. It took just 12 years for your country, which lost more than 25 millions of its children during the cruelest manifestation of human savagery, to open the road to space with the launch of Sputnik 1 on 4 October, 1957.

IKI was created in the wake of the spectacular momentum that this pioneering success induced, only 8 years after the birth of the space era and 4 after Yuri Gagarin's historical space flight. Soviet Union, with Sputnik 1 and Gagarin, shook the world a second time! IKI then evolved through the difficult, traumatic, and, at times, dramatic moments of the Cold War. It went through *Perestroika* and more recently though what resembles a phony cold war. Fifty years of the past life of IKI represents a true Russian Story, a story built by Russians, by talented and courageous Real Men and Women, from whom the Russian soul constantly manifests itself, blending altogether genius, flamboyance, passion, generosity, friendship, forgiveness, and... colourful parties!

SPACE LEADERS

At the origin of great achievements, we always find visionaries and leaders. At the origin of the pioneering space program of Soviet Union and of the whole world, we find Sergei Korolev, widely regarded as the founder of the Soviet space program. He deserves the most credits for turning rocket weapons into an instrument of pacific exploration and making the Soviet Union the world's first space-faring nation ever. Sergei was an engineer and Mstislav Keldysh was his scientific inspirer. We celebrated the 100th anniversary of Keldysh's birth here in that same building four and-a-half years ago. He became President of the USSR Academy of Sciences, a position that he occupied between 1961 and 1975. In 1956 Keldysh headed a special commission at the Soviet Academy of Sciences that coordinated the launch of the first artificial satellite scheduled for 4 October 1957. These two great men led the first space program, which, I remember personally very well, yielded many historical discoveries granting right away to the Soviet Union, from the first attempt, the first place among all space-faring nations, a position that it kept for many years.

Everyone would identify the names of Sputnik 1, Yuri Gagarin, and Valentina Tereshkova as vivid symbols of these early successes. But as I am celebrating IKI today, let me focus on a few achievements of the great brains that very early in the history of space have marked the evolution of this Institute and the history of science.

YOU WERE THE FIRST REACHING THE MOON!

Konstantin Gringauz using *Luna 1* was the first to directly observe the solar wind and to measure its properties. That discovery was verified by *Luna 2* and *Luna 3* then by *Venera 1* and three years later by the Americans with *Mariner 2. Luna 2* (September 1959) successfully hit the Moon's surface, becoming the first man-made object to reach the Moon, while *Luna 3* (October 1959) rounded the Moon later that year, and returned the first photographs of its far side.

In February 1966, *Luna 9* became the first probe to achieve a soft landing on another planetary body. It returned five black-and-white stereoscopic circular panoramas, which were the first close-up shots of the Moon's surface. In March 1966 *Luna 10* became the first artificial satellite of the Moon, and on 10 November 1970, *Luna 17* landed *Lunokhod 1*, the first remotely commanded vehicle on an extraterrestrial object. Its successor, *Lunokhod 2*, held the historical record of the longest travel (39 km) on an extraterrestrial object, until 2014 when the US *Opportunity* robot beat the record, accomplishing a 40 km-long trip on Mars. The Soviet rover roamed around the lunar surface for nearly a year, analyzing soil samples and transmitting photographs. It stopped communicating on September 14, 1971. Of course, the USA landed men on the Moon and that was a historical achievement of immense dimension, but you, the Soviet and Russian people and your ancestors, opened the way to the Moon!

YOU WERE THE FIRST REACHING VENUS!

Venus was a second successful target and a cornerstone of the Soviet space program. *Venera 1* weighing 643.5 kg launched in February, 1961 flew past Venus on 19 May of the same year. *Venera 3* (960 kg) on March 1, 1966, became the first spacecraft to impact the surface of another planet (Fig. 3), and *Venera 9*, in 1975, became the first probe to orbit Venus, to make a soft landing on the planet, and the first to take photos of its surface (Fig. 4).

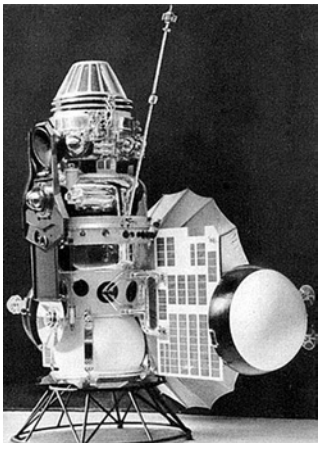


Fig. 3. The mission of *Venera 3* was to land on the Venusian surface. The entry body contained a radio communication system, scientific instruments, electrical power sources, and medallions bearing the Coat of Arms of the Soviet Union. The probe was launched on 16 November 1965 and possibly crash-landed on Venus on 1 March 1966, making *Venera 3* the first spacecraft to impact the surface of another planet

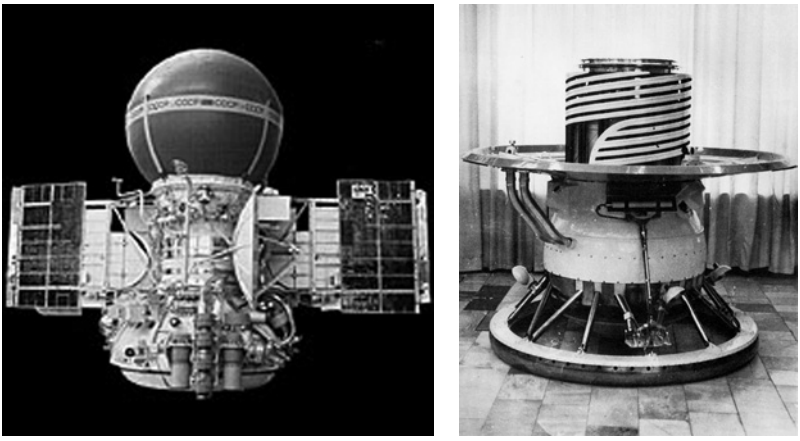


Fig. 4. *Venera 9* consisted of an orbiter (left) and a lander (right) and had a mass of 4,936 kg. It was launched on June 8, 1975. The orbiter was the first spacecraft to orbit Venus, while the lander was the first to return images from the surface of another planet

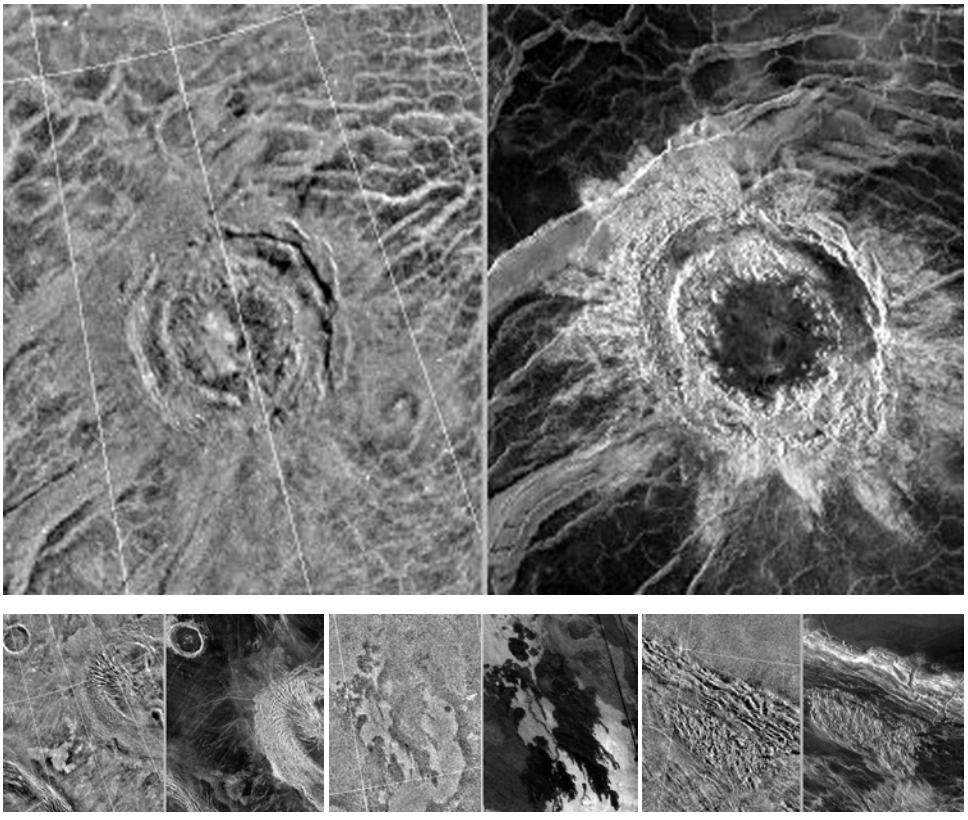


Fig. 5. Comparison between four sets of radar images of several identical areas on Venus obtained by the USSR *Venera 15/16* spacecraft in the early 1980s (left) and the U.S. *Magellan* spacecraft in 1991 (right). Credit: JPL

Venera 15 (4000 kg) launched on June 7, 1983 by a Proton rocket using 8 cm-band side-looking radar mappers, sent to the Earth spectacular pictures of the Venus surface three years earlier than the American NASA *Magellan* mission launched on May 4, 1989. With no discussion, the *Magellan* pictures covering the entire planet's surface and of a better quality than the *Venera* ones that focus on a limited region, give the Americans a comfortable advance in that kind of scientific competition. The Fig. 5, which compares pictures of the same area taken by the two missions, evidences the differences but do also pay credit to the high quality of Soviet technology of the time. A year and a half later, the five-tons *Vega 1* and *2*, launched by a *Proton* respectively on December 15 and 21, 1984, were the first probes to deploy robotic balloons into the atmosphere of Venus.

YOU WERE THE FIRST RECHING MARS, BUT…

Mars, the third target was a hard one to hit but once more, you were the first to attempt visiting that mysterious red planet: *Mars 1* was the first probe ever launched to Mars (1962) and nine years later, *Mars 2*, (1971) was the first probe to impact the surface of Mars immediately followed by *Mars 3* (also in 1971), the first one to land on Mars. Unfortunately, you have been victims of a very large number of failures in the history of Mars exploration, which is entirely dominated as of now by the Americans and more recently by the Europeans. The long series of these Soviet failures certainly deserve to be remembered and understood while looking at future missions to Mars as envisaged by Russia in the near future.

YOU WERE THE FIRST TO ACCOMPLISH CLOSE FLYBYS OF A COMET

During two short-distance thrilling flybys, the twin probes *Vega 1* and *Vega 2*, in March 1986, were also occupying the first rank among all other space missions to take pictures of a comet nucleus, Halley, and to successfully return to Earth the first close-up images of that object that nobody before was able to describe properlye: was it like a sand bag, a non-cohesive structure or, as Fred Whipple liked to assimilate it, a "dirty snowball" (Fig. 6)? France was very much involved in this extraordinary project through the Venus balloons and several other instruments.

Fig. 6. First ever picture of a comet nucleus: that of the 16×8×8 km nucleus of comet Halley obtained by IKI's *Vega 2* mission on 9 March 1986 at about 8,030 km distance

VISION, CLEVERNESS, AND INVENTIVENESS

All these successes have been possible as a fruit of the Russian inventive capability, its cleverness and the smartness of its technical concepts, which throughout its history have marked the development of the Soviet and Russian space program. Let me select some of the most striking examples of these.

The Korolev R-7 *Semiorka* (synonymous of "number seven") was the first rocket proving the feasibility of intercontinental ballistics, and the first to place an artificial satellite in orbit (Sputnik 1, on 4 October 1957). It was continuously improved and became better known as the then famous *Soyuz* back in 1966. It surprised the Western world by its simplicity and the elegance of its mechanisms. In particular, contrary to the majority of similar engines, it was integrated horizontally and towed by train also horizontally from its hangar to the launch pad. Such an approach was eventually found very practical, in particular in ensuring a cleaner environment. Furthermore, maintaining the rocket close to the floor made it possible to use entirely non-crane equipment and materials, reducing structural overhead and risk to the staff. It is remarkable that the newly approved European *Ariane 6* rocket, which will make its first launch around 2020 some 63 years after the launch of Sputnik 1 will also take advantage of a horizontal integration, still a very modern concept and at the same time also very simple. The same can be said of the RD-180 rocket engine, which found its origin in the framework of the Soviet *Energia* launch vehicle project. Characterized by its robustness, its simplicity, and furthermore being cheap, it is now used by the US military for powering their huge *Atlas V* launch vehicle.

The REGATTA Program was invented for the benefits of IKI. It was both unconventional and very clever in many respects. Two spacecraft would be positioned in large halo orbits, SSL-B around the Sun-Earth L1 point, and SSL-C around the Sun-Earth L_2 point, as shown on the Fig. 7.

Let me quote Bob Farquhar, the genial NASA-Goddard engineer who invented the revolutionary technique of interplanetary navigation through billiard-ball like trajectories of interplanetary probes when they approach planets or their moons: "*Perhaps the most unusual aspect of REGATTA was the revolutionary spacecraft design concept base-lined for all of the missions in the Program. The basic spacecraft, called Small Space Laboratory* (*SSL*), *uses a large circular solar sail and eight rectangular* "*solar rudders*" *for attitude stabilization and orbit control*". Regatta was a key element of IKI's Space Weather Sun-Earth relationships program. It was even proposed at some stage to be used in the development of ESA's *Cluster* mission. Unfortunately, in the early 1990s, the REGATTA Program lacked sufficient funding to remain viable, and was terminated.

In fact, solar sailing has been a long-time dream of NASA and of IKI. The Planetary Society had a long-lasting working relationship with IKI and Lavochkin Association and they together developed the *Cosmos 1* spacecraft, so named in memory of Carl Sagan and of his famous TV *Cosmos* series. It was the world's first solar sail spacecraft. Two launch attempts from a submarine-based ICBM in July 2001 and June 2005 failed. Eventually the solar sail was re-developed on a CubeSat by the Planetary Society. Renamed *LightSail*, it hitched a successful ride to space aboard an *Atlas V* in May 2015, which allowed the testing of the sail's deployment sequence.

I may end that list of remarkable achievements by mentioning one concept, which always impressed me and not only me: the way of getting to Mars by shooting first at Phobos.

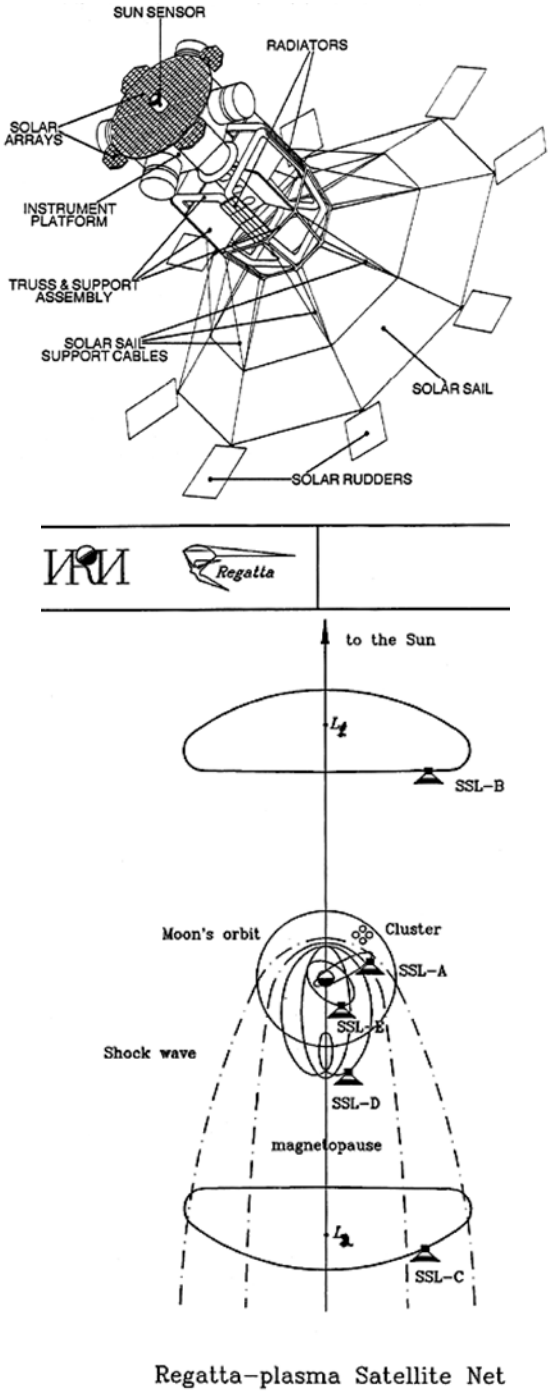


Fig. 7. The *Regatta* concept was based on a spacecraft called the Small Space Laboratory (SSL). It used a large circular solar sail and eight rectangular "solar rudders" for attitude stabilization and orbit control. *Regatta* was a key element of IKI's Space Weather Sun-Earth relationships program

That concept was used for the two *Phobos* missions launched in 1988 and by *Phobos Sample Return* in November 2011. Unfortunately that last spacecraft could not be placed on its transit orbit to Mars and fell on Earth 1250 km west of the Island of Wellington in the Pacific Ocean. However, the idea of an incremental multiple-mission approach to send astronauts to Mars copied on the original approach to the conquest of Mars by IKI has been retained: "*Getting astronauts to Phobos by 2033, then down to the Martian surface by 2039 could make manned Mars exploration technologically and economically feasible*," says Firouz Naderi, head of the Solar System Exploration Directorate at NASA's Jet Propulsion Laboratory in Pasadena, California.

SPACE MAKERS

The four Directors of IKI: Georgy Petrov (1965–1973), Roald Sagdeev (1973–1988) Albert Galéev (1988–2002), and Lev Zelenyi, who took the reins in 2002, can undoubtedly be considered as the Space Makers of the Soviet-Russian space research program. The role of Roald Sagdeev in particular has been determinant and crucial.

Roald was the key person behind the opening of international cooperation in the Soviet space science program, in particular in the *Venera* — and later *Vega* — program, introducing a more rational system of planning not based only on short-term political considerations. He was surrounded by a group of extraordinary brains and collaborators: including Mikhail Marov, Yakov Zeldovich and his inseparable pupil, Rashid Sunyaev, Iosif Shklovsky and his inseparable pupils Nikolai Kardashev and Alexander Boyarchuk, Vasily Moroz, Vladimir Kurt, and Konstantin Gringauz, and many others. I hope those whom I forgot to quote in this list will forgive me not mentioning their name. They are also my friends. I happened to know all of them in the frame of the cooperation started by the French President in 1966.

One year after the creation of IKI, on 25 June 1966, Charles de Gaulle was invited by Leonid Brezhnev to visit Baikonour. He was the first Chief of State of the Western world to watch live the launch of a Soviet satellite. That historical visit opened the way to what would become a very intense and successful cooperation between France and the USSR, and more precisely between France (CNES) and IKI. It is in the course of the early annual meetings held between CNES and our Soviet colleagues that I happened to know Roald Sagdeev and many of his collaborators, among whom, many are here today. Bi-national cooperation was later followed by other countries and eventually very successfully implemented by ESA where my predecessor, Ernst Trendelenburg, a German Third Reich Officer, who was defeated as a former German Soldier in Stalingrad, developed a warm friendship with Roald.

In April 1983, one month before I took my duties at ESA, Roald organized a magnificent farewell visit to Samarkand, in honor of Ernst Trendelenburg, an unforgettable event to which both Trendelenburg and Roald had the elegant attention of inviting me. That visit cemented even more strongly the ESA-IKI friendship and triggered an irreversible impulse to the development and the strengthening of future IKI-ESA cooperation, embracing all domains of space research. These were reviewed every year in the framework of regular meetings between the two organizations alternatively convened in the Soviet Union and ESA member states. Astronomy, planetary exploration, solar and plasma physics were offering exciting perspectives for unique ambitious missions and concepts. All these jointly planned activities illustrate

the strong common desire to cooperate that developed between IKI and ESA made of common admiration and respect. In the midst of the Cold War that was not so easy in spite of several natural technical and management difficulties. Undoubtedly, the climax of that international cooperation was reached at the occasion of the return to perihelion of Halley's comet.

PEACE MAKERS

Remarkable occasion indeed, which saw the joint undertakings between NASA, ISAS, ESA, and IKI of a most comprehensive set of observations of the comet, and the creation of the so-called Inter-Agency Consultative Group (IACG) and of the *Pathfinder* concept, which (Fig. 8) allowed the European *Giotto* spacecraft to get as close to the nucleus as 600 km, thanks to the previous observations made by the VEGA missions and the recourse to VLBI technique using the NASA/JPL Deep Space Network (DSN).

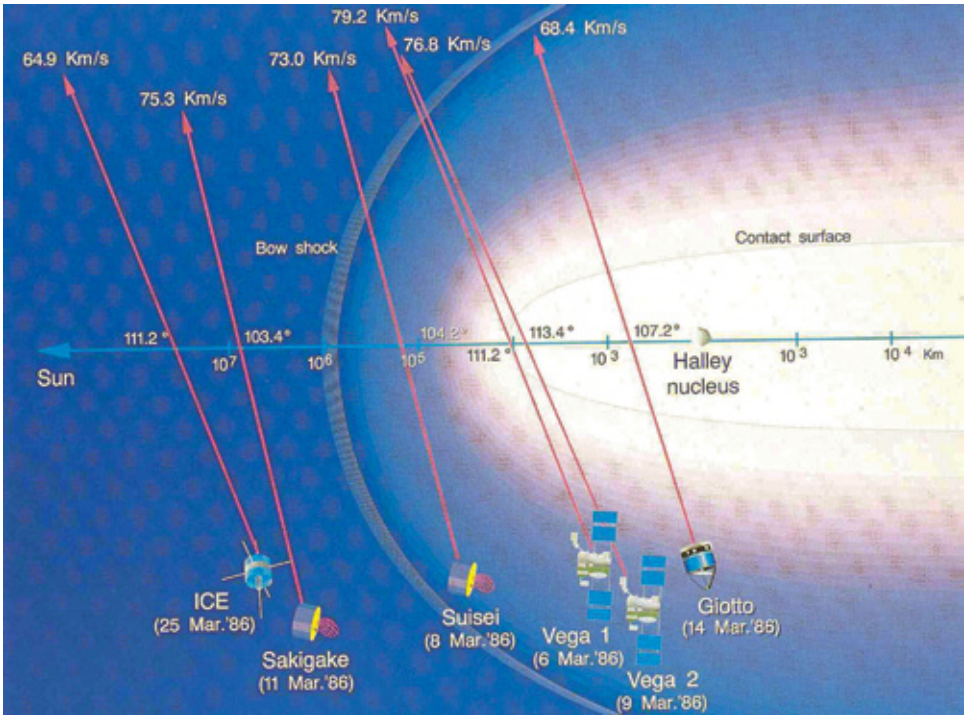


Fig. 8. The accuracy with which Halley's comet orbit was known from measurements made at the 1835 and 1910 passages, as well as near its perihelion, two months before the *Vega* and *Giotto* encounters was insufficient for getting the best quality high-resolution images of the nucleus. IKI, NASA, and ESA set up the *Pathfinder* project according which the orbits of the two *Vegas*, close to their encounters with the comet, would be precisely estimated through VLBI techniques using NASA's Deep Space Network. Their positions' relative to the comet measured by the two probes enabled the calculation of a more precise orbit of Halley at the time of the *Giotto's* fly-by, a few days later. The shortest distance of *Giotto* to the comet was 605 km, with a residual error of some 30 km

Organized in the coldest period of the Cold War, that venture remains in history as one of the most successful examples of an immensely successful cooperation, where the forbidden became possible through political willingness, scientific motivation and the desire to go beyond the prejudices. Celebrating that immense success in the Vatican in November 1986, Pope Jean-Paul 2nd did not hesitate to call all those involved in that unique venture the "Peace makers" of the 20th century (Fig. 9)!

After that world-celebrated success, the IACG, which until that time was dealing essentially with comet science, was looking forward at its future, possibly adding new scientific objectives in order to benefit from the positive effects of its existence and unique historical achievement. The Vatican ceremony offered an excellent opportunity, for the four agencies meeting in Padova (where the IACG was created in 1981), a few days before catching the train to Rome, and discuss an extension of their activities in prolonging their successful cooperation and coordinating their approved missions, which for most of them dealt with Sun-Earth relations, what today we would call Space Weather.

That second phase was quite successful too. Over a period of 14 years, the progresses of common programs and projects were reviewed every year by the four agencies in a different place, offering the possibility of organizing at the same time dedicated scientific symposia on the various topics of interest to their respective scientific communities.

Fig. 9. On 7 November 1986, celebrating the immense success of the IACG, of the *Pathfinder* concept and admiring the results it contributed to in the observations of comet Halley, Pope John Paul II did not hesitate to call all those involved in that unique venture the "Peace makers" of the 20th century!

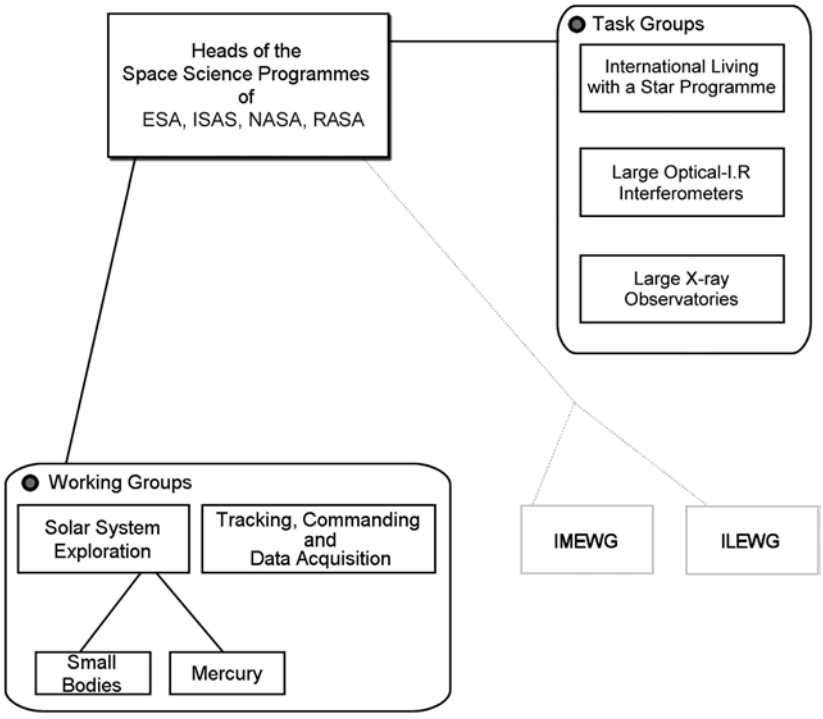


Fig. 10. The concept of the follow on activities of the IACG after two successful phases of international cooperation and approved mission coordination was reviewed in La Jolla (California) on 27–28 September 2000. The major change was for the IACG to coordinate future and not yet approved programs/projects. That change eventually signed the end to the IACG, as NASA was very reluctant to adopt that principle

The achievements of that second phase were reviewed at the 20th IACG meeting in La Jolla, California, on September 27–28, 2000. All four delegations expressed their satisfaction of the success of the second phase and discussed the opportunity to extend once more their joint activities. They established a plan whose "architecture" is illustrated on the Fig. 10, which would result into the transformation of the IACG, into an international group of agencies coordinating their future programs in all domains of space science. NASA was not very enthusiastic, to say the least, and reluctantly agreed to the new mandate. They silently accepted to add to their *Living With a Star* program (LWS) a capital I for "International", but the spirit of IACG seemed lost in La Jolla.

It was agreed, however, that the 21st Meeting would be held in September 2001 in Padova for the third time (Italy), the birthplace of the IACG, twenty years earlier. Unfortunately, that was cancelled because of the Sept-11 tragedy and postponed to September 2002 in Moscow. That meeting would in fact be the last one. I must confess that I was rather lucky not to be there and to not participate in the burial of the joint, truly international, group of the largest space agencies in the world, putting to an end 20 years of a very successful and remarkable endeavor. However, and for the benefit of international cooperation, in parallel to the IACG annual meetings, IKI and ESA were also meeting regularly to discuss their ongoing and future projects, and that continues still today, even after the IACG was abandoned.

Fig. 11. The picture features Albert Galeev and Roger Bonnet at the 1991 IKI–ESA annual meeting on 17–19 June in ESTEC. The meeting was particularly rich, reviewing progress accomplished on *Integral* data exchange, the *qui pro quo* to launch the observatory with a *Proton*, the provision by ESA of the *Mars 94* mass memory, the *Regatta-Cluster* cooperative program, and discussing future Mars missions, as well as the potential Russian interest in future Comet Nucleus Sample Return (CNSR) missions

In astronomy, two domains were particularly dear to IKI: VLBI astronomy and high-energy astronomy, because of the presence of key personalities interested in these domains, working at or with IKI. The ambition of IKI scientists always impressed me. That certainly was the case of the *RadioAstron* project also known as *Spektr-R* dear to Nikolai Kardashev and of the *Spektr-Roentgen-Gamma* mission dear to Rashid Sunyaev. These missions however have followed long and tortuous paths, remarkably illustrating the motto dear to me: "*while confronting adversity*, *never give up*"!

RadioAstron came first to my attention in April 1983 in Samarkand, and then in Leningrad in 1985. It offered unique opportunities to discuss VLBI and space radio astronomy at several IKI-ESA meetings. A large part of the discussions held there concerned the test of the antenna at ESTEC, which offered ESA an opportunity to follow the progress of the project, unfortunately continuously delayed: in 1989, the launch was foreseen for 1993, in 1994 for 1996. Finally it was launched in July 2011!

An even more hectic story could be told about *Spektr-Roentgen-Gamma*. The concept was proposed in the early 1990s, with a launch date in 1995, and then postponed to 2008. It was cancelled in 2002 and revived in 2005. The mission is now in development as a joint project between Roscosmos and German Aerospace Agency (DLR). It is now scheduled to launch in 2017! Parts of the difficulties of the project find their origin in the race led by IKI to interest international partners including ESA. I must admit that this option was not popular in the ESA Science Directorate, as the mission was in direct opposition or competition against *XMM-Newton*, whose development was much more advanced.

In the meantime, Rashid initiated promoting *Integral*, a much more interesting mission for ESA, which at the same time was in the search of a medium size mission in gamma-ray astronomy. The offer by Russia to launch *Integral* with a "free" *Proton* launcher and the possibility to use a copy of the *XMM-Newton* bus made it possible for ESA to transform a cornerstone size mission (*XMM-Newton*) into a medium one. Even though the cooperation on *Integral* was not always a bed of roses, the launch occurred on 17 October 2002 and *Integral* is still in operation until at least the end of 2016. It is a great success! Thanks to its broad energy range (3 keV – 10 MeV), its fine imaging (12′ FWHM over a very wide field-of-view ~100 square degrees), together with its high-resolution spectroscopy (2 keV FWHM at 1 MeV), millisecond timing resolution and polarimetry capability, *Integral* contributed many "firsts" in gamma-ray astronomy. It represents an excellent example of a very successful IKI-ESA cooperation.

The photo (Fig. 11) illustrates the excellent atmosphere of the joint annual IKI-ESA meetings when the two heads of delegation, usually the Director of IKI and the ESA Director of the Science program reviewed their interests in cooperating in space astronomy (including submillimeter astronomy), planetary exploration (*Mars 94* and *Mars 96*, *Mars Express*, *Phobos*, Venus), solar physics (*Interhelioprobe*), plasma physics (*Cluster*, *Regatta*, *Interball*, *Phobos*), and of course comet science (*Rosetta*).

THE DARK AGE

The period following the success of the *Pathfinder* VEGA-*Giotto* venture was unfortunately followed by more difficult times. The problems encountered on the IKI *Mars* program were very sad for all partners involved in *Phobos 1* and *2*, and in *Mars 94*, later renamed *Mars 96*! At the onset of *Perestroika*, the political context changed drastically

and unexpected difficulties arose. The morale of our IKI partners went down, lower and lower. At the same time, the perspectives for cooperation started to be less visionary and became fuzzier.

In 1992, as the USSR became the Community of Independent States (CIS), the Russian Academy became our official partner, replacing IKI. Consequently, our contacts tended to be more official and our friendly meetings more business-like. At the same time, travel money became more strained for our Russian partners. As the Russian Space Agency came to birth, our IKI partners often expressed their fear of the bureaucratic approach adopted by the new organization of Russian space science.

In September 1992, the new governance gives priority to *Mars 94* and to *Spectr-Roentgen-Gamma* above *Integral*. Unfortunately, *Mars 94* and *Integral* schedules as well as future cooperation plans start loosing credibility and we at ESA are also becoming destabilized. On top of that, Roald moved to the US, leaving IKI orphan of its charismatic leader. Even though the vision is still present — a Russian *Solar Probe* is mentioned for the first time, and new Mars projects are envisioned — the relatively poor rate of success of the Mars missions after 1988 is of course a great concern for the future. On top of that, the surprising long series of *Proton* failures did not contribute at recovering the glorious and success-oriented spirit of previous years: something wrong was happening! The Russian successes in space science seemed to be something of the past. In fact, looking at the table (Fig. 12), it appears that the Soviet approach to space exploration based on large number of missions with a low percentage of success had not changed, excepted for the number of missions which diminished drastically.

	USSR/ Russia	USA	Europe	Japan	India	China	TOTAL
MOON	50 24 26	43 28 15	1	2	2	3	101 60 41
MARS	20 (1) 20	21 16 5	2 1 1	1	1		45 19 27
VENUS	32 16 17	8 6 2	1	1			42 23 19
JUPITER		7					7
SATURN		4	1				5
COMETS ASTEROIDS	2	6	2 2	3			12
MERCURE		1 (2)	(1)				2
OTHERS		4	1				5
TOTAL	104 42 63	92 73 22	9 7 1	7 5 2	3	3	218 133 87

Fig. 12. This table shows the statistics of all planetary missions launched into space since the beginning of the space age, comparing the rate of successes and failures between the various space agencies. USSR/Russia is clearly number one with the largest number of missions launched. Its rate of failure is however also the first one, close to 50 % on average. The table evidences also the strong emphasis on the Moon and Venus exploration, which characterized the Soviet program until 1988

While space was considered a high priority by the Soviet regime, it lost its financial support after *Perestroika*. That period witnessed the start of a harmful hemorrhage of talented scientists and engineers leaving the country to offer their knowhow to the USA and Europe.

Indeed, I was personally very concerned when in 2005 ESA announced its ambitious plans to swap its defunct cooperation with NASA on Mars exploration for a cooperative venture with Russia on *ExoMars*. Let me quote part of a message, which I sent to Lev Zelenyi on 22nd August 2012:

I had discussions with Jean-Jacques Dordain, ESA Director General, expressing my strong concerns, following the Phobos-Grunt failure. We came to the conclusion that both (RSA** and ESA) would have to address the essential issue of quality insurance and should set-up a process through which both agencies can re-assure themselves that the problems which affected all Russian Mars missions in the past, starting with Phobos (1988), followed by Mars 96, and Phobos-Grunt, have all been understood and that the proper measures will be put in place in order to avoid the occurrence of such problems in the future. I cannot underline more frankly and directly the ESA concerns to you as a friend, in view of the fantastic opportunities that the foreseen future cooperation might offer. I hope you understand my own concerns and why that message is important for the future.*

Remarkably, on both the Russian and the European sides, all what could be done has been done to ensure that this new joint process would be crowned with success. *ExoMars* seems to be now on track and on schedule with the first launch scheduled in March 2016***. That allows me to look optimistically to the future and reflect on what the next 50 years will be for IKI, for the Russian space science and for international cooperation.

THE NEXT 50 YEARS

The next 50 years should and will be based on scientific and technological excellence, on the genius and on the originality, which have constantly characterized the Soviet/Russian space program. They will exploit the rich Soviet/Russian heritage, and rest on the high-level education, the training and the development of a new talented scientific community, which will draw the lessons of the glorious past, which placed Soviet Union and Russia in the first rank of the world spacefaring nations for many years.

In order to achieve this goal with the maximum rate of success you, the IKI players, cannot and should not accept compromising on the quality of your ideas and of your work: failure cannot any more be an option! You should systematically analyze the reasons for deviating from success and you should systematically draw the lessons you learn from such accidents. If you follow that successful track, you should once again be the leaders of ambitious international projects. Indeed, international cooperation will be a must, especially in big programs such as planetary exploration and large astronomical telescopes.

The fantastic and impressive heritage of your past success can be calibrated thanks to the long history of your contributions to lunar exploration (*Luna* and

* Phobos Sample Return mission — *ed*.

** Russian Space Agency, aka Roscosmos — *ed*.

*** *ExoMars-2016* was successfully launched on 14 March 2016 from Baikonur — *ed*.

Lunokhod), Venus and comets exploration (*Venera*, *Vega*), high-energy and radio astronomy (*Integral*, *Spektr-Roentgen-Gamma*, *RadioAstron*) as well as heliospheric physics (*Coronas*, *Interhelioprobe*). This rich heritage allows you to look and contribute with vision and ambition to leading future lunar bases, going back to Venus, to Mars and to Phobos, as well as contributing unique observations in the exploration of Mercury, in heliospheric physics and space weather science. Future international large telescopes in high-energy astronomy, radio astronomy, and Very Long Baseline Interferometry, will also amply benefit from your leadership and expertise. Not forgetting Earth space observation for which all agencies of the world should unit their forces and knowhow to make our own planet a safe place to live on, sometimes to leave out, temporarily, planning a pleasant return.

Dear IKI scientists and engineers, collaborators in all sectors, be the heroes we admired and loved. Be successful! Dare! Keep being imaginative! Innovate and be proud of yourself! Be the real men and women of space science. Let me wish you all, as well as IKI, a very happy fiftieth birthday.

THE SCIENTIFIC PROGRAMME OF EUROPEAN SPACE AGENCY

Alvaro Giménez

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INTRODUCTION

The Science Programme of ESA (originally born as the European Space Research Organization, ESRO) has been in existence for 50 years, during which it has incessantly been working to provide the best possible tools in all fields of space science to the scientific community in order to achieve and sustain excellence with discoveries and innovation. For this purpose, the Science Programme has consistently supported the development of curiosity-driven scientific missions, promoting new knowledge about our neighbourhood in the Solar System, the different components of the Universe, its nature as a whole, and the fundamental laws of physics that underpin its behaviour.

The idea of a European Space Agency to coordinate national efforts and provide the necessary budgets to develop ambitious scientific programmes dates back to the early sixties. Different European countries formed two organizations at that time: the European Launcher Development Organization (ELDO) and the European Space Research Organization (ESRO). The first one to provide independent access to space and the second to develop programmes for the scientific exploitation of space missions, very much in the spirit of the other large European joint scientific effort, the European Centre for Nuclear Research (CERN) established near Geneva. Joint scientific and technical resources, coming from different countries, are necessary since individual European countries on their own can hardly make the effort required to be competitive in world-class space research. Space is indeed an example of the many great challenges that Europeans can only afford together, making our investments more efficient as well as strengthening our common identity.

By 1975, the two organizations, ELDO and ESRO, were merged into the European Space Agency (ESA), which now has 22 Member States. Activities of ESA go from launcher development for access to space, to Earth observation programmes, telecommunication satellites, navigation, human spaceflight (including the European contribution to the International Space Station), future technology programmes, the exploration of the Solar System, space physics and space astronomy. The annual budget of ESA is close to 4 billion €, out of which 500 millions are in the mandatory Science programme. Nevertheless, taking into account the scientific activities carried out in other programmes, essentially optional, the ESA efforts in science reach around 1/4 of the total budget.

As indicated above, the general goals of the Science Programme of ESA are: a) to understand our Universe; its structure, content and evolution, b) to understand the physics underpinning the observed processes, and c) to explore the Solar System; understanding its origin and evolution, as well as life. With these aims, ESA provides scientists with the necessary space tools to carry out their scientific research.

In order to achieve these goals, the Science programme of ESA is structured as Mandatory, i.e. Member States contribute to the budget according to their Gross National Product and not their specific interests in proposed missions. Moreover,

the programme has a long-term planning allowing for the balanced development of the scientific areas that the community needs. The content of the long-term planning, i.e. the specific missions to be developed and operated are selected in competitive bottom-up processes to ensure scientific excellence. The current plan is called *Cosmic Vision* and succeeds the previous *Horizons 2000* whose implementation is now being finished. Projects are developed in cooperation with scientific institutes in Member States that essentially contribute with the in-kind provision of the scientific instrumentation. Instruments, like missions, are selected in a competitive process with the involvement of the scientific community.

THE FIRST MISSIONS: EXPLORING THE ADVANTAGES OF SPACE

During the first decade of scientific research in and from space, under the structure of ESRO, ideas were centred in acquiring the necessary technological capabilities or to explore the advantages of space for science by having instruments above the Earth atmosphere. This implied mainly the use of satellites to study the sky in high-energy wavelength ranges for which the Earth atmosphere is opaque. Global surveys to identify sources and their luminosities emitting from the ultraviolet to gamma rays were thus planned.

Within a series of small missions with technology and space physics goals, the first astronomical satellite was ESRO-2B, also called IRIS, and launched with a *Scout* in May 1968. The ESRO-2B satellite was designed to measure the X-ray and energetic particle flux of the Sun but could also detect other sources. After 6.5 months of normal operations it showed problems with the data recording system and by the end of the year it was no longer scientifically operational.

A more ambitious satellite was TD-1, launched from California on a *Thor-Delta* rocket (hence the acronym of the mission) in March 1972. The 470 kg spacecraft, with a scientific payload of 120 kg, was put in a Sun-synchronous orbit. The main objective of the mission was to survey the ultraviolet sky, though several instrument for higher energies were also on-board. A problem with the data recording system soon after launch was mitigated by means of a rapidly developed ground-system rescue for real-time telemetry. Most of the sky was scanned and more than 30,000 ultraviolet sources were catalogued. Interstellar dust could also be studied and its distribution throughout the Galaxy initially plotted. The mission was operational until May 1974.

In August 1975, another satellite was launched called COS B, this time with a *Delta* rocket, just after ESA had been formed. The mission was designed to perform an extensive, pioneering survey of the Galaxy at energies of 50 MeV to 5 GeV. Major achievements included observations of the Crab and Vela pulsars, the discovery of numerous point sources in the galactic disc and the first observation of gamma rays from an extragalactic source (3C273). Operations were terminated in April 1982 and the database was formally released to the scientific community in September 1985.

The International Ultraviolet Explorer (IUE) was the first real observatory mission, in cooperation with NASA and the UK, to observe individual sources in the ultraviolet domain between 1150 and 3200 Å. It was launched with a *Delta* rocket in January 1978 and was operated successfully until September 1996, well beyond its design lifetime and becoming the longest-serving astronomical satellite. It returned more than 104,000 high and low resolution spectra providing astronomers with a unique

tool for the study of many astrophysical problems. IUE was also the first scientific satellite that allowed astronomers to make real-time observations in the UV and provided an unprecedented flexibility in scheduling targets of opportunity. The satellite could be operated continuously, and for one third of the time the operational responsibility was taken by the newly created centre by ESA in Villafranca del Castillo, near Madrid, which later became the European Space Astronomy Centre (ESAC). Users around the world are still actively using this data despite the time passed, and the collected information has been incorporated in developments for multi-mission archives.

Initially selected to be COS A, a highly performing X-ray mission had been delayed to incorporate the latest developments in building X-ray imaging systems at the time. X-ray Observatory Satellite (*Exosat*) was finally launched in May 1983 with a *Delta* rocket and was operated until May 1986. ESA's *Exosat* studied the X-ray emission from most classes of astrophysical objects, including active galactic nuclei, white dwarfs, stars, supernova remnants, galaxy clusters, cataclysmic variables, and X-ray binaries. *Exosat* obtained 1780 observations locating the sources and analysing their spectral features and time variations. Though it was designed to observe previously detected X-ray sources, it could also discover many new ones serendipitously. *Exosat* was operated as a real-time observatory and the spacecraft was in a highly eccentric orbit. European astronomers learnt about the possibilities of the X-ray domain for the understanding of the physics underpinning high-energy sources, and started to work in the definition of a much more performing mission that later became XMM.

Despite all these activities in space astronomy, European scientists did not forget the possibilities of space technology to explore some objects within the Solar System. The initial mission in this new field was *Giotto*, the first close flyby of a comet. *Giotto* was launched on July 1985 with an *Ariane 1* rocket from French Guyane, and passed by comet Halley on March 1986. The mission was later extended for a flyby of comet Grigg-Skjellerup on July 1992. Halley had been selected because its uniqueness in being young, active, and with a well-defined path, essential for an intercept mission. *Giotto* was the first spacecraft to take a payload close in to a comet (600 km) and obtained the first image of Halley's comet nucleus showing a lumpy body of 15 by 7–10 km, the full width being obscured by two large jets of dust and gas in the active sunward side. The dark side, with an unexpected low albedo, was quiescent but circular structures, valleys, and hills, could be identified. The jets broke through the dark crust that insulated the underlying gas from solar radiation.

The following mission was a breakthrough for fundamental astronomy. *Hipparcos* (High Precision Parallax Collecting Satellite) was launched in August 1989 with an *Ariane 4*. The spacecraft, at 1140 kg, contained a science payload of 215 kg and was expected to be in geostationary orbit but a boost motor failure forced the mission to be put in a highly elliptical orbit and a completely revised operations scenario was needed. Operations were nevertheless finished by March 1993 with a very successful scientific outcome fulfilling all expectations. The most accurate positional survey of more than 100,000 stars had been performed leading to the determination of their distances on the basis of trigonometric parallaxes, their proper motions and other characteristics such as their variability or binary nature. Improving on ground-based accuracies by a factor of 10 to 100, *Hipparcos* fundamentally affected every branch of astronomy, and specially theories of stars, their structure and evolution. 1000 Gbit of data were returned during the 4 years of operations, making the production of the catalogues the largest data analysis problem ever undertaken to achieve precisions within about

0.001 arcsec. The final processed data set was published in 1997. *Hipparcos* not only put Europe in a leading role in stellar astronomy but also demonstrated that space could provide excellent opportunities even in optical wavelengths when global measurements or precision photometry is required.

THE OBSERVATORY MISSIONS: EXPLOITING THE ADVANTAGES OF SPACE

The times of the survey missions exploring the sky in different regions of the electromagnetic spectrum were to finish by the nineties and a new phase in the development of large observatories had to start. This new era was to be devoted to detailed analyses of the physical processes taking place in a variety of objects, from the Solar System to the largest structures of the Universe.

The first of these large observatories, still in operation, was the Hubble Space Telescope (HST), a NASA-led mission with a European contribution to its development, as well as to the operations. In return, European astronomers from ESA Member States are guaranteed a minimum of 15 % of HST observing time. HST is a 2.4 m astronomical telescope operated as an international observatory with the advantage over a ground-based facility of adding to diffraction-limited angular resolution, access to the UV and near-IR ranges. It was launched with the Space Shuttle in April 1990 carrying on-board the European Faint Object Camera (FOC), which was returned to Earth in March 2002. Despite some problems at the very beginning of the mission with the optical focus of the mirror, the Space Telescope has become the greatest observatory available in space for astronomy. The possibility to service the observatory with manned missions by the *Shuttle* has allowed upgrading instruments at the focal plane, using more efficient detector technologies at each opportunity, and moving from the original optical-ultraviolet domain to the current near-infrared main objective.

Scientific results go from the study of stellar formation regions and proto-planetary disks, through the characterization of extra-solar planets, using high-resolution measurements during transits, to the original scope for which it was designed, the large structure of the Universe; for example, measuring the Hubble constant using Cepheids in other galaxies. Disturbed-looking galaxies of the early Universe have been imaged by means of the Ultra Deep Field exposure and type Ia supernovae have allowed to demonstrate that the universe is not slowly decelerating its expansion, as previously expected, but actually accelerating, what requires the introduction of dark energy. Dark matter has also been studied through weak-lensing effects in distant galaxies, leading us to a vision of our universe where the normal matter content is not more than 5 %; dark matter contributing with some 25 % and the rest being dark energy. Not only are we not located near the centre of the Universe; we are not even made of what 95 % of the Universe is made of!

The spectacular success of the Infrared Space Observatory (ISO) provided a fresh perspective on the cold component of the universe, boosting most areas of astrophysics. It was launched with *Ariane 4* in November 1995 and remained operational until May 1998. With a launch mass of 2,500 kg, ISO was cryogenically cooled to study the universe in the 2.5 to 240 microns IR domain, as a follow-up to the all-sky survey of IRAS in 1983, with sensitivity about 1000 times greater and spatial resolution 100 times higher. ISO was operated from Villafranca in Spain as an observatory and

measured from planets to quasars, studying in detail the early evolution of galaxies and the history of star formation. Clouds of gas and dust leading to collapses where stars are formed could be analysed with particular attention to disks of matter to understand planetary formation. Complex molecules, including organic compounds, were identified in the interstellar medium boosting the development of astro-chemistry. Spectrographs found abundant water in many different places, like planets and comets, young and evolved stars and even in external galaxies. Thanks to ISO, the cosmic history of water was traced for the first time. Moreover, ISO could find the characteristic chemical signatures of bursts of star formation in ultra luminous IR galaxies. The scientific community is still actively using the database and obtaining great results.

Our star, the Sun, could of course not be left forgotten by the scientific community as a key reference for the behaviour of the Earth's magnetosphere and stellar astrophysics. A mission in cooperation with NASA, *Ulysses*, was launched in October 1990 to study the solar polar regions by bringing the spacecraft to a perpendicular orbit to the plane of the ecliptic. Designed for one orbit around the Sun, *Ulysses* managed to be operational for three orbits by ending its life in 2009. During this period it provided an unprecedented view of the solar environment at different latitudes, analysing the solar wind that fills the heliosphere as an outward racing plasma of charged atoms and electrons that cause Earth's magnetic aurorae and magnetic storms. *Ulysses* found that the wind coming from the poles blows at a speed twice that emerging from equatorial zones. An important element of the mission was the study of the magnetic field of the Sun and its variations with latitude, an essential element to understand the solar wind. In addition, *Ulysses* could be used in the search for gamma-ray bursts thanks to its instrumentation for the study of cosmic rays and high energy radiation.

A NEW PLANNING SCHEME: THE HORIZON 2000 PROGRAMME

By the mid-eighties, it was already understood that a long-term programmatic view was necessary for science missions to be manageable and to achieve the goals of a broad scientific community. Such an approach could be used to maintain scientific skills and expertise in Europe as well as a balance between the different scientific domains. Moreover, the long-term plan defines the resources needed for a sustainable programme, allows preparing technology plans and ground infrastructures and provides continuity to industry with challenging projects and a balances industrial policy. Another essential added value of a long-term planning is to enable coordination with other Agencies, in developing joint missions, and National programmes in providing payloads. Of course, the necessary flexibility has to be maintained in the programme to adequately respond to the evolving development of science and technology.

The first long-term plan of the European Space Agency scientific programme was approved in 1985 with the name of *Horizon 2000* and duration of 20 years, up to 2005. The programme contained four (4) cornerstone or Large Missions with European leadership and requiring long technology preparations. The solar-terrestrial programme, including SOHO and *Cluster*, was the first cornerstone and an X-ray observatory, *XMM-Newton*, was the second. The third cornerstone was a mission to explore comets, *Rosetta*, and the final was a far-infrared observatory, *Herschel*. In addition the programme contained a number of medium-size missions, less ambitious, requiring less technology preparation, but providing excellent science and allowing

an increasing support to a demanding scientific community. The missions selected before 1985 but not yet launched, were naturally included in *Horizon 2000*, namely, *Hipparcos*, HST, *Ulysses*, and ISO. New missions were to be approved in a competitive process following calls for proposals to the scientific community.

A mission devoted to the study of the Sun, the Solar and Heliospheric Observatory (SOHO), was developed as a cooperative project between ESA and NASA, and launched in December 1995. SOHO is providing solar physicists with the first long-term uninterrupted view of our star, allowing us to understand its interactions with the Earth's environment. SOHO has revolutionized our knowledge of the Sun by answering questions of the internal structure and dynamics, how is the corona heated and how is solar wind accelerated. It is of particular importance for astronomers the results obtained by means of helioseismology about the internal density distribution and differential rotation of the Sun, leading to an accurate comparison with theoretical models and clarifying long unsolved issues like stellar convection or the expected flux of solar neutrinos. SOHO discovered new phenomena such as coronal waves and solar tornadoes while becoming the most prolific discoverer of comets in astronomical history. The observatory is still in operation, monitoring solar variability to understand climate impact with dramatically improved space-weather forecasting capability.

The Earth magnetosphere mission *Cluster* is giving new clues about the physical processes underpinning space weather in our neighbourhood in coordination with SOHO data. *Cluster* is a mission to study plasma structures in 3-dimensions with 4 identical spacecraft. Launched in July and August 2000, after the failed launch of the first *Ariane 5* in 1995, *Cluster* is still in operation discovering magnetic nulls, giant rolled-up vortices, the origin of "black" aurorae, or surface waves in the magnetotail. A new vision of magnetic reconnection has been provided together with the first measurement of electric current in space or the localization of the sources of natural plasma waves.

Continuing with large observatories, Europeans decided to build on the previous experience of *Exosat* and developed the large X-ray Multi-Mirror (XMM) observatory with sets of co-aligned instruments. Named *Newton* after launch, *XMM-Newton* provides high-throughout, broadband (100 eV to 10 keV), medium spatial resolution (20 to 30 arcsec) X-ray spectrophotometry and imaging of sources, ranging from nearby stars to quasars. The launch took place with an *Ariane 5* in December 1999 and operations continue providing excellent scientific results. Achievements cover a large number of topics thanks to its large collecting area provided by three mirror modules each carrying 58 nested gold-coated nickel mirrors using shallow incidence angles to guide the incoming X-rays to a common focus for imaging by the scientific instruments. Examples are isolated neutron stars, interacting X-ray binaries, distant galaxy clusters, the study of the galactic centre black hole as revealed by X-ray flares, dark matter maps based on the combination of hot matter pictures with HST weak-lensing studies, bursts of star formation, etc.

The third of the cornerstones was an ambitious project: a probe to escort comet carrying a lander to do *in situ* measurements. With the name of *Rosetta*, the mission was launched in 2004 towards the comet Churyumov-Gerasimenko. This is the most challenging of ESA missions in exploring our Solar System. The success of the flyby of comet Halley by *Giotto* in 1986 was the kick-off of a long process leading to a fascinating mission. On its way to the comet, *Rosetta* performed a flyby of asteroid Stein and later asteroid Lutetia. Arrival to the comet's distance took place in early 2014

and, after a long period of hibernation, the spacecraft woke up in time. Reaching the orbit of the comet as far as possible from the Sun and thus as little active as possible was needed to characterize the target and land on it. This exploration phase took place in the summer of 2014 showing an unexpected and complex shape of the comet. Nevertheless it was decided to land *Philae* in November. After a few touchdowns, the probe stabilized on the surface of the comet and broadcasted a good amount of scientific data. These, together with measurements from the mother spacecraft, are revolutionizing our knowledge of comets and their role in the formation of the Solar System. After discharge of the on-board batteries, *Philae* stopped working, but signals were again received by summer 2015 when the comet was close to perihelion and thus illumination was much higher. Unfortunately, this was also the time when *Rosetta* had to get away from the comet to avoid the effects of outgassing due to enhanced activity. Now, the mission is still in operation with *Rosetta* navigating again closer to the comet and preparing the end of life by September 2016, when on-board fuel will run out.

Another great achievement took place 10 years before. The first of the medium missions of *Horizon 2000* was selected to be a joint mission with NASA to explore planet Saturn. European scientists focused on the study the atmosphere of Titan, the giant satellite of Saturn showing a dense pre-biotic atmosphere. *Cassini-Huygens* was launched in October 1997 and arrived to Saturn in July 2004, little after the launch of *Rosetta*. ESA provided the *Huygens* probe that landed on Titan in January 2005 with a 150 min parachute descent and presented an extraordinary view of a world dominated by methane in different physical states. This is still today the furthest ever landing in the Solar System and only metre-resolution images of Titan's hidden surface. *Huygens* discovered "Earth-like" landscapes and signs of fluvial erosion activity. The main objective of *Huygens* though was to make the first *in situ* measurements of Titan's atmospheric structure (temperature and density) as well as direct measurements of winds, confirming super rotation. The analysis of the first direct sampling of the atmospheric chemistry, rich in hydrocarbons or prebiotic, is giving clues as to how life began on Earth.

Integral was launched on October 2002 with a *Proton* rocket from Baikonur to provide detailed spectroscopy and imaging of celestial gamma-ray sources. It is a large spacecraft, weighting 4 tons at launch, that carries sophisticated instruments providing an unprecedented combination of celestial imaging and spectroscopy over a wide range of hard X-ray and gamma-ray energies, including optical monitoring. Gamma-ray astronomy explores nature's most energetic phenomena and addresses some of the most fundamental problems in physics and astrophysics. Phenomena like nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic ray interactions and sources, neutron stars, black holes, gamma-ray bursts, and active galactic nuclei, are among those studies where *Integral* mission has made essential contributions. First investigations to be carried out showed the point sources responsible for the apparent diffuse radiation of the galactic disk or the distribution of the annihilation emission line at 511 keV recently interpreted as due to positrons formed as decayed products of the explosion of massive stars. The ^{26}Al emission line at 1.8 MeV allowed an independent estimate of the galactic core collapse SN rate of 2 %. Gamma-ray bursts (GRBs) of course attracted much attention of *Integral* and recent results showed polarized prompt emission of GRB 041219A and a new population of low-luminosity GRBs. In 2014, the analysis of *Integral* data from a type Ia supernova in M82, could confirm the presence of elements predicted by explosive models for this events, key

to measure the distance to the furthest away galaxies in the Universe. More recently, a period of renewed activity in the binary system V404 Cygni could be monitored giving information about the process of matter pilling up in the disk around the black hole component.

After the cooperative development of *Cassini-Huygens*, Europeans concentrated in a number of missions to study the inner rocky planets of our Solar System, starting with *Mars Express*. This mission, the first European spacecraft to the Red Planet, was launched in June 2003 and is still in a healthy state of operations. During this period, breath-taking high-resolution images of the surface in 3D and in colour have been collected. *Mars Express* has also provided the first subsurface sounding and the discovery of water-ice deposits below the surface. Moreover, mineralogical evidence for liquid water throughout Martian history has been provided as well as a detailed study of the crust density. In the atmosphere, first detection of atmospheric methane, night glow, and mid-latitude aurorae have been achieved while escape rates have been estimated in the upper levels. *Mars Express* carried a small lander, *Beagle 2* that was released at arrival to the planet. Unfortunately no further communication was obtained and this element of the mission was considered lost. After a decade, high-resolution images of the surface found *Beagle 2* on the Martian surface. Apparently it landed safely but the deployment of the solar panels petals did not work properly and the transmitting antenna could not operate.

Within this ambitious Solar System exploration programme, *Venus Express* was selected to reuse the *Mars Express* platform as much as possible allowing a fast development time. *Venus Express* was launched in November 2005 and has studied our sister planet until the end of 2014, when it run out of fuel to maintain its operating orbit. The spacecraft studied the dense atmosphere of the planet with great detail in order to understand why Venus is so different from Earth while having similar mass and radius. It was found that Venus is much more dynamic, and variable on all timescales, than earlier thought. The southern pole atmospheric dipole could be studied in detail as well as northern hemisphere cloud structures and gravity waves. Moreover, a 30% increase in wind speed of the already super rotating atmosphere could be detected. But an even more essential result was the evidence of data showing a young unweathered surface indicating recent volcanism.

In 2009, the International Year of Astronomy, ESA returned astronomy to the frontline of its science programme and launched two very ambitious far-infrared and sub-millimetre missions. *Herschel* and *Planck*, were launched in May 14 from Kourou in French Guyana. *Herschel* is the first space facility to completely cover the far infrared and sub-millimetre (57–670 microns) range with a large (3.5 m), low emissivity (~4 %), passively cooled (<90 K) telescope and three cryogenically cooled science instruments. *Herschel*, the fourth cornerstone mission of ESA, was not only unique but also complementary to other facilities. For wavelengths below 200 microns it provides much larger (but warmer) aperture than missions with cryogenically cooled telescopes. *Herschel* provided larger colder aperture, better 'site', and more observing time than balloon- and airborne instruments, as well as larger field of view than interferometers. Active cooling at detectors level brought them below 1 K ensuring a very low background noise. The operational lifetime of the observatory lasted for around 4 years when the cooling of the detectors was finished and their temperature increased.

Herschel was a giant leap forward in the study of star and galaxy formation and evolution; the largest telescope ever flown in space, addressing infrared wavelengths

never covered before, and details never before seen. A previously unexplored window to the earliest stages of star formation was opened and unprecedented studies of the formation and evolution of galaxies in the Universe, back to 10 billion years ago has been achieved. The youngest stars in our Galaxy have also been revealed together with the most detailed and complete study of the vast reservoirs of gas in the Galaxy. *Herschel* has discovered numerous giant gas and dust filaments revealing how matter is distributed in the Galaxy. The filaments are dotted with bright clumps where new stars are being born — the filaments clearly play a major role in star formation. But the flow of new results from *Herschel* data is now actually increasing steadily, in the mission's archiving phase.

Planck, selected as the third medium mission of ESA, and launched with *Herschel* in 2009, was designed to provide imaging of the whole sky at wavelengths near the peak of the spectrum of the Cosmic Microwave Background (CMB) radiation field with an instrument sensitivity $\sim 10^{-6}$ in temperature variations, an angular resolution ~5′, wide frequency coverage, and excellent rejection of systematic effects. With this performance requirements, Europe's first mission to study the relic radiation from the Big Bang could look back to the dawn of time and provided more information about the infancy of the Universe than any predecessor mission, detecting the primeval cosmic seeds that led to the structures we see in the Universe today. As a result, a detailed census of the Universe's constituents — normal matter, dark matter, and dark energy — could be accurately taken as well as of its shape and dynamics. In addition, unprecedented polarimetric measurements of the CMB increased our knowledge of the early phases of the Universe; and all the foreground observations provided a completely new view of the cosmos and its phenomena at sub-millimetre wavelengths. The final release of *Planck* data, including all temperature and polarization measurements is planned for mid-2016.

Concerning smaller projects, a technology mission to test navigation by means of electric propulsion was launched in September 2003, short after *Mars Express*, with the name of *Smart 1*. It was decided to use it to go to the Moon and orbit around it resulting in a successful study of our satellite during almost two years. The cruise phase was used for all the propulsion technology tests and the spacecraft arrived to the Moon in November 2004. The mission finished with an impact on the lunar surface, in the visible side, in September 2006 after all the fuel had been exhausted.

AN EXTENDED LONG-TERM PLANNING: HORIZON 2000 PLUS

In 1995, it was decided to extend the successful long-term planning of *Horizon 2000* for 10 more years, up to 2015. The new programme was initially called *Horizon 2000 Plus* and later *Horizons 2000* by combining it with its predecessor. The extension included the termination of those missions that were selected but could not be launched in the period of *Horizon 2000*, notably *Herschel* and *Planck*. But it also included two new cornerstones, a sophisticated astrometry mission orders of magnitude better than its predecessor *Hipparcos*, and a mission to study in detail planet Mercury. Medium missions had to be significantly reduced due to financial problems and the carry over of costs from *Horizon 2000*. Still, a mission in cooperation with NASA to replace and improve HST and a technology probe to enable the search for gravitational waves from space, were included.

Both *Herschel* and *Planck* were operated in L_2 orbit. This has been found to be an excellent location for astronomical missions because of the possibility to block Sun, Earth, and Moon light, the use of passive cooling to achieve temperatures around 50 K, the stable environment, easy communications, all allowing long uninterrupted observations. Because of these reasons, the coming new astronomy missions of ESA are planned for this L_2 orbit.

GAIA is an astrometric mission launched in late 2013 following the experience and European leadership achieved with the *Hipparcos* satellite. Though using the same principles, GAIA uses completely different and much more performing techniques. A large focal plane assembly of multiple CCDs is the essential element in order to measure the position of every source brighter than 21st magnitude in the field of view while scanning the whole sky. In five years of observations every star will be observed at an average of 100 epochs and the accumulated information will allow accurate determination of distances, proper motion, and properties of more than 1 billion stars with unprecedented precision, thus producing an excellent 3D map of our galaxy. With the addition of photometric information, the database of GAIA will allow a detailed understanding of the structure and evolution of our Galaxy. GAIA will revolutionize stellar astrophysics by providing comprehensive calibrations and physical properties across all types of stars and ages, but it will also add essential information in other fields like distant quasars, minor bodies of the Solar System, Kuiper belt objects, extra-solar planets, and many more. In its first year of routine scanning GAIA already performed 270 billion astrometric measurements, 54 billion photometric measurements, and 5 billion spectroscopic measurements. Collected data show an excellent performance of the mission and, after 2 years of nominal operations, out of the planned 5 years, an intermediate release of the final catalogue, with positions and broad-band photometry, is scheduled for mid-2016.

The other cornerstone, or large mission, of *Horizon 2000 Plus* is a very ambitious mission to study the closest planet to the Sun in our Solar System: Mercury. *Bepi Colombo* is being developed jointly with the Japanese Space Agency, JAXA, and is expected to be ready for launch before the end of 2017. It is a dual spacecraft mission: a planetary orbiter, led by ESA, will focus on surface and interior science, and a magnetospheric orbiter, led by JAXA, will focus on the planetary environment. *Bepi Colombo* is the first European project to make the most extensive study of Mercury — from the interior to the exosphere. *Bepi Colombo* is expected to reveal the evolution of Mercury and the formation of the inner planets, including the understanding of Mercury's global magnetic field, the only one of a rocky planet other than Earth. In addition, the mission aims testing Einstein's theory of General Relativity.

In December 2015, the *LISA Pathfinder* mission was launched with a *Vega* rocket from Kourou. This is a technology-driven mission to test the concept of gravitational wave detection in space, paving the way for future missions to test Einstein's General Relativity and understand the fabric of 'space-time'. This is done by following motion of two masses in gravitational free-fall with unprecedented accuracy. For this purpose, *LISA Pathfinder* includes state-of-the-art technology, inertial sensors, laser metrology, and an ultra-precise micro-Newton propulsion system. All experiments will be completed by the end of 2016.

The James Webb Space Telescope (JWST) is the flagship mission of NASA to replace HST. Europe is contributing to this project with a significant effort that guarantees an access to at least 15 % of the observing time for astronomers in ESA Member

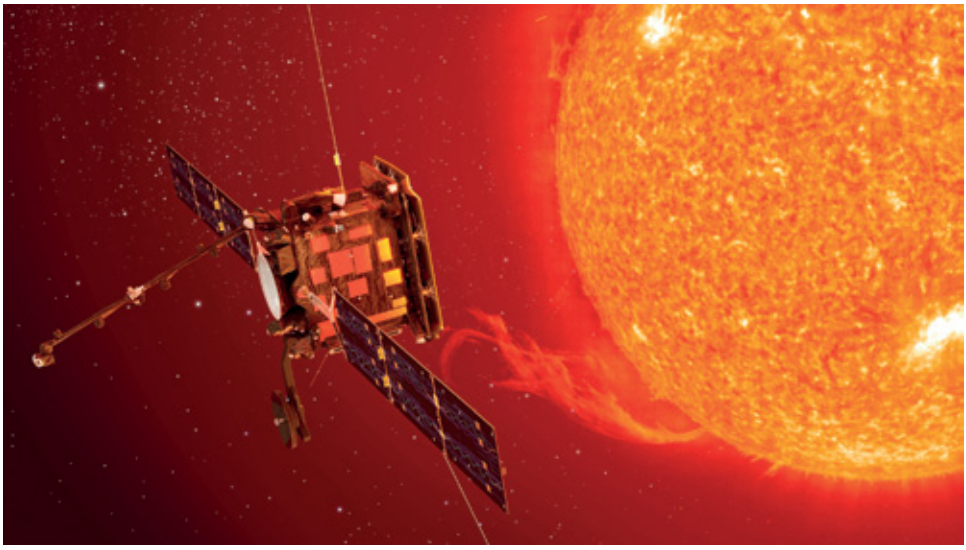
States. JWST is a 6-m class telescope (25 m^2 area) with 18 segments made of beryllium allowing superb image quality, diffraction-limited at 2 μm. The wavelength range of the instruments goes from 0.6 to 28 microns thus enlarging the capabilities in the infrared of HST and approaching the short wavelength limit of *Herschel*. The three core instruments are a 0.6–5 microns wide field camera, a 1–5 microns multi-objects spectrometer, and a 5–28 microns camera/spectrometer. A large sunshade (about the size of a tennis court) folded to fit in the launch shroud will protect the instruments from the sunlight and the design is made to ensure operations for at least 5 years with a 10 year goal. The mission will be launched in 2018 from Kourou with a Europe-provided *Ariane 5* rocket. JWST will quest for origins in four major science themes: the end of the dark ages (the first luminous objects from z around 20 up to the epoch of re-ionization), the assembly of galaxies (from the epoch of re-ionization to z around 1), the formation of stars and stellar systems (from gas clouds to planetary systems), and the planetary systems (from their physical and chemical properties to their potential for life).

It is worth mentioning the launch at the end of 2006, of the CoRoT mission, a French-led project in cooperation with ESA, to study the structure of stars and search for relatively small planets. For the first objective, the same technique developed by SOHO for the study of the Sun, was applied to stars bringing astro-seismology to the front line of stellar astrophysics. In the domain of extra-solar planets, the search for super-Earth candidates showed the power of the technology to identify new candidates and the need of an established cooperation with ground-based facilities to achieve the scientific objectives. Indeed, new candidate planets need follow-up observations to secure radial velocity measurements to obtain orbital parameters and high-resolution imaging and photometry to identify and characterize the host star. The results of CoRoT, until its end of life by mid-2013, have been very important for the definition of the next European extra-solar planet mission mentioned below.

Two elements of *Horizon 2000 Plus* could not be launched before the nominal termination of the programme, namely, *Bepi Colombo* and the JWST. Accordingly, they are taken into account in the new planning exercise, like it was the case with *Herschel* and *Planck* that were not launched in the period of *Horizon 2000*, but *2000 Plus*.

COSMIC VISION: NEW TOOLS FOR NEW QUESTIONS

ESA is preparing for new ideas to get deeper into issues raised by the large observatories just described. Specific problems need specially designed missions and the new programme of ESA, with the name *Cosmic Vision*, is being implemented. The new long-term plan of the scientific programme of ESA was initiated in 2005 and considered to cover a decade after *Horizon 2000 Plus*, i.e. up to 2025. The plan, called *Cosmic Vision*, envisaged nevertheless ambitious science goals that required extending it for two decades, up to 2035, similar to the original *Horizon 2000*. A realistic and affordable planning was considered, including the cost of extending missions in orbit and appropriate margins to avoid cost overruns leading to delays in the implementation of the plan. As a consequence, 3 large missions were planned together with 7 medium missions. Of course, the termination of *Bepi Colombo* and JWST is also included so that again, as in *Horizon 2000*, 4 large and 8 medium missions are planned for two decades.



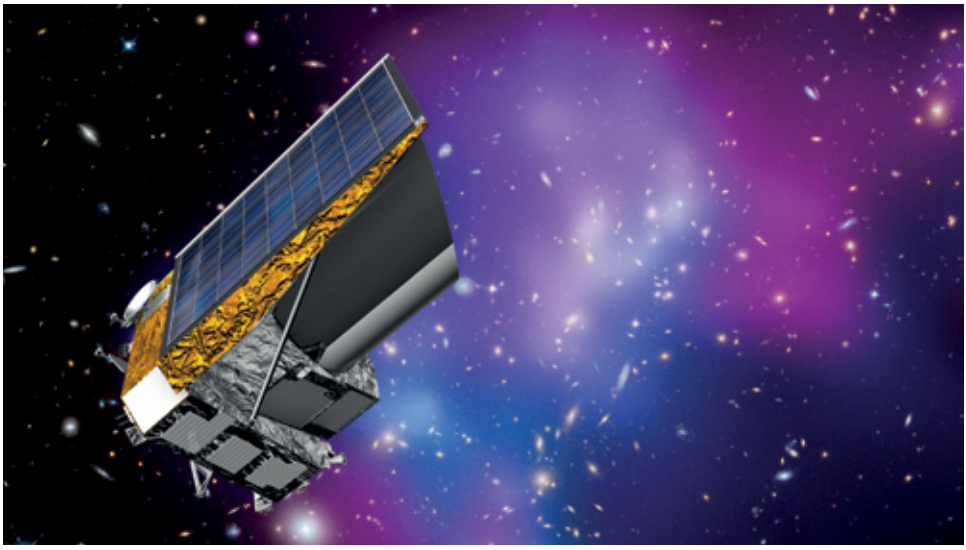
Solar Orbiter, © ESA

The first two medium-class missions selected in *Cosmic Vision* are *Solar Orbiter* and *Euclid*. *Solar Orbiter* is a project to explore the Sun-heliosphere connection, to understand how does the Sun create and control the heliosphere and why does solar activity change with time. For those purposes, it is essential to know what drives the solar wind and where does the coronal magnetic field originate, but also how do solar transients drive heliospheric variability. More specifically, *Solar Orbiter* will address how do solar eruptions produce energetic particle radiation, filling the heliosphere, and how does the solar dynamo works and drives connections between the Sun and the heliosphere. Different to SOHO, which resides in L_1, *Solar Orbiter* will get closer to the Sun and explore higher latitudes, making both remote and *in situ* measurements. The mission is planned to be launched in 2018.

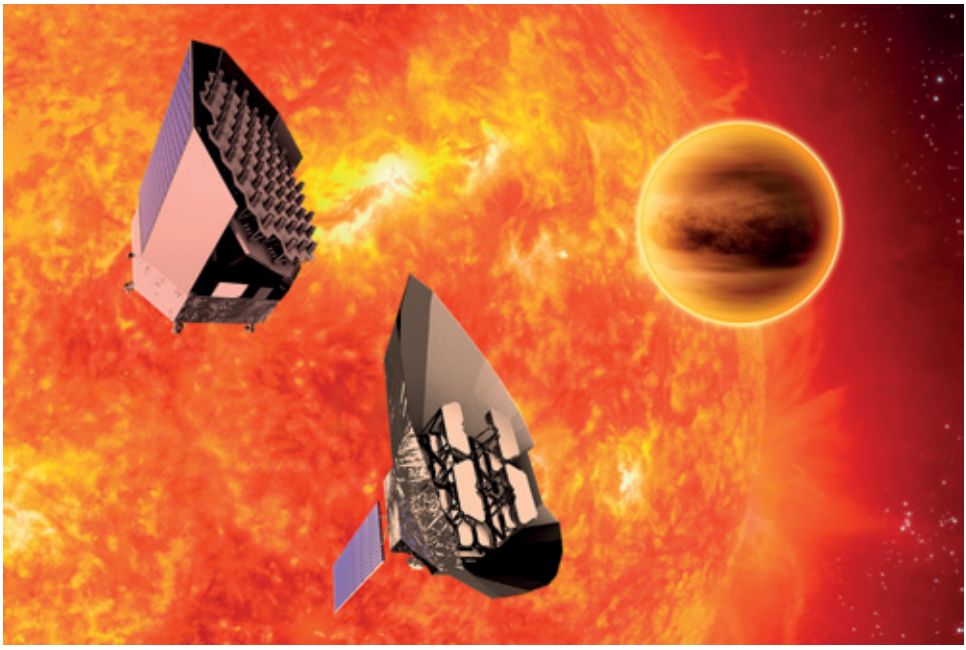
Euclid is a dark-energy surveyor project aimed at constraining the dark energy equation of state parameter w to <1 % by means of an imaging and spectroscopic survey of the entire extragalactic sky. *Euclid* will use two techniques: weak-lensing and baryonic acoustic oscillations. Weak gravitational lensing is a result of matter in front of galaxies distorting their shapes. This "shear" measures the amount of matter along the line of sight (dark & normal) to the galaxy. Shear must be measured accurately and it is expected to measure the shape of around 10^9 galaxies. In addition, measurements of distance by photometric redshifts in 3 near IR bands are needed. In the case of baryonic acoustic oscillations the size and distribution of cosmic structures depend on the expansion rate and gravity. For this purpose, *Euclid* will measure spectroscopic distances of all galaxies to $z = 2$. To achieve its goals, *Euclid* carries a 1.2 m telescope with 0.2″ PSF, which will perform a 5-year survey using a visual imager (VIS) together with a near-IR spectrograph/photo-imager (NISP). The mission will be launched in 2020.

A third medium-size mission has already been selected. *Plato* is the name of the planet finder, designed to find and characterise Earth-size planets in 1-AU orbit around 20,000 Sun-like stars. The method to do so is the occultation technique

already tested with CoRoT, i.e. to measure the star brightness to the highest accuracy. *Plato* will also characterise stars by astro-seismology in order to have a complete understanding of the size and mass of the host stars and their planets. For this purpose, *Plato* needs to survey large sky area for long time monitoring many stars simultaneously.



Artist's impression of Euclid, © ESA/C. Carreau



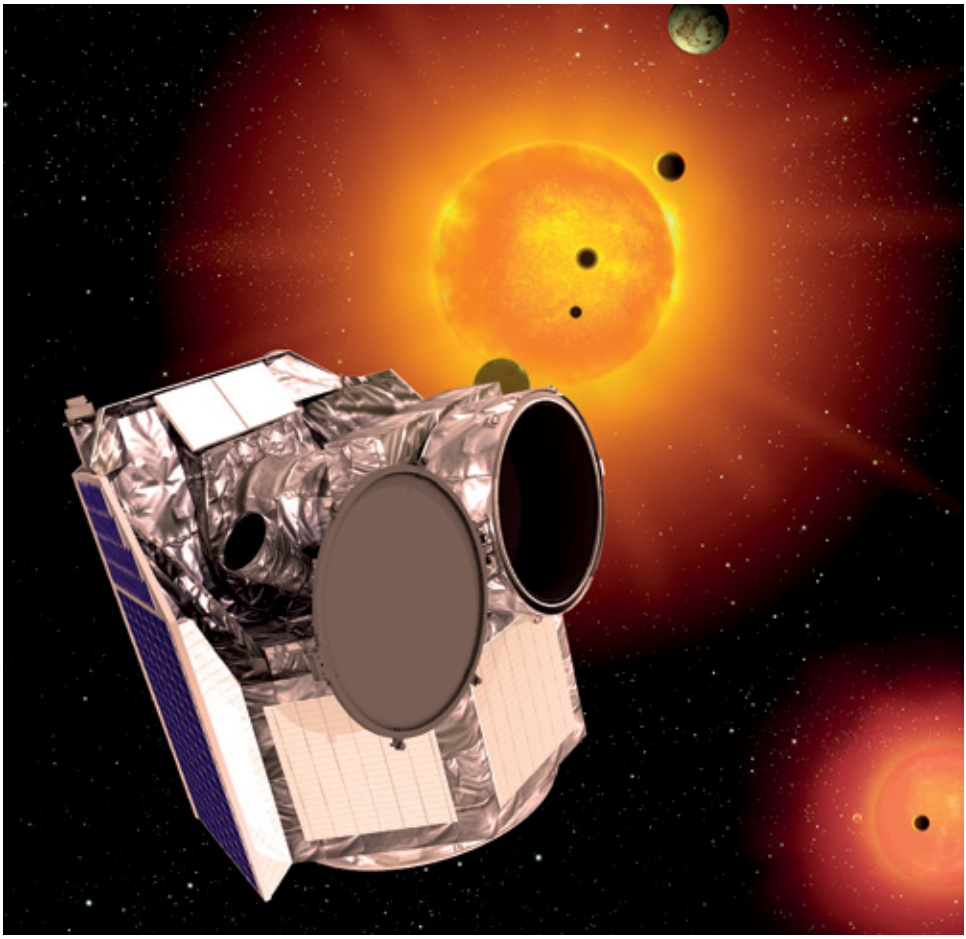
Two spacecraft concepts, © ESA

Artist's impression of the JUICE spacecraft, © ESA/ATG medialab

This is done by means of 54 co-aligned small telescopes that will observe several fields. In this way, *Plato* will detect and characterize Earth-like planets in the habitable zone of bright solar-like stars, obtaining radii down to 2 % accuracy together with masses around 10 % accuracy from radial velocity follow up at ground-based telescopes, thus leading to planetary mean densities. *Plato* will detect and characterize thousands of rocky, icy, and giant planets, the architecture of their planetary system and their host stars.

The next medium-class mission, M4, is currently in study phase with three candidates in competition: ARIEL, THOR, and XIPE. Future calls are planned for the coming years in order to select new missions from proposals presented by the scientific community.

Concerning large projects, the first one, JUICE, will be a mission to explore the icy moons of Jupiter. The goal is to analyse the emergence of habitable worlds around gas giants, like those detected by extra-solar planets finders, and use the Jupiter system as an archetype for gas giants. The main target of the mission is Ganymede. JUICE will be the first spacecraft to orbit a satellite of another planet and will allow studying the sub-surface, ice-shell, ocean, and interior of such a planetary object, but also its surface composition, atmosphere, ionosphere, magnetosphere, and plasma environment. In addition, JUICE will perform several flybys of two other extremely interesting worlds: Callisto, a remnant of the early Solar System, and Europa showing water ice with surface minerals and recent activity zones. The current planning is to launch the mission by 2022.



CHEOPS, © ESA/C. Carreau

The second large mission selected is *Athena*, an X-ray observatory under study for a launch in 2028. Athena is designed for the study of black holes at the centre of galaxies and their evolution since they were formed as well as the study of the formation and evolution of large-scale structures in the Universe. It is a follow-up, much more ambitious, of the *XMM-Newton* observatory introducing novel instruments together with new lightweight mirror technology. The general theme of the mission is the "Hot and Energetic Universe" implying science objectives like how do large-scale hot gas structures form and grow as well as a census of black hole growth in the Universe. In addition, providing a unique contribution to multi wavelength astrophysics, *Athena* will enable observatory and discovery science. For the third large mission, only the science theme has been selected and further studies and technology developments are foreseen before the actual project selection and adoption, the launch year estimated for 2034.

The theme selected is "The Gravitational Universe" and the tool envisaged to address it is a gravitational wave observatory with the goal of studying mergers of black holes and neutron stars almost since the beginning of the Universe through the gravitational waves they emit. This is obviously very challenging endeavour currently con-

sisting of 3 interacting spacecraft in an equilateral triangle with 5 million km arms orbiting the Sun. As gravitational waves pass through, they distort space-time and therefore the shape of the triangle. The expected tiny distortion (10^{-12} m!) requires accurate laser interferometry measurement of the distance between the spacecraft. The basic measuring principles are currently being validated by *LISA Pathfinder*, which was launched at the end of 2015.

Small missions have also been incorporated to the *Cosmic Vision* programme. *Cheops* is currently being developed and should be ready for launch before the end of 2017. This mission is a 3-axis stabilized, 280 kg spacecraft in polar low-Earth orbit developed in partnership with Switzerland. The science goal is to follow up on known transiting exoplanets to investigate mass-radius relations of super-Earths and Neptunes. Another small mission has been selected recently as an opportunity to develop further cooperation with China. This is an explorer of the solar wind magnetosphere-ionosphere link, called SMILE, which should be ready for launch in 2021. Indeed, SMILE could also be classified as a Mission of Opportunity, like *Double Star* in 2005, an earlier less ambitious cooperation with China that paved the way for the new venture. A number of this type of missions has facilitated the participation of European scientists in missions led by partner agencies, particularly with Japan, like *Akari*, *Hinode*, and the soon to be launched *Astro-H**, but also with the French CNES, like the previously mentioned CoRoT and also *Microscope* to be launched in 2016.

FINAL COMMENTS

ESA's scientific programme success, despite the moderate budget available, is based on a combination of scientific excellence with stability in the funding and the long-term planning of missions within affordable limits. This stability requires maintaining a balance at four different levels: a) a discipline balance to serve all science communities, b) a budgetary balance defining the size of the building blocks of the programme, c) a time balance ensuring the correct number of missions in preparation, in development and in operation, and d) a cooperation balance between ESA-led missions and the participation in missions led by partners.

As a result, the science programme of ESA is a flagship and symbol for the Agency with the added value of fascination for our society. Community- and science-driven, now the programme has many highly successful missions in orbit, delivering new scientific results back to scientists worldwide, but many challenging missions are also in development or under study, ensuring that the flood of new science will continue.

By achieving world-leading scientific results, the space missions of ESA's Science Programme are also inspiring a generation of young Europeans in undertaking science and engineering careers, fostering innovation and thus growth in Europe. Indeed, by consistently pushing the boundaries of technological capabilities, the programme has a fundamental role in contributing to the sustainability of technological and scientific skills, capabilities and infrastructure in Europe, promoting innovation in both industry and academia, and fostering international cooperation worldwide.

* Launched in February 2016, but lost soon after launch — *ed*.

THE INSPIRING 50++ YEARS OF LUNAR EXPLORATION

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The first 50+ years of lunar exploration are summarized in three phases. The first *Insight* phase began at the dawn of the space age and lasted from 1959 to 1976. After a long period of inactivity, the second *Reawakening* phase of lunar exploration occurred from 1994 to 2014 with remarkable new discoveries from more modern experiments. The third phase of *Long-term Presence* is just beginning as serious exploration of the Earth-Moon system and evolves in an international environment.

INTRODUCTION

Much has happened during the last 50 years of planetary exploration and it all started with the Moon. There have been three general phases of Lunar Exploration since the dawn of the space age when spacecraft were first able to explore beyond Earth. These are summarized here with example missions; highlights are discussed in the following pages. All exploration activities were both challenging and inspirational as they pushed human ingenuity to accomplish the ambitious goal of exploring and understanding our nearest neighbor in the Solar System, the Moon. Phase I was an intense first look at the Moon from orbit, with landers, with rovers, and briefly with human explorers. The momentum was lost for several decades and then restarted in Phase II with a series of orbital missions that included an increasingly sophisticated array of sensors that were able to probe the character of the Moon more deeply with remote sensors. We are now at the cusp of Phase III, which is ultimately expected to enable long-term human and robotic presence in space.

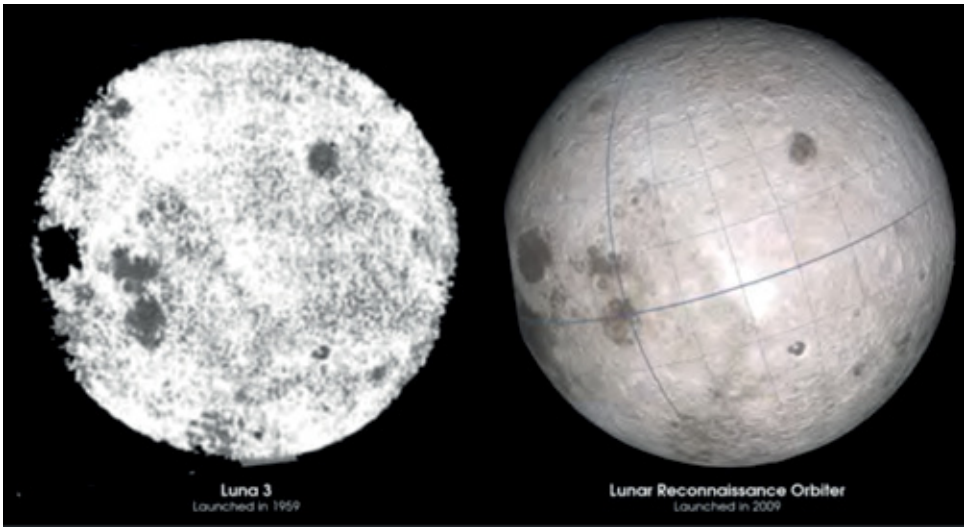
Phase I: 1959–1976. First Insight (from the USSR/Russia/ and the USA):
- *Luna*, Zond, Lunokhod;
- *Ranger*, *Surveyor*, *Lunar Orbiter*, *Apollo.*

Phase II: 1994–2014. Reawakening, New Views (International):
- *Clementine*, *Lunar Prospector*, SMART-1;
- *Kaguya*, *Chang'e*, *Chandrayaan*, LRO, *Artemis*, GRAIL, LADEE.

Phase III: 2016–. Long-term International Presence begins:
- *Chang'e-5*, *Luna 25*, *Resource Prospector*, *Chandrayaan-2*;
- Next generation initiatives by Russia, Europe, USA, China, Japan, India, Korea...

PHASE I. FIRST INSIGHT: 1959–1976

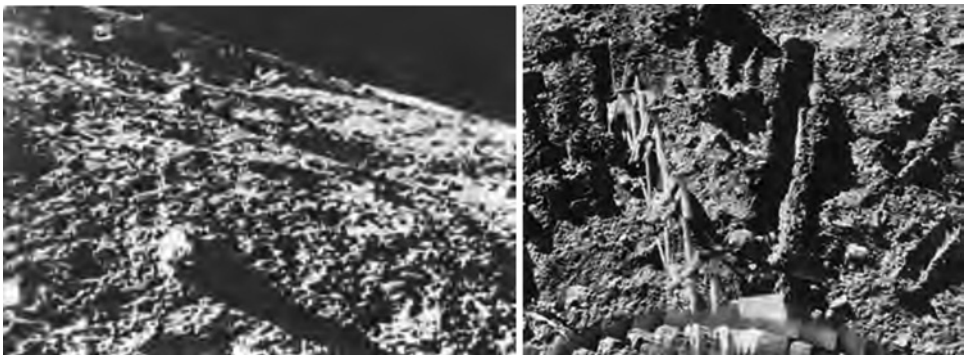
The first period of lunar exploration was dominated by two competing space-faring nations, Russia (then the Union of Soviet Socialist Republics, USSR) and the United States (USA). In 1959 *Luna 3* was launched by Russia and flew past the Moon when the far side was well illuminated (a crescent Moon from Earth). Images were successfully transmitted to Earth and this first look at the other side of the Moon was startling. It looked completely different from the familiar near side and appeared to contain very few of the large regions of dark maria (later shown to be extensive deposits of volcanic basalts).



Slightly enhanced first image of the lunar far side from *Luna 3* in 1959. Shown for comparison is a comparable view from the *Lunar Reconnaissance Orbiter* obtained 50 years later

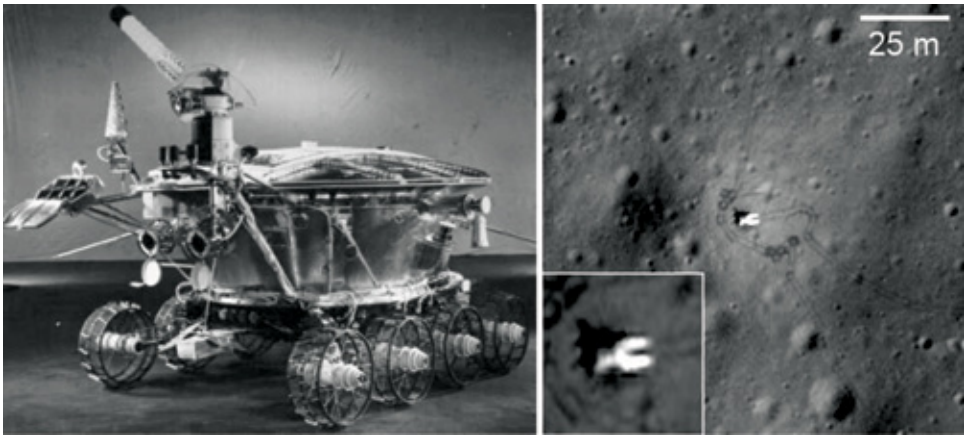
The first soft landings on the surface of the Moon were achieved a few years later in 1966 first by *Luna 9*, which landed in Oceanus Procellarum west of Reiner and Marius craters, and later by *Surveyor 1*, which landed in Flamsteed Crater in Oceanus Procellarum. These near side landings provided an important piece of information that was critical for future missions, namely that the surface of the Moon is indeed solid and can support a landed spacecraft.

Orbital missions were also initiated by both countries in 1966 while several additional landing missions continued to be sent to the Moon (not all of which were successful). A major goal of the orbiting spacecraft was to obtain images of the surface in order to develop a base from which to plan further and more detailed exploration. In parallel, although not discussed here, human exploration of the Moon began in 1969 with the *Apollo* landings and continued until 1972.

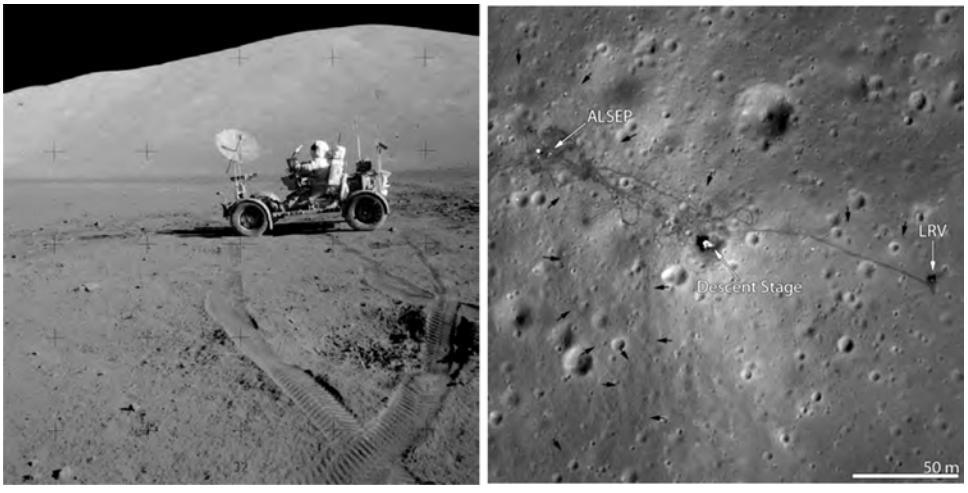


Images from the first landings on the surface of the Moon in 1966: *Luna 9* (left); *Surveyor 1* (right)

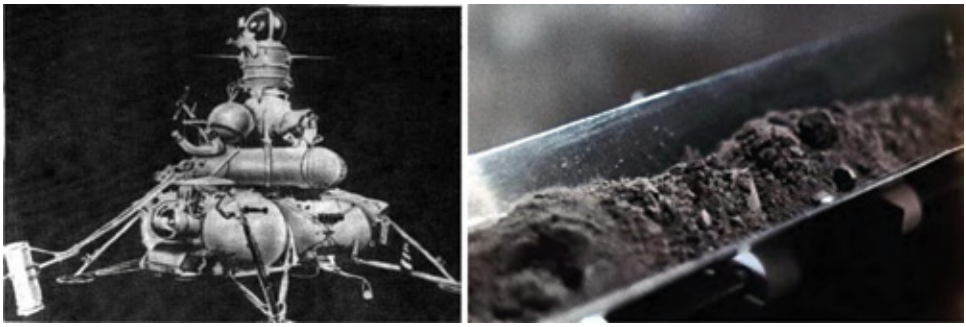
As technology improved (strongly pushed and encouraged by politics), the ability to use roving vehicles to move around on the surface and explore beyond a landing site was achieved. In 1970 the *Luna 17*, carrying *Lunokhod 1*, first automated rover, landed in Mare Imbrium near Sinus Iridium. *Lunokhod 1* traveled a total of 10.5 km and operated through an extended period of eleven lunar days (~11 Earth months) transmitting a rich array of new data to Earth (see [Basilevsky et al., 2015]). A human operated lunar roving vehicle, first included in 1971 for the *Apollo 15* mission, greatly expanded the range of exploration options. This roving capability allowed a combined traverse of 27.9 km over the limited 18.5 hours of extravehicular activities by the astronauts.



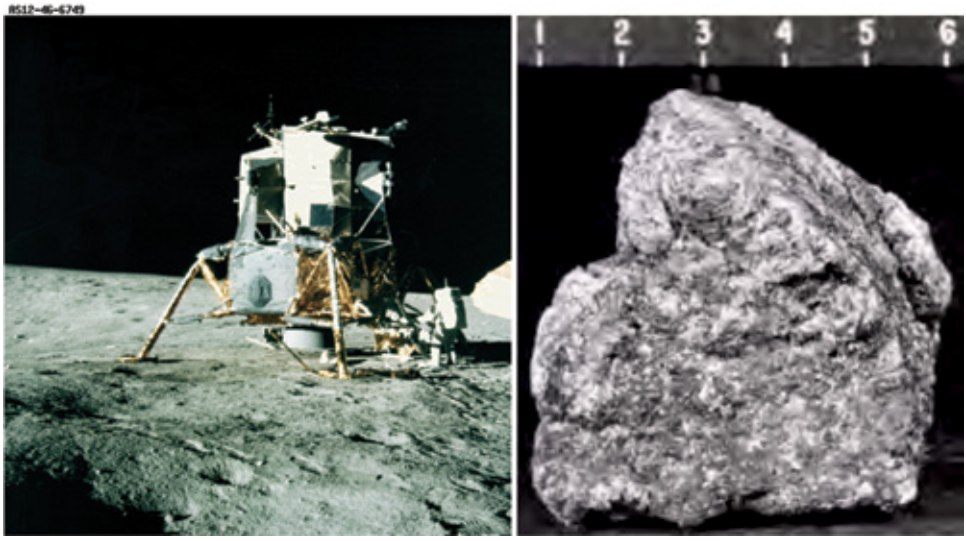
Luna 17 Lunokhod 1: the 2.3 m long *Lunokhod* vehicle with its solar panel in the closed position (left); image of *Lunokhod 1* on the lunar surface obtained decades later by the LRO Narrow Angle Camera (right)



Commander Dave Scott in the *Apollo 15* Lunar Roving Vehicle (LRV) (left). Image of the *Apollo 15* landing site on the lunar surface obtained decades later by the LRO Narrow Angle Camera (right). Arrows indicate faint LRV tracks



Luna 16 autonomous sample collection from a basaltic terrain in eastern Mare Fecunditatis: the *Luna 16* lander (left); image of the bulk sample (soil and pebbles) returned to Earth for analyses (right)

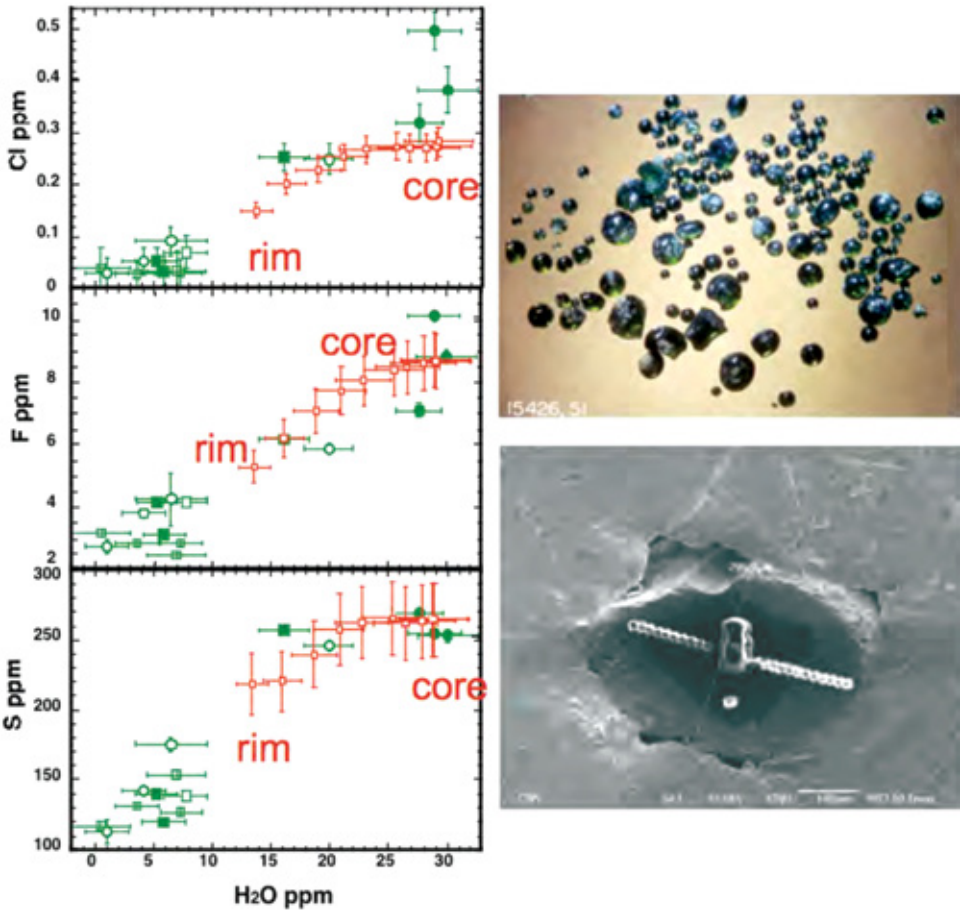


Apollo 12 sample collection from a basaltic terrain in east central Oceanus Procellarum: the *Apollo 12* lander and astronaut on the surface (left); image of *Apollo 12* basaltic rock 12031 returned for analyses (right)

From the long-term scientific perspective, a major highlight of lunar landing missions was the return of lunar samples from selected lunar sites to Earth-based laboratories for analysis. This occurred from 1969 to 1972 during six separate *Apollo* missions and from 1970 to 1976 through three different *Luna* missions. Each of the *Apollo* and *Luna* missions sampled completely different lunar terrain. During *Apollo*, samples were collected by astronauts and returned to Earth with them. For the *Luna* missions, samples were collected and stowed autonomously and returned to Earth by the spacecraft (e.g., see [Basilevsky et al., 2013]).

The lunar samples are valuable treasures that provide unique insight into our home at 1 AU in the context of the Earth-Moon system and the Solar System as a whole. Since the samples were obtained from several known locations across

the near side of the Moon, they allow investigations into the character and evolution of a planetary body that is both so closely tied to Earth throughout its history as well as so fundamentally different from Earth (ancient, dry, etc.). As earth-based laboratory instruments and facilities have become more capable over the last 50 years with advancing technology, our ability to identify and probe new questions and issues continues to improve. Return from the samples is never stagnant. The lunar samples are indeed 'gifts that keep giving'. As new discoveries continue to be made, results are widely shared among the international science community through scientific reports in peer-reviewed journals and formal sample exchanges.



Example of recent discoveries from lunar samples enabled by continuing improvement in earth-based laboratory facilities. Evaluation of the water content of some of the most primitive basaltic material from the Moon, the very-low-Ti volcanic glass beads [15426, 15427]. Major advances in secondary ion mass spectrometry (SIMS) have improved the detection of volatile species several orders of magnitude. Bulk measurements of individual beads are shown in green and a profile from the core to rim for a single bead is shown in red (left). The pattern is inconsistent with terrestrial contamination and clearly demonstrates that indigenous lunar volatiles were present when emplaced on the surface but partially lost through diffusion. 15427 green glass beads and SIMS traverse across a single bead (after [Saal et al., 2008]) (right)

Things dramatically changed after the last footsteps were made in 1972 and the last lunar sample returned in 1976. In spite of the long-term merits of leveraging progress with continuity as well as the demonstrated bloom of technological advancement and giant leaps of knowledge gained during this period of First Insight, lunar exploration effectively shut down for several decades as politics moved in other directions.

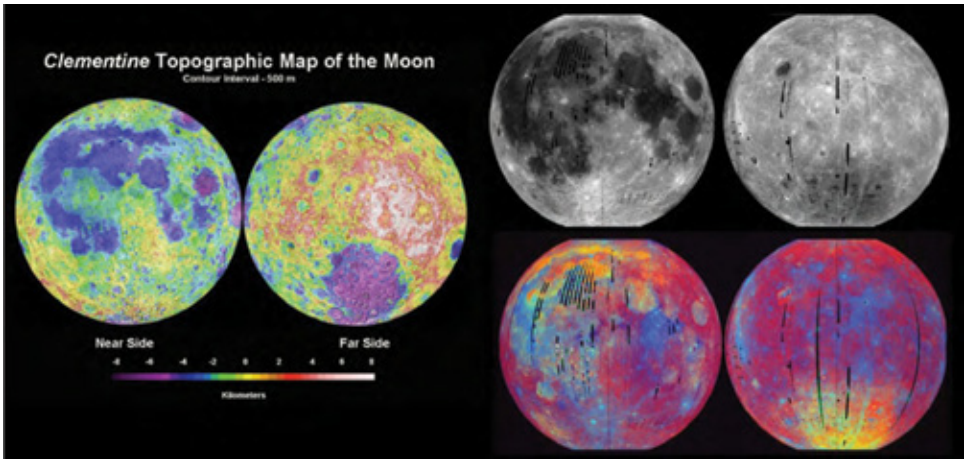
PHASE II. REAWAKENING AND NEW VIEWS: 1994–2014 (INTERNATIONAL)

After the intense first phase of lunar exploration ended, data analysis activities nevertheless continued with modest vigor across the lunar science community in spite of limited resources for support and a highly competitive planetary scientific environment. Telescopic measurements and lunar sample analyses produced new data, both benefiting as new instrument capabilities were eventually achieved. Although telescopic sensors improved dramatically over the decades (adding digital detectors and imaging as well as spectroscopic methods), only the near-side of the Moon was available for study with Earth-based telescopes.

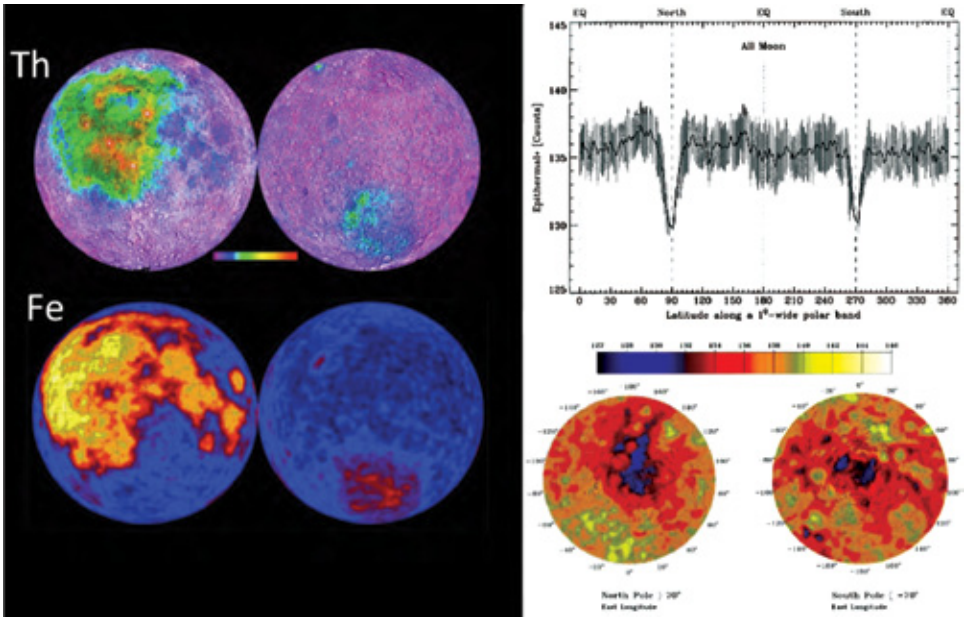
Even though there was no coherent plan, small new missions began to be flown to the Moon. These included *Clementine* (a DoD instrument test mission for which NASA provided science expertise in exchange for the data), *Lunar Prospector* (the lowest-cost viable mission proposed for NASA's new *Discovery* line), and *Smart 1* (a clever and determined technology demonstration by ESA). Data returned from this first new wave of lunar exploration with small spacecraft and a few new sensors seemed to shock a complacent planetary science community (and their respective space agencies) by illustrating the depth of ignorance about global properties of the Moon and revealing unexpected and fundamental new science results about Earth's nearest neighbor. Measurement highlights included an initial global definition of lunar topography along with a general assessment of elemental and mineralogical compositional diversity. In addition, the cold and permanently shadowed poles of the Moon appeared to harbor volatiles such as H, and by association H_2O.

The remarkable combined results from *Clementine*, *Lunar Prospector*, and *Smart 1*, (integrated and summarized by the science community in *New Views of the Moon* in 2006) inspired an international renaissance of lunar exploration. Although the amount of new data from these first new missions was relatively small, the impact was enormous for two obvious reasons: 1) the decades-long drought of new data from the Moon with capable sensors meant the science and engineering communities had little to no new information or stimulus and their lunar knowledge therefore had been stunted; 2) the small amount of new data for the Moon was sufficient to highlight the fact that the Moon has had a rich and complex evolution as a planetary body with much to inform scientists about how small rocky planets work.

This jolt of new insights about Earth's nearest neighbor occurred at the turning of the millennium. A reawakening of serious lunar exploration began using modern instruments in 2007 with the launch of SELENE/*Kaguya* and *Chang'e 1* by Japan and China respectively, in 2008 with the launch of *Chandrayaan 1* by India, and in 2009 with the launch of *Lunar Reconnaissance Orbiter* by the USA. These were followed shortly thereafter by additional *Chang'e* missions as well as by *Artemis*, GRAIL, and LADEE.



Global *Clementine* results for the Moon: topography (left); albedo at 750 nm (right top); color composite derived from ratio images — red-blue tones reflect variations in the slope of the continuum between 414 and 750 nm related to composition and exposure age and yellow-green tones indicate where abundant Fe-bearing minerals occur (right bottom). The enormous South Pole-Aitken basin dominates the southern far side of the Moon with its unique morphology and composition



Global *Lunar Prospector* results for the Moon: elemental abundances for Th (left; top, superimposed on a shaded relief map) and Fe (bottom). The Th map illustrates the notable concentration of radiogenic elements that occurs on the western nearside. The Fe map outlines the Fe-rich basaltic terrain that occurs largely on the near side and the Fe-enhanced interior of South Pole-Aitken basin on the far side. Low abundance of epithermal neutrons across the lunar poles [Feldman et al., 2001] reflect the presence of a H-bearing species (presumed to be H_2O ice) at the poles (right)

It is not possible to summarize the remarkable and extensive accomplishments diverse data from this fleet has provided over the last short decade, but here are examples of a few favorites:

1 New compositions have been discovered in unexpected geologic context

Although return of the first lunar samples hypothesized anorthosites to be the primary constituent of the lunar highland crust, this rock type was difficult to map with remote sensors. Near-infrared spectrometers on board *Kaguya* and *Chandrayaan* not only detected anorthosite in a spatial context, but also showed that this rock type often occurs in its crystalline form (rather than shocked amorphous) with a purity unrecognized in lunar samples (see [Cheek et al., 2013; Donaldson Hanna et al., 2014; Ohtake et al., 2009]).

The dark lunar maria that are concentrated on the lunar near side result from vast outflows of basaltic lavas derived from the lunar mantle. A different form of volcanism is now found to have occurred at several places in the lunar highlands. Perhaps the most prominent and unusual is at Compton Belkovich [Bhattacharya et al., 2013; Jolliff et al., 2011; Petro et al., 2013]. This is a small area on the far side that exhibits a high radiogenic (Th) anomaly. It appears to have emplaced pyroclastic deposits that are low in mafic materials and highly silicic with exceptionally high OH or H_2O content.

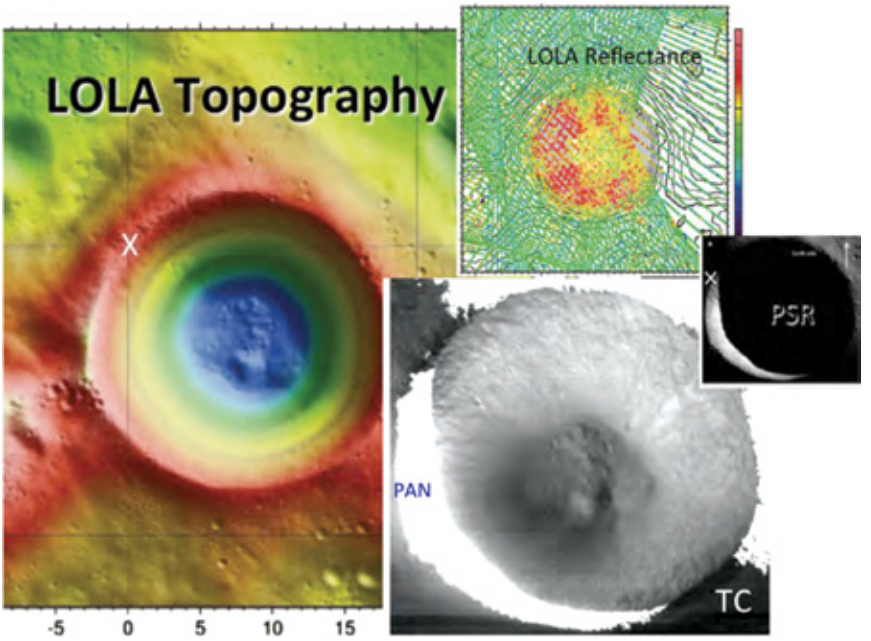
An unusual rock type (unseen in current samples) has been discovered associated with some large basins, craters, and special highland terrain [Pieters et al., 2011, 2014]. This newly recognized Mg-rich Al-spinel anorthosite is now thought to result from interaction of primitive magmas with the early lunar crust [Prissel et al., 2014] producing a rock type that has remained largely buried. Its identification through remote sensing raises a question of how many other lunar materials have yet to be discovered.

2. Combined measurements and analyses reveal that water (H, OH, H_2O) is to be found in three environments on the Moon

When lunar samples were first returned to earth-based laboratories 50 years ago, initial analyses showed them to be very depleted in volatiles, and all subsequent models for the origin of the Earth-Moon system was based on that observation. That premise has been substantially altered over the last decade as water (H, OH, and H_2O) can now be detected or measured using new instruments and with higher accuracy. Three very different environments are found to harbor some form of water.

[1] Indigenous lunar water first became apparent when modern instruments demonstrated the presence of water in primitive lunar magmas to be comparable to that of Earth's mantle (see Fig. on the p. 74; [Saal et al., 2009]). The origin of this indigenous lunar water is also being addressed (e.g., [McCubbin et al., 2010; Saal et al., 2013]).

[2] An enormous surprise came with the discovery of pervasive surfacial OH (and perhaps H_2O) in small amounts all across the surface of the Moon resulting from solar wind H interacting with O of lunar rocks and soil [Pieters et al., 2009]. There is the suggestion of mobility and possibly the abundance varying with time of day [Sunshine et al., 2009].



A montage of images from modern sensors for the 21 km Shackleton Crater at the south pole of the Moon (X). The two colored images are derived from multiple passes of the LOLA laser altimeter on LRO [Zuber et al., 2012] and depict topography and reflectance (red being high). The two grey tone images are from the Terrain Camera (TC) on *Kaguya* [Haruyama et al., 2008]. Shackleton interior is a permanently shadowed region (PSR) and never receives sunlight. Nevertheless, the interior has been revealed by the sensitive TC (using the tiny amount of light scattered from the rim of the crater into the interior) and independently by the active laser experiment. Shackleton composition is purest anorthosite (PAN) consistent with the high reflectance of the walls measured by LOLA [Haruyama et al., 2013]. The morphology of the interior is not different from similar sunlit craters and no obvious ice is observed on the surface

[3] The expected accumulation of H_2O in the cold traps of permanently shadowed areas near the lunar poles [Feldman et al., 2001; Mitrofanov et al., 2012] has been illusive and has been difficult to directly detect with other experiments [Haruyama et al., 2009, 2013; Spudis et al., 2010]. Nevertheless, the LCROSS active impact experiment into one such target [Mitrofanov et al., 2010] demonstrated the presence of abundant volatiles in the regolith [Colaprete et al., 2010; Schultz et al., 2010].

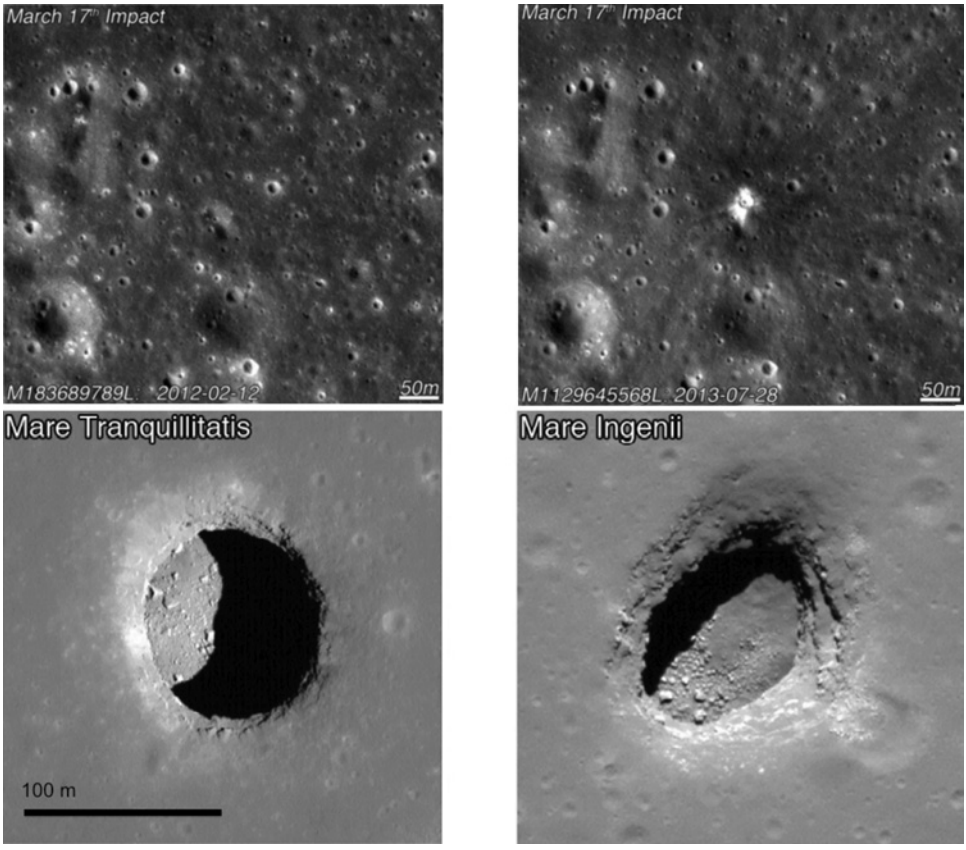
3. Secrets of the lunar interior are gradually being revealed

Recent analyses of the limited early seismic data for the Moon confirm the presence of a small lunar core [Weber et al., 2011]. In parallel, improvements in laboratory facilities have greatly advanced the ability to evaluate and characterize the magnetic properties of available lunar samples. There is now strong evidence that a lunar dynamo existed early in lunar history, and its activity has been dated to extend from 4.25 through 3.56 Ga [Weiss, Tikoo, 2014]. That sets stringent constraints on the internal thermal evolution and early history of the Moon.

Analysis of the high precision GRAIL gravity data is allowing the deep crustal structure of the Moon to be evaluated. Horizontal Bouguer gradients reveal features that result from stresses and/or patterns of weakness previously unseen from the surface [Andrews Hanna, 2013, 2014]. Such features reflect the early history of the planet and its crustal evolution in ways yet to be determined.

4. Special or unusual environments are being detected on the surface

Accumulation of high quality data, often from multiple sensors, provides a level of sophistication that enables new discoveries and understanding well beyond a single set of data. One example is the ability to document the formation of small new craters on the lunar surface with temporal pairs of images for the same area. Hundreds of small new craters have been detected along with thousands of smaller 'splotches' of reflectance changes associated with nearby areas [Speyerer et al., 2015]. At least one detected crater was explicitly linked to an observed flash by Earth-based monitors, providing a very precise time of crater formation [Robinson et al., 2015].



Before and after image obtained by the LRO Narrow Angle Camera of the documented impact crater formed March 17, 2013 (top); examples of two different collapse pits formed in volcanic terrain (bottom)

There is considerable interest in the small (~100 m wide) pits detected in volcanic terrain that appear to be holes into an underground cavern with layers of basalt forming the roof [Haruyama et al., 2009; Wagner, Robinson 2014]. These pits are believed to have been formed by a local collapse into pre-existing voids such as a lava tube. Although few in number, they hold great potential as a 'safe haven' from the harsh lunar environment for future explorers*.

EVOLVING QUESTIONS

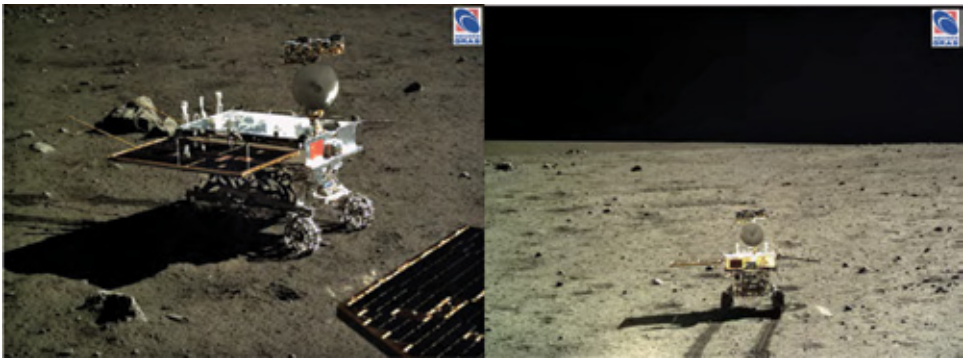
A large amount of diverse data from the fleet of Phase II missions are publicly available and are being analyzed by the international community of lunar scientists. Much will continue to be harvested as data analyses continue. The strength of combined results provides a pathway that leads to the next phase of lunar exploration. A host additional questions and issues emerge for this generation of explorers to address with new tools from orbit, placed *on the surface*, and/or with ***samples returned*** to Earth-based advanced facilities for analysis. The following are a few example questions that beg to be addressed [by one or more approach]:

- Where are volatiles concentrated on the Moon? What is their abundance? What is their origin? Are they renewable? [Orbiters, *Soft Landers*].
- What is the internal structure of this differentiated body, and how does it vary with different terrains? What planetary processes are responsible for forming the internal structure and its spatial variations? When? [*Soft Landers*, ***Sample Return***].
- What are the properties of unique or special environments on the Moon and how have they formed and evolved? (PSRs, swirls and magnetic anomalies, young volcanic vents, deflation features, deep holes, etc.) [Orbiter, *Soft Landers*].
- What composition or forms of new materials have yet to be discovered on the Moon? [Orbiter, ***Sample Return***].
- What is the current and past impact record for the Earth-Moon system at 1 AU? (present and previous periods of heavy bombardment) [Orbiter, ***Sample Return***].
- What forces act on and alter lunar soil and dust particles in the space environment? How are particles mobilized and how do they interact with foreign objects? [Orbiter, *Soft Lander*].

PHASE III. LONG-TERM PRESENCE ON THE MOON: 2016–

The recent successful landing of *Yutu* and operation of *Jade Rabbit* (China) through at least one lunar night provided a precursor for more complex achievements to come. The next serious phase of lunar exploration will not be easy, nor will it occur quickly, but the rewards will be enduring.

* See the paper by Jacques Blamont (see p. 195). — *ed.*



Successful landing of *Yutu* in Mare Imbrium and deployment
of the small rover *Jade Rabbit* by *Chang'e 3*

All eyes are on the next steps: *Chang'e 4*, *5*, *Luna 25*, *26*, *27*, *Resource Prospector*, *Chandrayaan 2*, SELENE 2, *SPA Sample Return*. Experienced international participants have expanded and now include Russia, the USA, Europe, Japan, China, and India, with Korea and others (perhaps some commercial) soon to join the group of lunar explorers.

As we progress beyond the first 50+ years, Phase III of lunar exploration clearly will be international in nature. With such activity comes both opportunity as well as competition among different interests. It will require interweaving four pillars of increasingly complex international efforts — the four "C"s: Communication, Coordination, Collaboration, and Cooperation. It is well worth the effort. When successful, our Earth-Moon system benefits in countless ways.

Acknowledgements

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   http://www.lpi.usra.edu/lunar/missions/
   http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html
2. Lunar Sample Compendium providing extensive information on individual lunar samples:
   http://curator.jsc.nasa.gov/lunar/lsc/index.cfm
3. Peer-reviewed sources of detailed information from the first two phases of lunar exploration:

Planetary Science: A Lunar Perspective, by S. Ross Taylor (1982) Lunar and Planetary Institute, pp 481.

Online [73 MB]: http://www.lpi.usra.edu/publications/books/planetary_science/

The Geologic History of the Moon, by Don E. Wilhelms (1987) U.S. Geological Survey Professional Paper 1348, pp 302 plus 12 global color maps.

Online [101 MB]: http://ser.sese.asu.edu/GHM/

The Lunar Sourcebook (1991), edited by Grant H. Heiken, David T. Vaniman, Bevan M. French, Cambridge University Press, pp 736.

Online [65 MB]: http://www.lpi.usra.edu/publications/books/lunar_sourcebook/

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PLANETARY SCIENCE IN IKI RAN: A PERSONAL ACCOUNT

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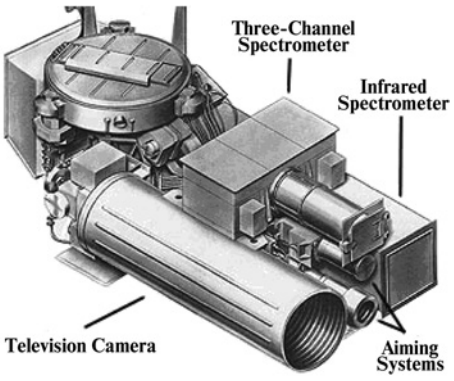
I feel much too young about writing any memoirs. I had not witnessed many, if not the most moments of the Institute's glory. That was underlying my initial reluctance to contribute to the 50-year IKI RAN anniversary book. But L. M. Zelenyi was insistent, and I surrendered after some thinking. Vasiliy Ivanovich Moroz created the Planetary Department of IKI in 1974. I am working in the department since 1985, 31 years out of 42, a supportable excuse. Some facts out of this paper appeared in Russian in the book [Vasili..., 2014]. This is a tribute to the elder generation, Moroz, Krasnopolsky, Linkin, Ksanfomality, and others, French colleagues with whom we were and still are extensively cooperating, and a very brief account for the recent 10 years, the period I was heading the Planetary Department.

VEGA

No doubt, VEGA is the most successful and glorious out of the USSR planetary, and likely of all science space projects. It was launched in October, 1984, the Venus probe released on June 11, 1985, and after a Venus gravity assist the carrier flew by the comet 1P/Halley on March 6, 1986. VEGA made possible that European *Giotto* made a close encounter with the comet, and it was the first Soviet mission widely open for international cooperation. I entered IKI in 1985, right after the laboratory celebrated 8th of March* at a high-spirited picnic in cold and snowy woods near Moscow, as I immediately learned. No big idea of the mission preparation, the novice had a chance to sense an after-launch calm, some distant fuss about the VEGA balloons, and to attend the culmination of the flyby.

During VEGA time the laboratory of Vladimir A. Krasnopolsky (named "Lab for Optical Spectrometry of the Upper Atmospheres") was deeply involved in TKS experiment (Three-Channel Spectrometer) on the flyby spacecraft. The experiment to study the exited gases in the cometary coma included two French channels (ultraviolet, or UV, and visible spectrometers), and a near-infrared (IR) spectrometer developed in IKI. The French partners were from Besançon Observatory, led by Guy Moreels. The third foreign party involved was Mitko Gogoshev, the director of Observatory in Stara Zagora, Bulgaria.

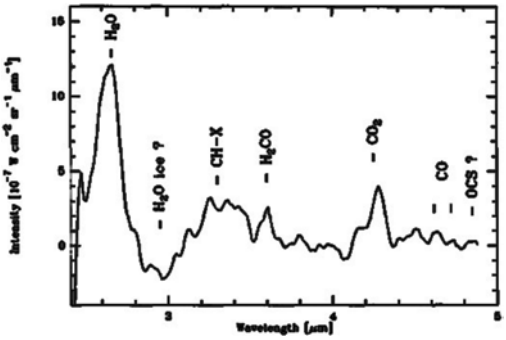
The UV and visible channels were classical grating spectrometers with modern silicon linear detectors (Reticon). The IR channel involved a single-pixel germanium detector and a rotating circular wedge interference filter. The filter and a chopper of this cannel were put into action with brush motor through a complicated gearing. To save the brushes, the motor was enclosed in a nitrogen atmosphere, the momentum passed via magnetic coupling. The whole thing operated with an awesome noise.



The VEGA steerable platform with TKS and IKS

* International Women's Day — *ed.*

March 6, 1986, the day of 1P / Halley encounter in IKI.
Alexander Krysko and Vladislav Jegoulev in the centre



IKS spectrum of the comet Halley with signatures of C-H at ~3.3 μm
and formaldehyde H_2CO at ~3.6 μm [Combes et al., 1986]

The technical head of the instrument Sasha Krysko was adjusting this mechanism using a sharpened pike called schaber (from German *schaben* — to scrape). All the three channels were fed with one Cassegrain telescope. IKI designing department led by Victor Troshin was bearing the responsibility of the instrument's structure, the telescope, covers, etc.

TKS was mounted at a stabilized platform ASP-G along with the famous television system by Genrikh A. Avanesov, and another French instrument called IKS (InfraRed Spectrometer). Remarkable was the pointing speed and autonomous navigation of the platform. IKS was to observe primarily the comet nucleus and to determine its surface composition. The PI was Michel Combes from Meudon Observatory. In IKI it was taken care of Vassiliy Moroz himself, and also by Nikolai Sanko and Alexei Grigoriev. The instrument on the same principle of the circular wedge interference filter allowed for the first detection of organics on a comet.

DEPARTMENT #4

In 1985 the Planetary Department was formally called Department #4, the Physics of Planets and Small Bodies of the Solar System. The numbering was fair enough: The #1 was reserved for secrecy; #2 for military records; and the #3 for astrophysics.

Planetary department in 1985: the head of department Vasiliy Ivanovich Moroz, and seven science laboratories led by Moroz himself, Lev M. Mukhin, Leonid V. Ksanfomality, Vyacheslav M. Linkin, Vadim G. Istomin, Vladimir A. Krasnopolsky, and Evgeni N. Evlanov

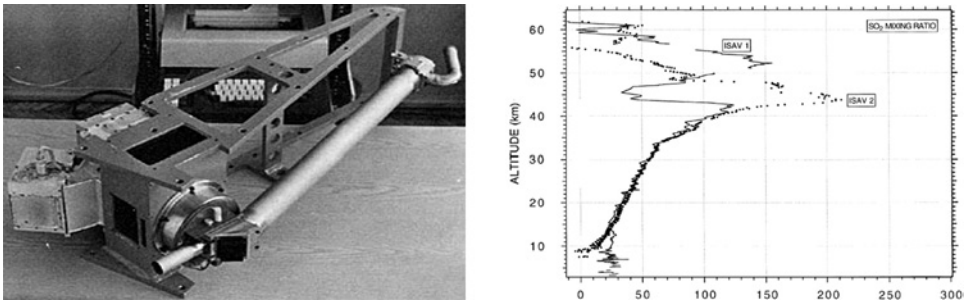
The evolution of the department since its creation in 1974 was significant. Regrettably, the laboratory of Planetary Geology led by Kirill Florensky was moved to Vernadsky Institute of the Academy (Geokhi). Vladimir Krasnopolsky from Moscow University created a laboratory of spectroscopy of upper atmospheres. Evgeni Evlanov headed a laboratory of mass-spectrometry of plasma and gases.

Several more VEGA experiments were conducted by the Planetary Department both at the flyby spacecrafts and on the Venus descent probes. Even though the department was much smaller and tighter than now, back in time I was absolutely not involved in these experiments personally, and was barely aware of them. There was no much opportunity. What I remember, is the chess club: Daily lunchtime gatherings of Vladimir Krasnopolsky, Sacha Krysko, Victor Gnedykh in Lev Mukhin's room on the fourth level of IKI building.

Still I envied the vivid activity in the laboratory of Slava Linkin. The story about VESTA project* and its transformation into VEGA was described many times by many authors. The cost of sending the carrier to the Halley's comet was that the large CNES balloon had to be discarded and replaced with a smaller 2-meter balloon developed by Lavochkin Association. This was to a great dissapointment of Jacques Blamont; to be noted, no contribution from his lab, Service d'Aéronomie, was proposed for the Halley flyby. Within the new project arrangement the Linkin's laboratory gained the crucial responsibility for the science payloads and operations of VEGA balloons. Slava (Vyacheslav Mikhailovich) himself with Sasha (Alexander) Lipatov led the development of the balloon gondola, both the systems and scientific instruments. Victor Kerzhanovich organized the radio link and Deep Space Network tracking. This made possible the first direct evidence for the Venus's superrotation [Sagdeev et al., 1986].

The laboratory by Evgeni Evlanov was responsible for PUMA experiment, to detect cometary dust particles, and to analyse them with a mass spectrometer. PUMA was essentially U.S. instrument. The US ban to participate in a Soviet mission was not a problem for Roald Sagdeev, and PUMA became a complicated set-up. The experiment was camouflaged behind "dummy PIs", first the Russian (Leonid Ksanfomality), then the European (Jean-Loup Bertaux), and a European technical lead (H. von Hoerner).

* Originally aimed at Venus only — *ed*.



ISAV_A (*in situ* UV spectrometer) (left). During the VEGA probes descent in the Venus' atmosphere the gas flushed through the tube, and the detector (drum-shape structure on the left) was lit with a Xe flash lamp through the length of the tube. The SO_2 profiles obtained by ISAV_A in the lower atmosphere of Venus [Bertaux et al., 1996] (right)

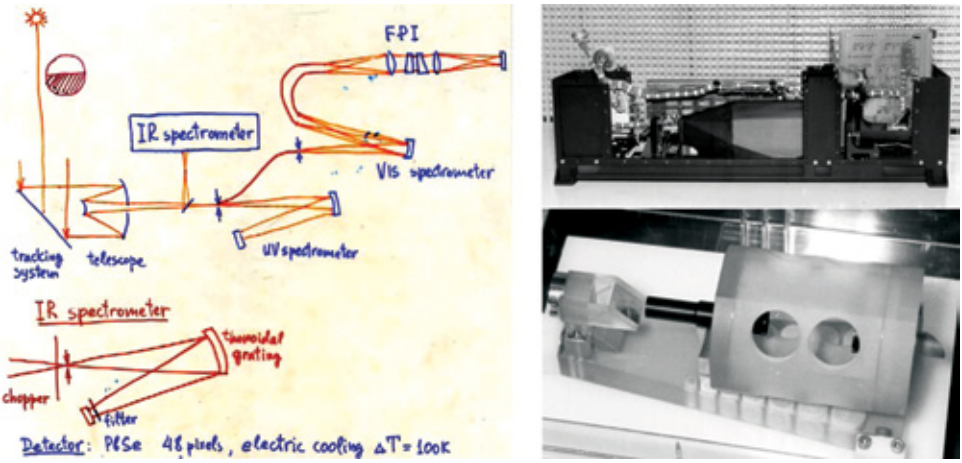
PUMA data were later analysed by Lev Mukhin, the head of "chemical" laboratory [Mukhin et al., 1991]. His laboratory also got a serious involvement in Venus descent probe: Nephelometer and X-Ray Radiometry to study cloud particles; gas chromatograph to study Venus atmosphere below clouds.

One more instrument on the descent probe was dedicated to optical measurements of the Venus atmosphere — ISAV_B, developed by Alexei Ekonomov. Like ISAV_A on earlier *Veneras* by Boris Moshkin, this instrument was mounted outside the thermally insulated body of the probe and operated down to lowermost few kilometres, an outstanding technical achievement as such. ISAV_A included French detector, which measured the first and so far the only profile of SO_2 down to 5 km [Bertaux et al., 1996].

PHOBOS 2 AND PHOBOS SAMPLE RETURN

The following planetary project was *Phobos*, a double launch in 1988. The Martian moon was to be studied from a close distance from synchronous orbit, and with a Long-Living Autonomous Station (DAS in Russian) on the surface. The focus of the mission was on two active experiments to study the Phobos surface activated by laser and ion beams. A number of experiments was dedicated also to Mars studies, to interplanetary media, etc.

Phobos 1 did not make it to Mars. The cause of the failure is often connected to a wrong command sent to one science instrument. *Phobos 2* orbited Mars, and entered the Phobos-synchronous orbit. But the final approach failed, and the spacecraft was lost just before the crux of the mission. Neither the active experiments by Georgy Managadze nor the DAS by Vyacheslav Linkin were performed. Most what I heard about the cause of the failure confirms the version described much later by V. A. Molodtsov from Lavochkin Association [in the monthly journal *Novosti Kosmonavtiki*, 03/2004]: It was a new spacecraft with serious commanding computer architecture problems, but also both spacecraft were slowly dying because of defective electrolytic capacitors used in numerous DC/DC converters. As an engineer involved in "soldering", I remember the capacitor type K52-1, which was exceptionally miniature and handy, but appeared to short-circuit with time.



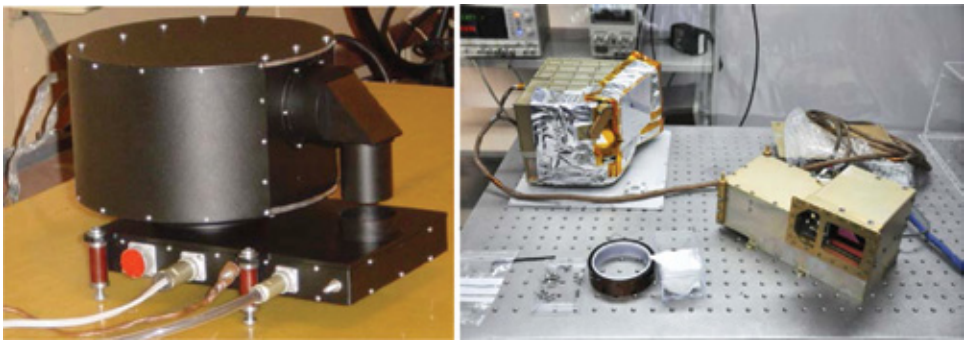
The sketch of *Auguste/Phobos-88* optics by V.A. Krasnopolsky (left); the hardware of *Auguste* (right). The main block with suntracker, and the telescope made from silica by molecular adhesion, designed by Jaques Porteneuve. No photograph of the ISO channel remained

On this mission I dealt with infrared spectrometer to measure the D/H ratio in the atmosphere of Mars. This spectrometer ISO conceived by Vladimir A. Krasnopolsky was actually a channel of French spectrometric complex *Auguste* by Jacques Blamont. It employed for the first time at another planet the technique of solar occultations. I'd got a chance to develop real space hardware, making tests, calibrations, and to work later with flight data. The observations of Mars were carried out during 1.5 month. *Auguste* was not a full success; there were problems with tracking the Sun, and with stray light from fancy quartz optics. ISO failed to quantify the D/H ratio (already measured by that moment from the ground [Owen et al., 1988]), but gave priority results on water vapour and dust vertical profiles [Korablev et al., 1993; Krasnopolsky et al., 1991,]. There was some questionable behaviour of the multipixel PbSe-detector, so we could not measure small absorption in the 3.7 μm region, where deuterated water absorption is located. Instead we detected some spurious features and attributed them to formaldehyde, but later we understood their instrumental "origin". While working on *Phobos* hardware and then the data, I made myself acquainted with French colleagues and met Jean-Loup Bertaux, later a close friend.

The sad *Phobos* story repeated more than 20 years later. The *Phobos Sample Return* mission of tremendous complexity relied again on a fully new development. IKI added its noble share of problems: A massively overpopulated science instruments list evolved from 28 instruments weighting 80.5 kg in 1999 to 24 units of 64.5 kg in 2011. The science operations, foreseen in the mission, involved a robotic arm and other mechanics and were very complex as well. But the spacecraft flight test never reached that far. Even the most critical and early sequences like injection into the interplanetary trajectory were not properly exercised.

Why a proven *Fregat* booster was not used? The *Phobos Sample Return* project received first considerable funding in 2007, with a target launch date in 2009. Before 2007 in trend was to discuss "non-budgetary" contributions. And Lavochkin Association has indeed found one: The Chinese partners were ready to contribute few dozen million dollars for delivering their "small" satellite into Mars' orbit.

Phobos Sample Return spacecraft at Baikonur



Spectrometers on *Phobos Sample Return*. AOST Fourier spectrometer (left), and two newcomers, *MicrOmega* and TIMM-2 (right)

Accommodation of the YH-1 satellite drew the overall mass of the dual craft beyond the *Soyuz-Fregat* capacity. It was suggested to send the fourth stage* to Mars, and to use its main engine with the remains of its propellant for the Mars orbit insertion.

Fregat was therefore stripped off its avionics, and was commanded by the central computer of the *Phobos Sample Return* spacecraft. Someone may see it elegant, but in fact insupportably risky.

Zenit S2B launcher, which was eventually used, had higher lifting capacity and could carry a non-compromised *Fregat*, but the development went ahead, and the delivery scheme remained untouched. In 2011 the main computer sequence was not safe

* i.e. Fregat booster — *ed.*

enough, and *Phobos Sample Return*, otherwise apparently healthy, remained at LEO with the only communication capacity in X-band. This range and relevant ground antennae are useful for deep space communication only. Using them at LEO is the same as trying to pick a spacecraft with a needle. None of redundant back-up systems of *Fregat*, like a UHF command line were available.

V. I. Moroz, first enthusiastic, in the end of his life advised me to "better keep away" from the *Phobos Sample Return* project. I didn't really follow his advice, and got involved when the mission turned serious. After the two-year launch shift in 2009, on the top of an inherited AOST Fourier spectrometer, I jumped on more experiments, an Echelle spectrometer TIMM-2, and microscope-spectrometer *MicrOmega* by J. P. Bibring. A hot summer of 2011 was difficult, and the disappointment was serious in November, but still these hurried developments helped later with *ExoMars* proposals.

MARS 96

"One of the largest planetary spacecraft ever" *Mars 96* was also the largest, if not the only funded IKI project during difficult *Perestroika* period. V. I. Moroz, demanded and perturbed as never before, was in fact leading the project in IKI. At that period R. Z. Sagdeev left for the U.S., followed by V. A. Krasnopolsky and V. V. Kerzhanovich from our department. The joke was that the whole Communist Party committee of IKI found better grounds in the U.S. Then L. M. Mukhin also moved to the U.S., he became a science attaché in the Russian embassy.

I was to take the lead of Krasnopolsky laboratory, a tight group involved into a next generation occultation instrument for Mars, now SPICAM for *Mars 96*. The spacecraft was equipped with two stabilized platforms; one ARGUS under the responsibility of G. A. Avanesov carried the HSRC camera by G. Neukum and OMEGA scanning spectrometer by J. P. Bibring. The smaller one PAIS was taken care of by V. S. Troshin and A. Krysko. It was given to two French instruments: EVRIS to study stellar oscillations and SPICAM, or SPICAM-E (E stands for *étoile*) to probe the atmosphere of Mars while observing stars and their occultation by the planet's limb. SPICAM included also a solar occultation channel, SPICAM-S. An international consortium of the experiment was formed by Jean-Loup Bertaux from Service d'Aéronomie, Marcel Ackerman, the director of Belgian Institute of Space Aeronomy (IASB), and V. A. Krasnopolsky.

For SPICAM we developed the infrared channel, a modified version of ISO with more advanced detector and steerable grating, to cover a wider spectral range, but also to have a better certitude about the detector's behaviour (remembering the formaldehyde story on *Phobos* in 1988). Our spectrometer was a part of SPICAM-S developed in IASB, which in turn was commanded by the French electronics unit, common for SPICAM-E and SPICAM-S.

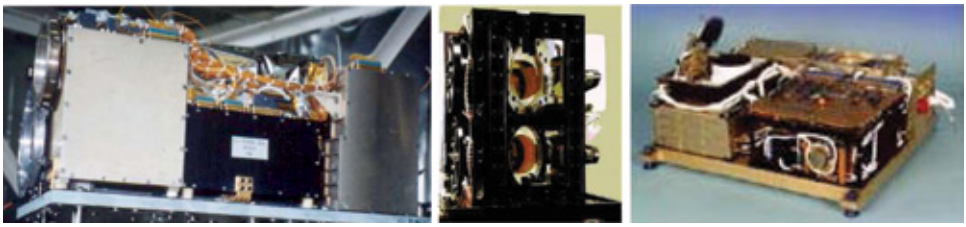
The infrared block of SPICAM was not the only Russian contribution to *Mars 96* spectrometers. All the foreoptics of SPICAM-E was designed and provided by IKI (V. S. Troshin), as well as the foreoptics and scanning device of OMEGA (V. A. Kotsov and E. I. Rozhavskii). Fourier spectrometer (PFS), initially Russian, was gradually becoming more and more Italian. But the activities related to OMEGA and PFS were mostly out of my vision. Vasiliy Ivanovich was taking care of them himself.

Aviation Week from 18 November 1996. "*Mars 96* poised for liftoff after tortuous development"

With SPICAM I was given a full *carte blanche* and eventually developed the IR channel of my own, in very close cooperation with Marcel Ackerman and the IASB team. I have learnt a lot. Not that the Western designs were better, sometimes our solutions seemed smarter. But we faced far better technologies and equipment. And the scope of the project was different. Later tests were organized in ESTEC, extensive calibrations, including even a stratospheric balloon flight, were held in the south of France.

The cooperation was of tremendous value also in a different sense. All our missions to Brussels (or wherever in France) were paid by IASB, Service d'Aéronomie, or CNES. Savings made on *per diem* (canned food from Russia accompanied by the cheapest local drinks in a shared hotel room) allowed to survive "comfortably" between the missions. Moreover, we were supplied by components, bits and pieces of equipment, tools, even with office stuff, like computers, copying, and fax machines. A situation was similar with OMEGA, and even in larger extent with PFS in Italy. To remind, during these years many scientists in Russia were driving taxies, putting tiles, making geodesy works, etc. The cooperation on *Mars 96* instruments was doubtlessly crucial for conserving the optical spectroscopy line in our Planetary Department.

A faulty valve in the *Block D* of *Mars 96* was not the only, and not the last one. One military satellite was lost due to the same reason before, and one commercial telecommunication satellite after. Late at night 16.11.1996 after a grim voyage by bus from TsUP (Flight Control Center) in Korolev, Emmanuel Dimarellis, the project manager of SPICAM told me: "*We won't leave you behind*". But I was devastated: Unexperimented, I did not do anything besides SPICAM and *Mars 96* during several years. All eggs in a single basket...



Three spectrometers of *Mars 96*: OMEGA, PFS, SPICAM
(only the SPICAM-S block is shown with the IR channel in front)

SPICAM-S cooperation. After meeting in IASB, Brussels, sometime in 1994. In front: E. Dimarellis, J. Runaveut, J.-L. Bertaux, M. Ackerman; second row: F. Canovas, S. Schadeck V. S. Troshin, A. Krysko, P. Verhaert, (unknown person); third row: C. Muller, O. Korablev, (unknown person), E. van Ransbeeck, M. Cau, E. Neefs, (unknown person), (unknown person); in the back: W. Peetermans, (unknown person), (unknown person), V. S. Jegoulev, C. Hermans

MARS EXPRESS AND VENUS EXPRESS

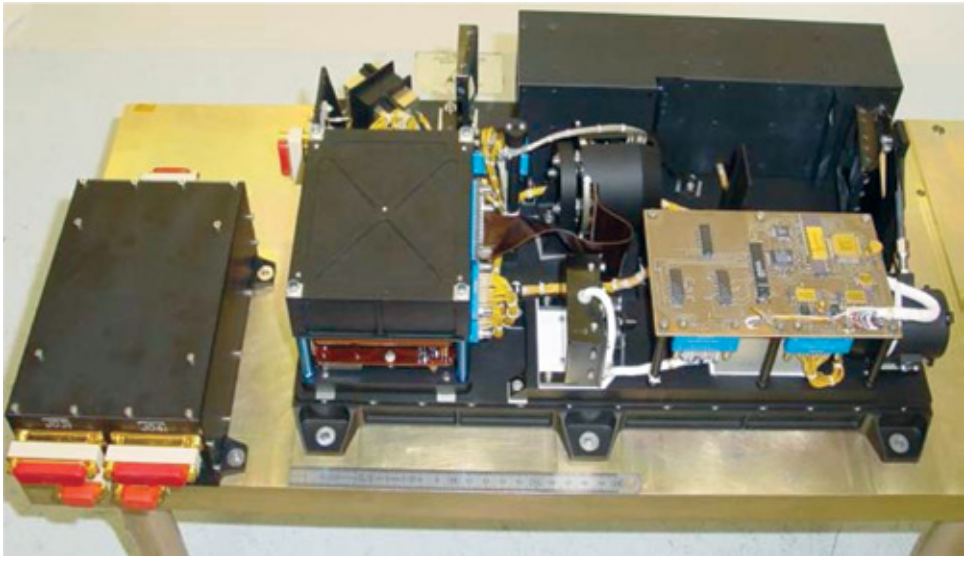
A defeat of a similar scale, the loss of *Mars Observer* launched in 1992 did not stop the Martian programme in the U.S. Already in 1996 a good share of its science instruments was flown aboard *Mars Global Surveyor*, one of the most successful orbital missions to Mars. The remaining experiments were flown in 1998 (new failure, the famous imperial to metric units mismatch), 2001, and in 2005.

Situation was very different in Russia. *Mars 96* was long blocking the development of the three out-of-atmosphere astronomy projects conceived in the 1980s: *Spektr-R*, *Spektr-RG*, and *Spektr-UV*. No chance for any planetary project to go before them.

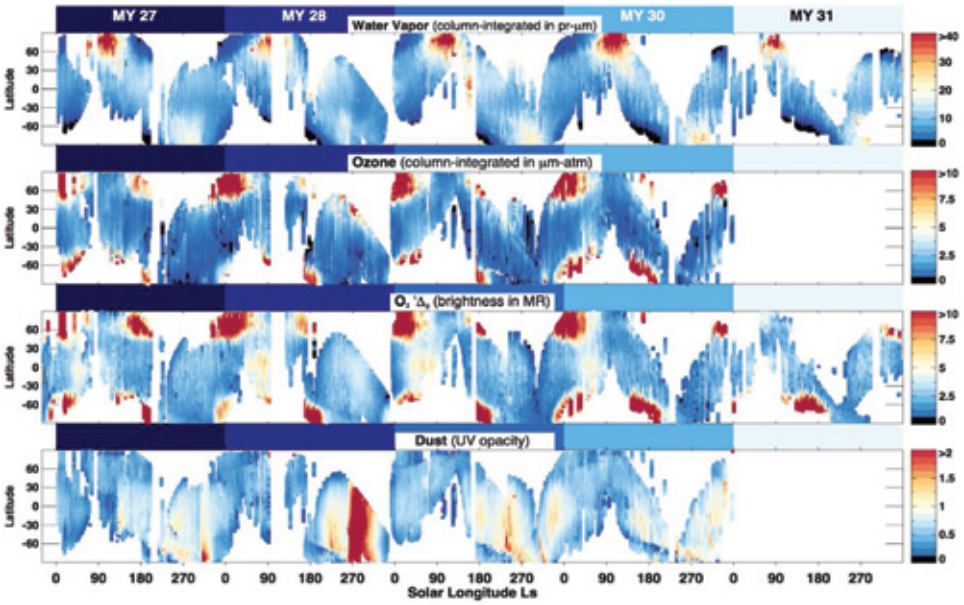
The initiative to recover some of the *Mars 96* science, in particular the experiments with massive European involvement, was taken by ESA. I do not know the details of the decision-making. R. M. Bonnet and M. Coradini must have been involved. The model payloads of the future project to Mars, called *Mars Express* and to be developed in five years included a high-resolution camera (keeping in mind HSRC), PFS, mapping spectrometer (OMEGA), penetrating radar, and a plasma package. No occultation experiment.

This was fair: The configuration of SPICAM on *Mars 96* was frightening, 45 kg of overall mass, plus a dedicated platform to track the stars. But with a new spacecraft the platform was not needed. It could turn its line of sight toward the needed star and remain in an inertial attitude during the occultation. The Sun is also a star, with the difference that a different optical entry should be used.

In 1997 J.-L. Bertaux started working on the proposal, and I had a chance to help him from the very beginning. The new instrument was called SPICAM-Light. It weighted only a few kilograms and included two scientific channels, UV to observe in nadir, stellar and solar occultations and IR to observe in solar occultations. ESA accepted the UV channel only.



SPICAM versatile spectrometer for *Mars Express*.
The Russian AOTF channel is in front on the right side



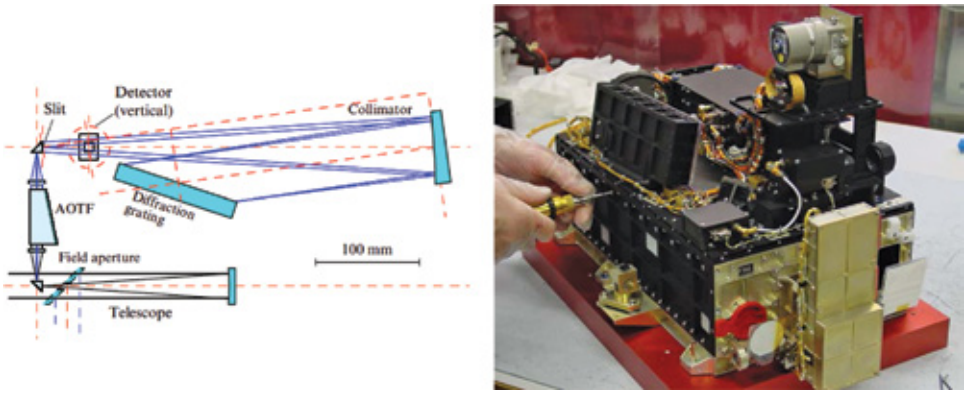
A synthesis of SPICAM monitoring during five Martian years. The water vapour [Trokhimovskiy et al., 2015] and $O_2{}^1\Delta_g$ emission [Guslyakova et al., 2016] are measured by SPICAM IR; ozone contents and UV optical depth are measured by SPICAM UV. Courtesy of Franck Montmessin

In parallel in Moscow Alexei Grigoriev established a connection with Yuriy Kalinnikov from VNIIFTRI, a promoter of the acousto-optic tuneable filter (AOTF) technology. Together we drafted a small instrument, sensitive enough for nadir, and proposed it to replace the heavier SPICAM IR channel. Bertaux supported the idea, and eventually ESA allowed for SPICAM-Light incorporating this 0.7-kg AOTF channel within the unchanged mass allocation of 4.5 kg. We were on the board along with the grand players: PFS and OMEGA!

The infrared channel now remains fully operational and delivers information after 13 years in space. It characterized more than five annual cycles of atmospheric water vapour, and oxygen emission, a sensitive indicator of photochemical processes. One of its discoveries made during solar occultation is very high degree of atmospheric water supersaturation, which has significant implications on transport of water between the asymmetric hemispheres of Mars [Maltagliati et al., 2011].

We repeated the experience on the following *Venus Express* mission with SPICAV instrument; V stands for "Venus". This time the AOTF spectrometer was designed to be much more sensitive in order to observe nightside Venus emissions. This seemingly simple improvement turned perilous: To cover more shortwave spectral range suitable for the most interesting emissions we had to implement the AOTF with two peizo-transducers. This appeared to be a technological challenge, and the flight model of SPICAV-IR, with some deficiencies, was eventually delivered very late.

Venus Express brought also a chance to test something new. In our small world the idea to implement an AOTF for diffraction order sorting was first articulated by YuriyKalinnikov.



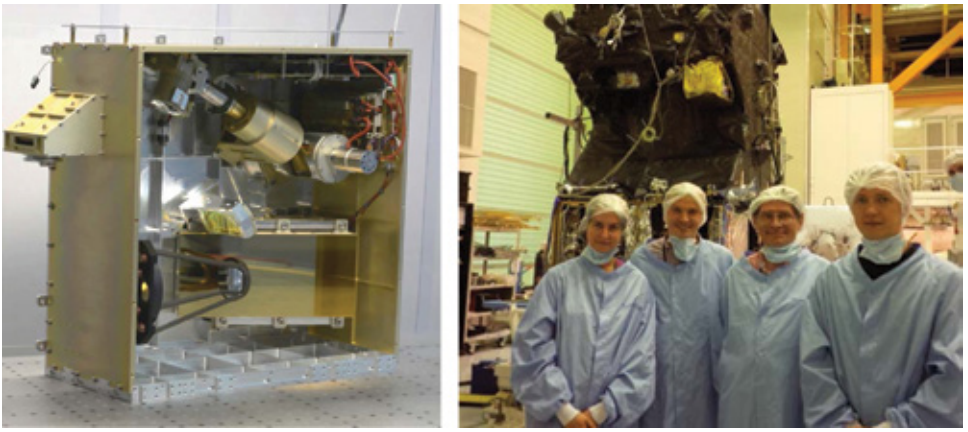
An early optical scheme of SOIR-type spectrometer (left);
SPICAV-SOIR instrument for *Venus Express* (right)

To achieve much higher spectral resolution he proposed to couple the AOTF with Michelson's echelon. The echelon is a kind of rough grating made of transparent slabs working in transmission. I didn't like the echelon, and once in 1999 suggested the same combination with a reflective grating (echelle). This scheme was successfully tested by Imant Vinogradov, and promoted by Jean-Loup Bertaux to be installed aboard *Venus Express*. There was no possibility in France or Russia to fund a new instrument on a short notice. A modest funding was found in Belgium, and the new instrument SOIR (Solar Occultation InfraRed) was included in SPICAV. Since then SPICAV-SOIR consisted of two "levels", one similar to SPICAM on *Mars Express*, and the "upper" level devoted to SOIR [Nevejans et al., 2006].

It was very difficult to build a completely new instrument in time. Two project managers from France and Belgium developed nervous crisis. But SOIR was successfully built, tested, accommodated on board, and flown. The whole 'ensemble' SPICAV SOIR operated through the whole *Venus Express* mission and made many measurements in the atmosphere, including, e.g., new estimate of the D/H ratio [Fedorova et al. 2008].

EXOMARS

For us the *ExoMars* story started in the fall of 2011. NASA was gradually withdrawing from the joint mission, and ESA has unearthed the earlier *Phobos-ExoMars* agreement. Following this document (signed back in 2008) ESA was supporting *Phobos Sample Return* data downlink, and Roscosmos was providing radioisotope heaters for the *ExoMars* rover, and a possibility of *ExoMars* launch by *Proton*. Now ESA was pushing the latter option (2016 launch) in exchange of a deeper Russian involvement in the project. After the *Phobos Sample Return* failure V.A. Popovkin, the head of Roscosmos liked this "conservative" approach. The Space Council of the Russian Academy of Sciences was advised to prepare the options of this deeper Russian involvement. At that moment NASA instruments were still aboard *ExoMars's Trace Gas Orbiter* (TGO): Four American instruments and the Belgian NOMAD. After deliberation the Solar System section of Space Council has formed the list of priorities:



ACS MIR channel (left); T. Kozlova, A. Shakun, A. Grigoriev and A. Trokhimovskiy at TAS-F in Cannes after the delivery of ACS flight model (right). The TGO spacecraft is behind, and the two Russian instruments are clearly visible thanks to golden-colour MLI protection

1. One or two *MetNet*-type stations.
2. Spectroscopic instrument for the Mars atmosphere composition and climate "complementary" to NOMAD, MATMOS, and EMCS, on the basis of *Phobos Sample Return* developments, later named ACS.
3. Collimated neutron detector to map the hydration of Martian soil, on the basis of LEND/LRO by Igor Mitrofanov, later named FREND.

The decisive meeting has to gather in ESA Headquarters in December 2011. The day before in Roscosmos the decision was unexpected: No go for small stations (*MetNet*-type). Executives decided to minimise risks and to keep the sure options, the launch, and the IKI instruments. We went to Paris with two instruments weighting jointly about 70 kg, roughly half of the TGO payload. The head of Roscosmos A. E. Shilov gave to scientists a full *carte blanche*, and G. G. Raikunov, at that moment the director of TSNIIMASH, is a hell of negotiator... After a difficult discussion the two Russian instruments were accepted by ESA and NASA colleagues.

ACS consists of tree scientific channels, it includes a SOIR-type near infrared channel, a cross-dispersion echelle instrument (mid-infrared) and a Fourier spectrometer. This is no doubt the most complicated development completed in the spectroscopy labs of our department. The funding started in March 2013 (thanks to Roscosmos and the *Phobos Sample Return* insurance refund) and the instrument was delivered to Thales Alenia Space factory in Cannes (TAS-F) in June 2015. The instrument has been already successfully tested in flight, but science operations of TGO will start only in 2017, after the aerobraking.

CONCLUSION: DEPARTMENT # 53

During the recent 10 years the number of people working in the Department of Planetary Physics has nearly doubled. The two spectroscopic laboratories are the core and gather the most of employees. They are concentrated around two centres, the

group of Alexei Grigoriev and the laboratory of Anna Fedorova. Starting from *Mars Express*, the laboratories contributed to and built more than 15 different instruments for deep space missions and for observing the terrestrial atmosphere. Among these *Phobos Sample Return*, *Bepi Colombo* (ESA), *International Space Station*, *ExoMars*, lunar missions.

Alexander Tavrov has taken the lead of the small laboratory by L. V. Ksanfomality, and is being now concentrated on planetary astronomy, including exoplanets. *In situ* methods, including sophisticated gas chromatography are being developed in the laboratory of M. V. Gerasimov. A separate group led by A. V. Zakharov and G. G. Dolnikov is developing contact sensors of dust particles. Former laboratories by Slava Linkin and Evgeni Evlanov are now concentrated on meteorological observations on planets and autonomous, stand-alone instrument suits. They are led by Daniel Rodionov and Alexander Lipatov. Two laboratories previously engaged with mass-spectroscopy are no longer active. Instead, the Department assimilated the laboratory of "Active diagnostics" by G. G. Managadze.

Department #4 IKI AN USSR → Department #53 IKI RAN

1974	2004	2014
IR-spectroscopy **V. I. Moroz**	IR-spectroscopy **V. I. Moroz**	Spectroscopy of planetary atmospheres **L. V. Zasova**
Physical-chemical studies **L. M. Mukhin**	Physical-chemical studies **M. V. Gerasimov**	Direct physical-chemical studies **M. V. Gerasimov**
IR radiometry and photomentry **L. V. Ksanfomality**	Space studies on small stations **V. M. Linkin**	Autonomous instrumental complexes **A. V. Lipatov**
Mass-spectrometry **V. G. Istomin**	Mass-spectrometry **V. Kochnev**	Interplanetary media **V. V. Izmodenov**
Planetary geology **K. P. Florensky**	Photometry and IR radiometry **L. V. Ksanfomality**	Planetary astronomy **A. V. Tavrov**
	Optical studies of upper atmospheres **O. I. Korablev**	Experimental spectroscopy **A. A. Fedorova**
	Mass-spectrometry of plasma and gases **E. N. Evlanov**	Physical investigations on planetary surface **S. A. Rodionov**
		Active diagnostic methods **G. G. Managadze**
		Sector of atmospheric dynamics and climate **A. S. Petrosyan**
		Support group **V. S. Jegoulev**

The Department now includes two theoretical groups, one led by Vlad Izmodenov, the student of Prof. V. B. Baranov, who worked in IKI yet with G. I. Petrov, the first director, and another by A. S. Petrosyan.

The lifetime of laboratories created by strong personalities (or for them) is often limited. Sometimes the change is almost abrupt, like with Service d'Aeronomie

in France, created by J. E. Blamont. After prosperous 50 years it changed its name, merged with another laboratory, and moved to a new location. Many people continue working, but it is obviously a different institution. In other cases the changes are more gradual, but still apparent. Is the spirit of the Planetary Department by V. I. Moroz still alive? Did we conserve the coexistence of rigor and democracy, of instrumentation and analysis? Younger generation would judge.

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FROM 1P/HALLEY TO 67P/C-G: A PERSONAL JOURNEY

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This paper describes my experience as the first foreign postdoc at IKI. I was fortunate to be mentored by some of the founding fathers of space research and benefited from working with the best space scientists and engineers. I also describe my journey from Hungary to Moscow to the United States and my adventures in comet research. The bottom line is this: everything I know about space science I learned at IKI.

FIRST FOREIGN POSTDOC AT IKI

My scientific career had a slow start. Hired with a Master's degree in physics, I was tasked to start a brand new scientific field in Hungary. Several groups were somewhat involved in research that fell under the broader umbrella of space research, but all these investigations were carried out with Earth-based observations. Nobody in Hungary could help me to understand how to use spacecraft measurements to understand the environment beyond the dense atmosphere, an environment that today is called geospace.

My first task was to work on the data analysis of the *Intercosmos 3* spacecraft built by Soviet and Czechoslovak scientists to study the Earth's radiation belts (Van Allen belts). Since Hungary did not participate in the design and manufacturing of the instruments, it got the unenviable task of converting telemetry signals to useful instrument measurements. My task was to do this conversion.

It was technically challenging and required long hours of repetitive work. Eventually, I found a very elegant solution to the problem which impressed my Soviet colleagues. It, however, involved extensive use of digitizing equipment that was available at KFKI* but required technicians to operate it.

I had learned computer programming during my university years. This was quite unusual in the late 1960s when computers were bulky and their computing power very limited. After starting work at KFKI, I became one of the most active users of its "mainframe" computer, a British-made ICL-1905. This computer had 32 kbytes memory, used 7-track magnetic tapes as "mass storage" and the computer codes were stored on paper punch tapes. The computer consisted of several cabinet-size racks and occupied a large air-conditioned room, at the time the only air conditioned room in the entire institute. For comparison, note that the first MacIntosh desktop computers in the 1980s had 32 kbytes of memory and more powerful processors. Today's desktop computers have about a million times more memory and computing power than the ICL machine had.

Most of my work was carried out on the ICL. This was a big step forward for the *Intercosmos* collaboration, since most participants did not have access to computers at all. My knowledge of computer programming gave me a competitive edge over peers in Hungary and Eastern Europe. Mainframe computers were kept in controlled environments and specially trained operators ran them. Computer operators worked in three shifts and — at least in principle — the computer was run on a 24/7 schedule (except for the frequent hardware failures). User programs were run in two shifts: short runs

* Központi Fizikai Kutató Intézet, in English Central Research Institute for Physics of the Hungarian Academy of Sciences — *ed.*

during the day and longer runs during the night. Most of the time, however, there were not enough programs to fill up the night shifts and the "idle" time was given to anyone willing to come in at night and operate the machine. Learning how to operate the ICL computer allowed me to increase my productivity. The price was countless nights away from my family and living in a state of near constant sleep deprivation. The upside: I made very good progress with my work and was able to defend my PhD dissertation in the fall of 1974.

Elyasberg

That first project, as it turned out, was the key to my later scientific career because it caught the eye of a very influential Soviet scientist, Pavel Efimovich Elyasberg. During World War II Elyasberg had been a Soviet artillery officer and had participated in the liberation of Hungary. He was a brilliant mathematician and quickly rose through the ranks of the officer corps; by the mid-1950s he had become a colonel in the Red Army. He survived the Jewish purges after Stalin's death, and in the late 1950s became a leader in the Soviet ballistic missile program. Eventually he became responsible for the trajectory determination of ballistic missiles. When the Soviet space program started in the late 1950s he also became responsible for the orbit calculations of Earth orbiting and deep space satellites.

Elyasberg's military career suddenly ended when the first Soviet mission to the Moon (*Luna 1*) missed its target (due to an incorrectly timed upper stage burn) and flew by the Moon. Since he was in charge of the spacecraft's orbit, Elyasberg was immediately discharged from the army and assigned to the civilian space program where he was put in charge of spacecraft communications, orbit determinations, and scientific computing. Though a very powerful job in civilian space exploration, it was a huge step down from his former military position.

Pavel Efimovich Elyasberg in the 1950s (left) and the 1970s (right)

After I presented my satellite data reconstruction method at a data processing meeting, Elyasberg took me under his wing. I was introduced to members of Elyasberg's own research group at the Space Research Institute of the Soviet Academy of Sciences (IKI) and Elyasberg started to spread the word at IKI that he had discovered a talented Hungarian. Elyasberg's mentorship gave me the opening I needed to break into the international scene.

As one can imagine, Elyasberg was a strong personality with quick (and usually correct) judgement and firm opinions. Being a World War II veteran he was very sensitive to historical revisionism. He could not stand fools and mediocre people. He ruthlessly humiliated those he considered unworthy of being in space research. At IKI everyone showed great respect and deference to Elyasberg and his opinions were not dismissed easily.

Sometime around 1974 Elyasberg convinced the leadership of IKI to involve me in the data analysis of the *Prognoz* satellites. Ten *Prognoz* satellites were launched between 1972 and 1985 to highly elliptic orbits. The satellites were primarily used for solar and magnetospheric research and were on par with the best NASA satellites of the times. I became involved in the third *Prognoz* satellite, launched in 1973. As part of the collaboration, satellite data on two magnetic tapes were sent to KFKI through diplomatic channels. The security services at KFKI panicked. Never before had the institute received satellite information, much less through diplomatic channels. After a short period of uncertainty the Hungarian security people did what any bureaucrat would do: classified the tapes as secret and locked them up in a safe. Fortunately, I had been able to make copies of the tapes before they were locked up, and so was able to complete the work and return the processed data to IKI.

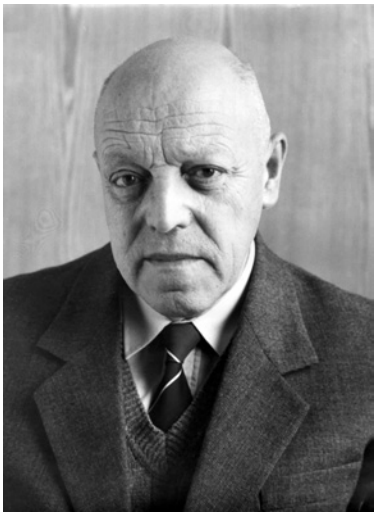
Gringauz

In 1975 I applied for an extended fellowship at IKI. Elyasberg decided that during my stay I needed to work with a space science group and not with his applied mathematics group. At that time I didn't understand the difference, but in retrospect it is very clear that Elyasberg was right (as usual). He recommended me to Konstantin Iosifovich Gringauz, the head of a space plasma instrumentation group at IKI. Gringauz accepted me and sometime in late November of 1975 I boarded the train to Moscow.

Konstantin Iosifovich Gringauz was born in 1918 in Tula, Russia. In 1941 he started to study frequency modulation of radio waves, then a brand new topic. During World War II he worked on the design of small, rugged, sensitive radio transmitters and receivers for tanks. After the end of World War II he started to study radio-wave propagation in the ionosphere. In 947 Gringauz moved to a laboratory for radio-wave propagation in Sergei Korolev's new Experimental Design Bureau for Rocket Development. In 1948 he participated in the launching of a V-2 rocket which carried a radio sounder to study the ionosphere. In 1949 he was put in charge of a laboratory for radio technology.

In 1956 he began designing instruments for measuring ions in the Earth's atmosphere from a satellite that became *Sputnik 3*, and was assigned to design the transmitter-antenna system for what became *Sputnik 1*. His idea that this satellite should use a decameter transmitter was intensely debated and Korolev decided in favor of Gringauz's position, partly because he wished *Sputnik 1* to be heard around the globe.

During 1957 Gringauz continued his ionospheric studies, and had radio and Langmuir probe experiments on two geophysical rockets. On October 3 he climbed the rocket at Tyuratam to check out the *Sputnik 1* antennae and transmitter. He was the last person to touch the satellite. Following the launch of the world's first artificial satellite, *Sputnik 1*, on October 4, 1957 the "beep, beep" of the transmitter, which was produced in his laboratory, was heard by politicians as well as by amateurs and scientists around the globe.



Konstantin Iosifovich Gringauz in the mid-1970s

From 1958 onward his research concentrated on *in situ* measurements of ionized gases surrounding the Earth and the planets Venus and Mars, where he is credited with numerous scientific discoveries and "firsts". He received the Lenin Prize (the highest civilian award in the Soviet Union) in 1960 in recognition of his pioneering work in these fields. In 1959 he moved with his group to the Radio-Technical Institute of the Soviet Academy of Sciences and became head of the space research department, which was transformed in 1971 to the laboratory for interplanetary and near-planetary plasma studies of the newly organized IKI.

Gringauz was a very strong personality, a true fighter. His nickname was "bulldozer", because he ploughed ahead with his ideas no matter the opposition. He was highly respected but not liked by his peers and managers. At the same time he always treated his people fairly and was willing to fight for them at any time. His group was very loyal to him and he very loyal to his group.

Venus Orbiters

The *Venera 9* and *Venera 10* spacecraft were launched in June 1975. In late October they successfully landed on Venus and operated in the extremely hostile environment for about an hour. The main spacecraft were captured by the gravitational field of the planet and they operated for two months providing a goldmine of information about our sister planet. These were the first orbiters around a planet other than Earth and they revolutionized our knowledge of Venus. When I arrived in IKI, the Venera orbiters were at the center of space research not only in the Soviet Union but in the USA as well.

I reported for work the day after my arrival. I was expecting to be assigned to a project investigating the Earth's space environment, since this was the area in which I had some experience. I was shocked when Gringauz asked if I wanted to work on the analysis of the Venus orbiter results. For an aspiring space scientist from Hungary, with no space program of its own, the opportunity to work on the hottest project of the times was like winning the lottery. I was a scientific adventurer and pretty self-confident (should I say cocky?). The fact that I knew nothing about Venus or planetary space environments did not even make me pause for a second. I immediately agreed, and jumped into a new adventure.

Top row from left to right: Valentin Etkin, Pavel Elyasberg, Yan Ziman, Yakov Zeldovich, Georgiy Petrov and Iosif Shklovsky. Second row from left to right: Georgiy Narimanov, Konstantin Gringauz, Yuriy Galperin, Semyon Moiseev and Vasiliy Moroz. I knew them with the exception of Etkin

I have a photo which demonstrates how highly regarded Elyasberg and Gringauz are in the Soviet-Russian space program even today (2013). The photograph shows the "Wall of Space Pioneers" at IKI. This exhibit is at a prime location in the institute (next to the Director's office). It shows a mock up of the first Sputnik and eleven of the pioneers who created Soviet space science. Both Elyasberg and Gringauz are among the pioneers. Of the others Petrov was the first director of IKI, Narimanov was the chief engineer of IKI, Etkin was the head of applied space science (he lead the early Earth observations program), while the others were leading scientists.

In the winter of 1976 life was not easy in Moscow. It was a particularly cold winter with food and fuel shortages. The only thing never in short supply was vodka. The temperature at IKI was kept at 12 °C (54 F); people worked in heavy coats and gloves. It was cold, but not so bad as outside where temperatures sometimes dipped to –40 °C (–40 F) and it was next to impossible to walk on the wide open, very windy streets. I lived in a bug infested room in the Hotel *Akademicheskaya* (Academy Hotel) that was at least well heated.

Eating was a challenge. The hotel had a restaurant, but it was very difficult to get in (there were few restaurants in Moscow then and they were almost always full). Besides, restaurant dining was a ritual with a dinner usually taking three to four hours. We just did not have the time during the week to go out to restaurants. The hotel also had two fast food type places, but they had very limited menus and very long lines. Cooking in the room was impossible (besides it was extremely difficult to buy ingredients), so we lived on a fast and feast diet, eating very little during the week and binging in restaurants during the weekend. Once we got into a restaurant, food was good

and cheap. We particularly liked Russian-style appetizers. Sometimes dinner consisted of two large portions of salmon caviar, two large portions of Beluga caviar, and a bottle of champagne. Such a dinner would cost over a thousand dollars in the West, but at this time caviar was cheap in Moscow, cheap enough that we could easily afford it almost every week. Needless to say, life was not all champagne and caviar, but these dinners made life bearable.

The daily routine at IKI was complicated. I took the direct metro line from Oktyabrskaya to Kaluzhskaya stations and from there walked to the 400-meter-long building that housed IKI. At the entrance I was met by one of my "mentors" who took me through security and accompanied me to the office with my assigned desk. There were six or seven desks in the large office, most occupied by young scientists working on various projects. My "mentors" were Tamara Breus, Anatoliy (Tolya) Remizov, and Mikhail (Misha) Verigin, all just beyond their PhD degrees and actively working on the *Venera* missions. Tolya was an instrument developer leading the development of the instrument operating around Venus. Tamara and Misha were data analysts. Their main job was to interpret the data and create models of the space environment of Venus. Needless to say, all three of them were among the best of the best young Soviet space scientists.

Tamara, Misha, and Tolya were tasked by the IKI internal security office to keep an eye on me at all times, including when I went to the bathroom. Needless to say, poor Tamara had difficulties fulfilling this task. She usually just waited outside the men's room. I did not care much about what the IKI security people thought, often escaping to the library, the computing center, or just to chat with colleagues. I was as undisciplined at IKI as I was all my life. The situation was best characterized by Tamara who in 1997 wrote an article about Gringauz's career. In the article "An unforgettable personality" (J. Geophysical Research 1997. V. 102. P. 2027) she devoted a paragraph to my adventures at IKI:

> *In 1975 we obtained results from the first near-Venus orbiters*, *Venera 9 and 10*, *during minimum solar activity. Tamas Gombosi*, *now a professor at the University of Michigan*, *came to Moscow to join Gringauz's team in processing and interpreting data from these missions. It was the time when Sagdeev had just started his* perestroika *in space research and Gombosi was practically the first foreign visitor-scientist in the history of the Institute. The charming young scientist from Hungary did not entirely care for the strong rules pervading our Institute. According to these rules*, *foreigners were obliged to be accompanied by a member of the Institute staff to any place they wanted to visit. I was responsible for accompanying Tamas to begin with but got into a lot of trouble because of his independent behavior. He very often appeared alone at another floor of the Institute*, *where the Computer Center was located*, *escaping somehow from my vigilant eyes. As a result Misha Verigin was ordered to take on this duty and Gombosi's care was in more suitable hands.*

During my stay at IKI, I automated the data analysis of the Gringauz's instrument. At this time computing facilities were quite limited at IKI and much of the data analysis was done by tedious manual work that took a long time. Taking advantage of my access to Elyasberg and my knowledge of computers, I quickly wrote a data analysis program that saved months of work for the group.

Tamas and his "mentors" in 1976. From left to right: Mikhail Verigin, Tamas Gombosi, Anatoliy Remizov, Tamara Breus, and Valeriy Afonin

I spent a few nights at the IKI computer center (accompanied by poor Misha Verigin) operating the computer myself and making fast progress in producing useable data products for Gringauz's group. In the end, the data analysis program even produced some simple plots visualizing the observations. Gringauz was so impressed that he took the computer output and went around the Institute's leadership to brag about it. While this part of my work was the least scientific, it was undoubtedly the most visible. Soviet scientists were used to smart young people making new scientific insights, but a space scientist with computer skills was something new.

Other Mentors

Three other people at IKI played an important role in my life: Roald Sagdeev, Albert Galeev, and Vitaliy Shapiro.

Roald Sagdeev is an ethnic Tatar. He had attended the Moscow State University (MGU) and was one of a few of Lev Landau's students, and the only space physicist, who passed the so-called "Landau minimum", the most challenging qualifying examination in the world. In the university dormitory he lived next to Mikhail Gorbachev, a law student (later to become General Secretary of the Communist Party and Head of State from 1988 until the dissolution of the USSR in 1991), and Raisa Gorbacheva, a sociology student. In 1955 he joined the Kurchatov Institute of Atomic Energy as a member of the controlled fusion team. From 1961 he worked at the Institute of Nuclear Physics in Novosibirsk. At the age of 35, he was one of the youngest people ever elected a full academician of the Academy of Sciences of the USSR. His work on the behavior of hot plasma and controlled thermonuclear fusion won international recognition. While working at the Kurchatov Institute he married Tema Frank-Kamenetskaya, daughter of the famous nuclear physicist David Frank-Kamenetskii.

Left to right: Roald Sagdeev, Albert Galeev, and Vitaliy Shapiro

In 1973 he was appointed director of IKI, where he modernized and opened Soviet space science. After my time there, in the 1980s, he became science advisor to Soviet leader Mikhail Gorbachev and played an important role in Gorbachev's *Perestroika*. In 1988 he divorced his wife Tema and married the granddaughter of the former U. S. President Dwight D. Eisenhower, Susan Eisenhower. Following his second marriage he moved to the USA where he became a Professor at the University of Maryland.

Albert Galeev was born in the city of Ufa, and like Sagdeev, to an ethnic Tatar family. From 1961 to 1970 he worked at the Institute of Nuclear Physics in Novosibirsk which was leading the nuclear fusion work in the Soviet Union. He worked with Roald Sagdeev on theoretical problems concerning magnetically confined plasmas. When Sagdeev became director of IKI he invited Galeev to join him as the head of the Space Plasma Physics Department. After Sagdeev moved to the USA in 1988, Galeev became the director of IKI and stayed in this position until his health forced him to retire in 2002. Galeev was an excellent space plasma theorist with major international impact.

Vitaliy Shapiro received his D.Sc. from the Institute for Nuclear Physics in Novosibirsk in 1967. He also worked with Roald Sagdeev on theoretical plasma physics and became the leading theorist of the institute. In 1976, Shapiro joined IKI, where he became head of the Laboratory for Fundamental Plasma Studies. He was also Professor of Space Physics at the Moscow Institute of Physics and Technology (FizTech), the "Soviet MIT". Shapiro followed Sagdeev to the USA and in 1992 he joined the faculty of the University of California at San Diego (UCSD).

Gringauz, Sagdeev, Galeev, and Shapiro all played different roles in my life. Galeev was the head of the Space Plasma Physics Department at IKI that included several experimental laboratories (Gringauz was head of one of these laboratories) and a powerful theoretical division (headed by Shapiro). Gringauz was my immediate supervisor and took me under his wing. He was not trained in space physics, but he had a great talent to recognize new ideas with potential. He had an instinct for science. Sagdeev was the "big boss", but he had a special talent for recognizing the potential of young people and helping them with their careers. He gave me opportunities very few people had at that time. Galeev was a more distant figure, but he was great in pointing me in the right direction. Shapiro was a complex personality.

Lev Matveevich Zelenyi
in the mid-1970s

He was very paranoid about his Jewish background, but probably he was the best plasma physicist in this group. He was always ready to share his ideas and was very patient with me when I did not immediately understand what he had in mind.

About the time when I was working at IKI a young graduate student started to work with the theoretical plasma physics group at IKI. He was talented and the word quickly spread that Galeev discovered a gem. Later Lev Zelenyi rapidly rose through the ranks of the Institute and eventually became the director of the institute. Today he is a world renown scientist and science politician who plays a very important role in national and international space exploration.

During my extended stay at IKI, I worked closest with Misha Verigin, a very well trained and talented space scientist who had a solid background both in theory and instrumentation. We made good progress with the analysis of *Venera 9* and *10* data and used the observations to explain the origin of the mysterious night-time ionosphere of Venus. This work was very enjoyable and productive. By the time I returned to Hungary, I was considered an expert in the space environment of Venus and had started to gain international recognition as an up-and-coming scientist.

VEGA

In the summer of 1980 the Committee on Space Research (COSPAR) held its 23rd annual Assembly in Budapest. After the USSR launched its first Earth satellite in 1957 starting the Space Age, the International Council of Scientific Unions (ICSU) established COSPAR in 1958. COSPAR's main objective is to promote peaceful scientific research in space. During the Cold War COSPAR represented one of the main venues in which the U.S. and Soviet scientists could meet and exchange results and ideas. Having the COSPAR meeting in Budapest was a very big deal for Hungary, offering an opportunity to showcase Hungarian involvement in space research. For me this was a special event since I had a chance to host my Soviet and American colleagues and bring them together to initiate some joint projects.

The results of the meeting exceeded all expectations. The scientific program was interesting, but the most important events took place outside the meeting rooms. It was customary for the local scientists to organize small receptions in their homes during large international meetings. My wife and I invited about 30 colleagues to our small condo for a wine and cheese reception. Among the invitees were my Soviet mentors Sagdeev and Gringauz, my American friends including Andy Nagy, and several well known European colleagues. One of these was Jacques Blamont, a colorful French space scientist who was a driving force behind the successful Franco-Soviet cooperation in space research. At the time France and the Soviet Union were nego-

tiating French involvement in a Venus mission that would deploy long-lived scientific balloons in Venus's atmosphere to study its properties. Sagdeev and Blamont were the leaders of this planned mission.

The two men had a very important discussion on the balcony of our apartment. Shortly before the COSPAR meeting engineers at IKI realized that the trajectory of the planned Franco-Soviet Venus mission (called VESTA) could be modified so that it would intercept Halley's comet in March 1986. Sagdeev suggested that the mission be modified and in addition to delivering scientific balloons to Venus it should also be instrumented to investigate the vicinity of this very famous comet. As a result of the change in mission, the French balloon payload had to be downsized and the two *Venera* spacecraft would no longer be placed into orbit to support them. Blamont liked the idea, but in the end the French decided to walk away from the balloon program, leaving the Soviets to build their own balloon payload instead. The French, however, became major participants in the Halley observations. In short, the Venus-Halley (VEGA) program was born on the Nagyenyed Street balcony.

Halley's Comet, or Comet Halley, is the best-known of the short-period comets and is visible from Earth every 75–76 years. It is the only short-period comet clearly visible to the naked eye from Earth, and the only naked-eye comet that might appear twice in a human lifetime. Other naked-eye comets may be brighter and more spectacular, but will appear only once in thousands of years. Halley's returns to the inner Solar System have been observed and recorded by astronomers since at least 240 BC. Clear records of the comet's appearances were made by Chinese, Babylonian, and medieval European chroniclers, but were not recognized as reappearances of the same object at the time. The comet's periodicity was first determined in 1705 by English astronomer Edmond Halley, after whom it is now named. Artists used the image of the comet in medieval paintings.

NASA missed the chance to visit Halley's comet. At least three initiatives for NASA to send a mission fell to budget cuts during the 1970s and early 1980s. These cuts were necessary to fund the *Space Shuttle* program. It is also true that the U. S. planetary science community was not willing to settle for a much cheaper fly-by mission, but insisted on a rendezvous that would have provided an opportunity to investigate changing cometary activity. Finally the combination of *Shuttle* overruns and the cost of a rendezvous mission killed NASA's mission to Halley's comet.

The European Space Agency (ESA) decided to launch its first deep space mission to Halley's comet. The *Giotto* mission, named after the Italian Renaissance artist Giotto di Bondone, was officially approved by ESA in July 1980, shortly after the birth of the VEGA project. *Giotto* carried ten science instruments to study Comet Halley and its environment.

Jacques Blamont in the mid-1980s

Ernst Trendelenburg in 1983 in the way I best remember him: a little drunk and with his mischievous smile

Japan also decided that they would attempt a much more modest, but still scientifically useful mission to Comet Halley. During the 1970s Japanese scientists and engineers began studies for a probe to be launched using their own launch vehicle. In 1979 the Japanese Halley mission was approved with six years to complete the project. It was decided to launch two spacecraft: the *Planet-A* (later renamed to *Suisei*) probe that would make the close pass of the comet and a technology demonstrator (later called *Sakigake*), launched seven months earlier in order to test the launch vehicle and the probe design as well as to allow distant observations of the interplanetary environment upstream of the comet.

By the fall of 1980 the international Halley armada had taken shape: the Soviets would launch two *Vega* spacecraft, ESA would launch *Giotto*, and Japan their two probes. Coordination efforts between ESA, JAXA (Japan Aerospace Exploration Agency), and IKI started in late 1980 and gradually accelerated as time went on. Even though NASA did not have a dedicated Halley mission they did not want to be left out of the international cooperation and joined the informal coordinating group.

Almost by chance, I found myself in the middle of international activities associated with the planned Halley armada. I was well known by IKI scientists and my scientific reputation had greatly benefited from my work in the USA. During the COSPAR meeting in Budapest Sagdeev invited me to participate in the new VEGA mission. The fact that at this time I did not know much about comets was not an obstacle, since around 1980 cometary science was in its infancy. Everyone had to learn the little we knew about comets and eventually a new area of space research emerged from the Halley missions. By luck, I was at the forefront of this emerging field and in a few years became one of the world's leading experts of the physics of comets.

The VEGA mission offered a great opportunity for Hungarian scientists and engineers to participate in a world class science project. This participation, however, needed significant resources. At the end of the hardware phase of the VEGA mission nearly a hundred scientists and engineers were working on the project at KFKI. This was a significant fraction of the institute's manpower and this much involvement could not have been done without the full support of the upper management of the institute. The Director General of KFKI at the time was Ferenc Szabó, who quickly understood the opportunity and became a strong supporter of the Hungarian VEGA project. The day-to-day management was delegated to Károly Szegő, director of one of the five research institutes that constituted KFKI. This institute, the Institute for Particle and Nuclear Research (RMKI), carried out most of the engineering work.

In 1980 the Cold War was still going on, even though some cooperation was taking place between the superpowers. The multinational Halley coordinating group offered a good opportunity to have some behind the scenes contacts between American and Soviet scientific leaders. This, however, could not be done overtly: they needed an intermediary to organize contacts at a somewhat neutral venue. Roald Sagdeev was

a major driving force of this scientific opening. He was a personal friend of Mikhail Gorbachev, who would become the leader of the Soviet Union five years later and who already had tremendous influence on Soviet policy in the early 1980s. Sagdeev's main partner in this effort was the Science Director of the European Space Agency, Ernst Trendelenburg.

Ernst Trendelenburg was a German scientist who, as a young conscript during World War II, was captured by the Soviet Red Army and kept in prisoner of war camps. Interestingly, his wartime experience did not make him hostile towards the Soviet Union. Rather, he had a grudging and cynical respect for Soviet space science and scientific accomplishment. He was a very good politician and a good manger, even though he was quite controversial. He was marginally alcoholic, had some personal scandals (he married his secretary after she became pregnant while working for him), and loved to play the political maverick. He was a strong supporter of East-West cooperation and the driving force behind ESA's *Giotto* mission. Sagdeev and Trendelenburg had a special personal relationship based on mutual respect and shared scientific and political interests.

Sagdeev introduced me to Trendelenburg sometime in late 1980. We developed an instant affinity for each other: my cynicism and irreverence was a great fit with Trendelenburg's style. Trendelenburg also liked the fact that I could keep up with him in drinking, and could even drink him under the table when it came to that (I was nearly thirty years younger, so I had a great advantage). He also liked my irreverent humor. He particularly liked my theory that NATO was very lucky not to have Hungary as its member, since Hungary had not been on the winning side of any war in more than 500 years.

By 1981 I had become an important intermediary between Sagdeev and Trendelenburg. This fact gave me visibility, not only in Hungarian and Eastern European science, but also in Western Europe. And within a year, I was quite well known in space science circles in Eastern and Western Europe, the Soviet Union and the USA.

First Public talk About VEGA

In late 1982 two opportunities increased my international visibility. The first successful planetary probe, *Mariner 2*, encountered Venus on December 14, 1962. The Planetary Society, a U. S. nonprofit organization founded by Carl Sagan to promote the exploration of the Solar System, organized a major event in Washington D. C. to commemorate the 20th anniversary of the *Mariner 2* flyby and to advocate for further exploration of Venus. The event was attended by politicians, NASA officials, and many luminaries. In the afternoon there was a symposium in one of the largest auditoriums in the city and it was followed by a large fundraising dinner. For the symposium Sagan scheduled three presentations: one by himself talking about the inspiration of planetary exploration, one by the famous science fiction writer Isaac Asimov who talked about his vision for humanity moving beyond Earth, and the last one by Roald Sagdeev, who was supposed to talk about the VEGA mission.

Even though the VEGA project was well under way, there had never been a public lecture about it. The Soviets were notorious for keeping their space missions under wraps until they were successfully launched. Sagan was eager to break this practice and wanted Sagdeev to talk publicly about the upcoming VEGA mission.

Clockwise from top left: Isaac Asimov, Carl Sagan, and I at the press conference; Isaac Asimov gives me advise; Carl Sagan and I before the presentations; Frank Press, Isaac Asimov, Carl Sagan, and I after the public lecture

Sagdeev very much liked Sagan's idea and agreed that a public lecture about VEGA at a high profile event would be very useful. For some reason, however, he did not want to give this lecture himself and he suggested me instead. People at the Planetary Society had never heard of me before and they were quite surprised by this suggestion. Their puzzlement was further deepened by the fact that Sagdeev did not recommend a Soviet scientist but a Hungarian one. These facts aroused both Sagan's and Asimov's curiosity and they gave me a royal reception. There was a press conference with the three speakers before the public lectures, and the speakers posed with the President of the National Academies, Frank Press, at dinner.

My lecture was a huge success. I was at ease and unintimidated by the fact that I was following two famous speakers. I even joked that Sagan and Asimov had just given the introduction and now I would give the "real" lecture. In some respects this was true, since the main attraction of the event was the introduction of the VEGA project to the American public.

One of the more interesting tidbits of the event was that after the talks were finished the science attache of the Soviet Embassy came over and congratulated me for the job well done. The Hungarian Embassy was not represented, even though one of the main speakers was representing Hungary.

After this event Carl Sagan stayed in touch with me and we occasionally got together until his untimely death. I had the highest respect for Sagan who accomplished something that very few scientists do: he made people interested and excited about basic science, especially about the exploration of the Solar System.

The other event was not public, but it brought together the space science elite of the Soviet Union with the leadership of ESA. The occasion was the ending of Trendelenburg's term and his replacement by Roger Bonnet, a French solar physicist. Sagdeev decided to organize an event to honor Trendelenburg and welcome Bonnet to the East-West collaboration.


Farewell party for Ernst Trendelenburg: Roger Bonnet (left);
Roald Sagdeev and Ernst Trendelenburg (rght)


Farewell party for Ernst Trendelenburg: Tamas Gombosi (left); Valery Barsukov (right)

Sagdeev selected picturesque Samarkand, Uzbekistan, as the venue and invited the cream of Soviet astrophysics and space science to attend. There was a scientific symposium and an unforgettable party to which Sagdeev also invited his arch-rival, Valery Barsukov, who was director of the Vernadsky Institute and an advocate of planetary geology missions. In addition, Károly Szegő and myself were also invited. It is interesting to note that we were the only invitees from Eastern Europe (outside the Soviet Union).

IAF Congress in Budapest

In 1983 I was one of the organizers of the annual International Astronautical Congress (IAC) organized by the International Astronautical Federation (IAF) that was held in Budapest. The IAF was created in 1951 with the aim of encouraging the advancement of knowledge about space and the development and application of space assets for the benefit of humanity. Usually, the IAC focused on space technology and space travel. It was a tradition for both the Soviet and the American human space flight programs to

showcase their astronaut corps. Because I was fluent both in Russian and English I was put in charge of the special programs the IAC provided for astronauts and cosmonauts.

The first American female astronaut, Sally Ride, had completed her space flight aboard the Space Shuttle earlier in 1983. She was the star of the U. S. delegation participating in the activities of the IAC in Budapest. The Soviets did not want to fall behind in the publicity competition. They sent the second Soviet female cosmonaut, Svetlana Savitskaya (who flew 19 years after Valentina Tereshkova became the first woman to have flown in space), to the conference. Since the IAC was about peaceful cooperation in space, the two women were supposed to make several joint appearances and they both were very much looking forward to meeting each other.

World events, however, can interfere even with the best laid plans. On September 1, 1983, just a few days before the start of the IAC, *Korean Air Lines* Flight 007 was shot down by a Soviet interceptor west of Sakhalin Island, in the Sea of Japan. All 269 passengers and crew aboard were killed. The aircraft was en route from New York City to Seoul via Anchorage when it flew through prohibited Soviet airspace around the time of a U. S. reconnaissance mission. The Soviet Union claimed that the aircraft was on a spy mission and that it was a deliberate provocation by the United States to test the Soviet Union's air defences. The incident was one of the tensest moments of the Cold War and resulted in an escalation of anti-Soviet rhetoric in the United States. The political climate during the IAC was very tense and the U. S. delegation cancelled all joint appearances of American and Soviet astronauts and cosmonauts. This was a huge disappointment for Sally Ride and Svetlana Savitskaya, who were very much looking forward to their meeting.

Astronauts and cosmonauts are selected from very large groups of strong individuals good at overcoming obstacles. Sally Ride quickly realized that I was not a KGB agent and did not care much about rules and regulations. She approached me and told me about her desire to meet with Svetlana Savitskaya in spite of the official position that there be no meeting between them. I had 24 hours to arrange a "secret" meeting because of the tight schedule of the astronauts.

I enlisted the help of the Hungarian cosmonaut, Bertalan Farkas, and the KFKI leadership. Farkas approached the Soviet delegation who were actually quite pleased by the idea of a private meeting between the two women. They, however, insisted that Svetlana should not go alone but be accompanied by the commander of the mission she flew on.

Sally Ride, Bertalan Farkas, Svetlana Savitskaya and Tamas (left);
Sally Ride and Svetlana Savitskaya (right)

The next evening there was a reception at the U. S. embassy, after which Sally sneaked out of her hotel room and was picked up by me in a private car that took us to the apartment of Bertalan Farkas. Svetlana and her chaperon arrived about the same time. A group of about ten people, including spouses, gathered, and the two women chatted for six or seven hours, until the early morning. I translated for them and by the end was quite exhausted. Not the women. They were as perky at five in the morning as they had been at the beginning of their meeting. It is interesting to note that Sally Ride remained forever grateful to me for organizing this meeting. She regularly kept in touch with me and we occasionally got together at various meetings until her untimely death in 2012.

Comet Halley

The first spacecraft launched to Comet Halley were the *Vega* probes. *Vega 1* and *2* were launched from the Baikonour Cosmodrome in Soviet Kazakhstan on December 15 and 21, 1984, respectively. *Vega 1* reached Venus first on June 11, 1985. As *Vega 1* passed 39,000 km from Venus, the lander successfully deployed the balloon payload in the Venusian atmosphere. Four days later *Vega 2* passed 24,500 km from Venus while its lander also successfully deployed a balloon as it descended to a nighttime landing 1,500 km southeast of *Vega 1*. With their missions at Venus successfully completed, the two *Vega* spacecraft were on their way to encounter Comet Halley in nine months.

Next out of the gate was the Japanese *Sakigake* ("Pioneer" in Japanese) mission launched from the Kagoshima Space Center on January 7, 1985. Course corrections performed on January 10 and February 14 decreased the miss distance to about 7 million km. After a series of engineering tests, all of *Sakigake's* instruments were turned on by the end of February 1985. The success of this technology demonstrator paved the way for the launch of *Planet-A* later that summer.

The next mission off the pad was the European *Giotto*. It was launched from Kourou in French Guiana on July 2, 1985, on an *Ariane* rocket. The first course correction was made on August 26 to move *Giotto's* initial aim point to within 4,000 km of Halley's nucleus.

Artist's rendering of the encounter of the VEGA spacecraft with comet Halley

The last dedicated mission to be sent to Comet Halley was the Japanese *Planet-A* probe. It was successfully launched on August 18, 1985 and subsequently renamed *Suisei* (Japanese for "Comet"). A course correction on November 14 moved *Suisei's* aim point to about 151,000 km on the sunward side of Halley's nucleus.

The first of the international armada to reach Comet Halley was the Soviet's *Vega 1*. It passed 8,890 km from Halley's nucleus at a relative velocity of 79.2 km per second on March 6, 1986. Near closest approach *Vega 1* was pummeled by up to 4,000 dust particles each second as it returned ghostly images of the 15-km-long peanut-shaped nucleus. *Vega 1* survived the dangerous encounter and successfully transmitted about 800 images and other data, but two instruments had been disabled and the output from the unprotected solar arrays was cut by 55 %.

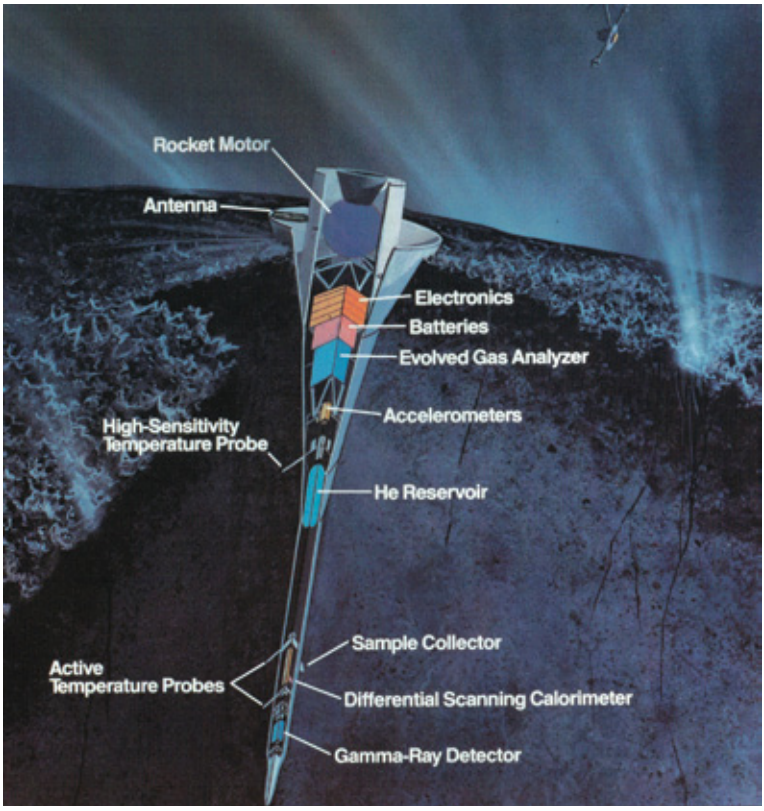
Next up was the Japanese *Suisei*, which had been observing Comet Halley with its UV imager since mid-November 1985. It passed at a much safer range of 151,000 km on March 8 where it secured useful data on the properties of the comet's extended cloud of hydrogen. Just 18 hours later, *Vega 2* made its dangerous plunge towards the nucleus. Its path through Halley's coma afforded a less obscured view of the nucleus compared to *Vega 1*. Although the main processor controlling the scan platform failed 32 minutes before closest approach (forcing a switch to a less capable backup system), *Vega 2* survived its 76.8 km-per-second encounter with Halley on March 9 at a range of just 8,030 km. *Vega 2* had several instruments lost or partially disabled during the encounter and lost 80 % of the power from the solar panels, although this was later revised to only a 50 % loss. In total the two *Vega* spacecraft returned 1,500 images and a mountain of other data on Comet Halley.

After *Sakigake* made its distant 6.99-million-km pass by Comet Halley at 4:18 UT on March 11, the last spacecraft in the international armada was *Giotto*. Data from the Soviet *Vega* probes had pinned down the position of Halley's nucleus to within 75 km at a 99.7 % confidence level — a 20-fold improvement over what was provided by Earth-based observations alone. With such an accurate fix, on March 11 *Giotto* project scientist decide to attempt a 500-km pass by the nucleus and performed a final course correction. *Giotto* made its closest approach on March 14 at a range of 605 km. It returned 2,112 images of the comet and provided the clearest views we have of Halley's nucleus. More images would have been returned except that a hard hit by a large dust particle just 16 seconds before closest approach knocked the spinning *Giotto's* antenna out of alignment with the Earth. While full contact with the probe was restored 32 minutes later after the wobble was dampened, several instruments were damaged including the camera, whose baffle was severely mauled, rendering it unusable.

CRAF AND ROSETTA

CRAF

In the middle of the 1980s I moved to the University of Michigan where I had an opportunity to continue comet research. Shortly after my arrival NASA announced a competition for instruments for the Comet Rendezvous Asteroid Flyby (CRAF) mission. I was invited by three proposing teams to be a co-investigator and to write the science section of the proposals. Two of these proposal were selected and I became a member of the CRAF science team.



Schematic view of the comet surface penetrator-lander designed for the Comet Rendezvous Asteroid Flyby (CRAF) mission

There were fourteen science investigations on CRAF and I was involved in the Comet Retarding Ion Mass Spectrometer (CRIMS) led by Tom Moore and the Suprathermal Plasma Investigation of Cometary Environments (SPICE) led by Jim Burch. In addition I did quite a bit of modeling work for the project to help with mission planning. During the second half of the 1980s I had a blast working on CRAF and I published quite a few papers from my results.

The main instrument on CRAF was the penetrator-lander lead by Bill Boynton of the University of Arizona. The instruments aboard the penetrator-lander would collect a sample of cometary ices, study how they change when heated, and perform a chemical analysis of the gases released from the ice. The penetrator was designed to bury its tip with a gamma-ray spectrometer measuring abundances of as many as 20 chemical elements up to one meter below the comet's surface. The penetrator was to carry accelerometers to determine Kopff's surface strength and its resistance to puncture, and thermometers to measure temperatures beneath the surface. The penetrator-lander was going to radio its findings to the spacecraft, which will then relay them to Earth.

From the beginning CRAF had problems on two fronts. The penetrator design was technologically not mature enough and it represented a high failure risk. At the same time it was considered the main instrument on the spacecraft and the risk-averse

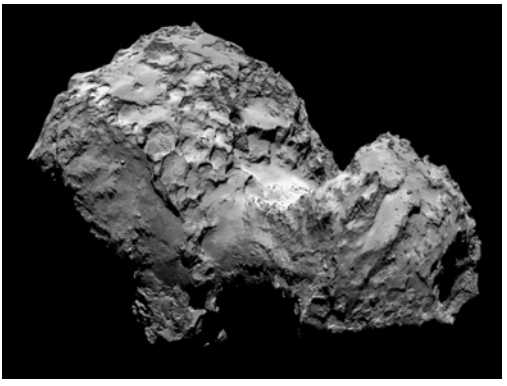
JPL engineering culture gradually made its cost prohibitive. When it was selected its cost was supposed to be just over $20 million, but by 1990 the estimated cost increased by more than a factor of six.

The second problem was the lack of political support. Most importantly, the powerful Chair of the relevant Senate Appropriations Subcommittee, Maryland Senator Barbara Mikulski, was not a friend of CRAF. She was supporting the *Cassini* mission to Saturn and its moon, Titan, mainly because these missions had important contributions from two Maryland based institutions: NASA's Goddard Space Flight Center and Johns Hopkins University's Applied Physics Laboratory. In addition to lack of congressional support CRAF also had a problem with the broader U.S. and European planetary communities. In the U.S. there was strong support for a robust Mars program and there was a vocal outer planets community. The cometary community in the U.S. was politically weak and was not able to rally the broader science community behind CRAF. In Europe there were two communities actively working against CRAF: the European outer planets community that wanted ESA to build the Titan lander (that eventually became the *Huygens* probe) and the European comet community that wanted its own comet mission with sample return (this mission eventually became *Rosetta* that could be considered CRAF light). The cost overrun and the lack of political support sealed CRAF's fate and it was cancelled in 1992.

Rosetta

European scientists proposed a comet rendezvous and sample return mission in the second half of the 1980s, long before CRAF was cancelled. They named the mission after the Rosetta Stone, a stele of Egyptian origin featuring a decree in three scripts. A comparison of its hieroglyphs with those on the Rosetta Stone catalyzed the deciphering of the Egyptian writing system. Similarly, it was hoped that the spacecraft will result in better understanding of comets and the early Solar System. By 1993 it was evident that the ambitious sample return mission was infeasible with the existing ESA budget, so the mission was redesigned and subsequently approved by the ESA, with the final flight plan resembling the cancelled CRAF mission: an asteroid flyby followed by a comet rendezvous with *in situ* examination, including a lander.

Rosetta was set to be launched on 12 January 2003 to rendezvous with the comet 46P/Wirtanen in 2011. This plan was abandoned after the failure of an *Ariane 5* rocket launcher on December 11, 2002, grounding it until the cause of the failure could be determined. A new plan was formed to target comet 67P/Churyumov-Gerasimenko (C-G), with a revised launch date of February 26, 2004 and comet rendezvous in 2014.



The nucleus of comet 67P/Churyumov-Gerasimenko (credit: ESA/Rosetta/MPS for OSIRIS Team)

After two scrubbed launch attempts, *Rosetta* was launched on March 2, 2004 from the Guiana Space Centre in French Guiana.

In August 2014, *Rosetta* rendezvoused with comet C-G and commenced a series of maneuvers that took it on two successive triangular paths, averaging 100 and 50 km from the nucleus, whose segments are hyperbolic escape trajectories alternating with thruster burns. After closing to within about 30 km from the comet on 10 September, the spacecraft entered actual orbit about it. The first images of the nucleus revealed that C-G is approximately 4.3 by 4.1 km at its longest and widest dimensions with a total volume of about 20 km^3. The two-lobe shape of the comet is the result of a gentle, low-velocity collision of two objects. The "terraces", layers of the interior of the comet that have been exposed by the partial stripping of outer layers during its existence, are oriented in different directions in the two lobes, indicating that two objects fused to form C-C.

The *Rosetta* spacecraft carried a lander called *Philae* (named after the Philae obelisk, which bears a bilingual inscription and was used along with the Rosetta Stone to decipher Egyptian hieroglyphs). *Philae* is an example of series of lucky breaks that is very unusual in space science. The landing operations started on Monday, November 10, 2014. It started with booting *Philae's* computers. This had to be done twice since it did not work successfully for the two data processing units in the first round. Nevertheless, the further start-up sequence of the lander worked well and it looked like that operations had stabilized in the course of the following day. In the following step the battery conditioning stopped onboard after just one minute into the sequence and the tank opening failed shortly thereafter. The lander was in a crisis. A software patch was applied and late during the night of November 11, 2014 the lander project manager gave the "go" for the release. The *Rosetta* spacecraft left its parking orbit soon thereafter entering the hyperbolic trajectory towards the release point for the lander. On November 12, 2014 at 08:35 UT the lander separated from the orbiter at a relative velocity of 19 cm/s. The *Philae* touch-down happened at 15:34:06 UT when the landing gear indicated contact with the surface at a speed of about 1 m/s.

A short time later it was realized that the lander had touched the surface, but the anchoring harpoons were not shot and the ADS (Active Descent System, a gas tank on top of the lander that was intended to provide the required impulse to stay on the surface) was not fired. *Philae* rebounded off the comet's surface at 38 cm/s and rose to an altitude of approximately 1 km. For perspective, had the lander exceeded about 44 cm/s, it would have escaped the comet's gravity. After detecting the touchdown, *Philae's* reaction wheel was automatically powered off, resulting in its momentum being transferred back into the lander. This caused the vehicle to begin rotating every 13 seconds. During this first bounce, at 16:20 UT, the lander is thought to have struck a surface prominence, which slowed its rotation to once every 24 seconds and sent the craft tumbling. *Philae* touched down a second time at 17:25:26 UT and rebounded at 3 cm/s. The lander came to a final stop on the surface at 17:31:17 UT. It sits in rough terrain apparently in the shadow of a nearby cliff or crater wall and is canted at an angle of around 30 degrees, but is otherwise undamaged.

Philae transmitted information about the elemental, isotopic, molecular, and mineralogical composition of the cometary material, probed the physical properties of the surface and subsurface material, and investigated the large-scale structure and the magnetic and plasma environment of the nucleus. On November 15, 2014 the batteries of *Philae* got depleted and the lander entered safe mode and stopped communicating

with the *Rosetta* spacecraft. Between June and August 2015 *Philae* sent engineering signals for several short periods, but no scientific information was received.

My participation in the *Rosetta* mission goes back to the mid-1990s when I was part of two successful instrument proposals: the ROSINA (Rosetta Ion-Neutral Analyzer) and RPC (Rosetta Plasma Consortium). In addition to participating in the instrument development my group also developed the ICES (Inner Coma Environment Simulator) software tool that provides modeling support for the entire mission. After two decades of preparation our instruments started operations near comet C-G in August 2014 and they are still operating perfectly, as I am writing this paper in March of 2016. The operational phase of the mission will end later this year when the *Rosetta* spacecraft will slowly spiral towards the nucleus and eventually land on the surface. Since the solar panels will not be able to power the spacecraft any more *Rosetta* will join *Philae* as the second inactive robot on the nucleus of comet C-G.

THANK YOU, IKI!

It is amazing that IKI is 50 years old. It is even more amazing that I have been associated with IKI for over 40 years. Looking back, I vividly remember when the "new" building of the Institute was constructed and I visited my colleagues in the small glass buildings, called "steklyashka". IKI, and space science, changed tremendously over these years. The founding generation is mostly gone and even the second generation — people of my age — are approaching retirement. What is very reassuring, however, is that after a difficult period of time IKI is again a dynamic place where highly talented people are working on advancing our knowledge of all aspects of space science: Earth science, astrophysics, heliophysics, and planetary science.

I feel tremendous gratitude for the opportunities, help, and education I got at IKI. I wish the Institute a very happy 50^{th} birthday and many, many more successes in the coming years.

SCIENTIFIC COOPERATION BETWEEN BULGARIA AND IKI-MOSCOW: FROM THE ONSET OF INTERCOSMOS TO EXOMARS

Jordanka Semkova, Rositza Koleva

On behalf of the Space Research and Technologies Institute, Bulgarian Academy of Sciences (SRTI-BAS), Sofia, Bulgaria

We began our careers in the Central Laboratory for Space Research at the Bulgarian Academy of Sciences only three-four years after its establishing in 1975. From our very first steps in space physics till now we have been working in common with colleagues from the Space Research Institute (IKI) of the USSR Academy of Sciences. The common work turned to a strong friendship. In our long-lasting collaboration with IKI colleagues we jointly initiated exiting projects, obtained good scientific results, overcame number of dramatic situations, suffered the lost of colleagues and friends, expect new interesting results and enjoy beautiful social contacts. All our meetings always passed in a creative, friendly, and supportive atmosphere.

The scientific cooperation between Bulgaria and IKI has many aspects. In some common deeds we have been participating and we know many details; in others we have been witnesses; about third we know from friends. The story below neither presents the full history of this cooperation nor pretends to be exhaustive. We would like only to share with you some of our memories.

HISTORY

The modern space research in Bulgaria started at the beginning of the International Geophysical Year in 1956-1957 when the USSR proposed to the Bulgarian government to begin ground-based ionospheric investigations in addition to the direct investigations of the near-Earth space with the firsts Soviet satellites [Серафимов, 1979]. Following that, optical, photometric, and radio observations of the firsts Soviet satellites were conducted.

The renowned Bulgarian scientists L. Krastanov, G. Nestorov, N. Kalitsin, N. Bonev, K. Serafimov, D. Mishev were the founders of the space research in Bulgaria.

Participation in the INTERCOSMOS program

The participation in the INTERCOSMOS program is a major stage and the most fruitful period in the Bulgarian space research.

The Bulgarian governmental delegation led by Acad. L. Krastanov, the President of the Bulgarian Academy of Science (BAS) and minister in the Bulgarian government at that time took part in the INTERCOSMOS constituent meeting in Moscow in 1965.

Fig. 1. Acad. Kotelnikov (left), the President of INTERCOSMOS Council, and Acad. Serafimov (right), the President of the Bulgarian National Committee on Space Research

The scientific priorities and the organizational structure of the space research in Bulgaria were closely connected with the INTERCOSMOS program (Fig. 1). In 1966–67 the National Committee on Space Research led by Acad. L. Krastanov and Acad. K. Serafimov was established. In 1969 a group "Space physics" was created at BAS that later evolved in several laboratories and institutes. Nowadays the Space Research and Technologies Institute (SRTI) is their successor and the main institute of BAS conducting space research. Other institutes of BAS as well as some Bulgarian universities also participate in space activities.

Main results of the INTERCOSMOS era

In the early years of INTERCOSMOS Bulgarian scientists together with Russian colleagues (led by Prof. Yu. Galperin) participated in the development of the scientific programs of a series of *Cosmos* satellites: *Cosmos 261*, *348*, *381*.

During the INTERCOSMOS era Bulgarian space researchers participated in the development of experiments and equipment for the *Intercosmos* satellites *Nos 8*, *12*, *14*, *19*, the geophysical rockets *Vertikal 3*, *4*, *6*, *7*, *10*, the space missions VEGA (Venus-Halley), *Phobos 1* and *2*, APEX, ACTIVNY, *Coronas-F*, *Interball*, *Mars 96*, etc. The scientific programs and equipment for two *Bulgaria-1300* national space research projects and the flights of the first and second Bulgarian cosmonauts were created.

Those were years of inspiration and exiting achievements for the Bulgarian space researchers.

Most of the above activities were conducted in close cooperation with scientists from IKI. Below we present some results of this cooperation.

On 1 December 1972, the first probe device (P1) for direct measurements of the ionospheric plasma parameters [Чапкънов и др., 1974] was launched onboard the *Intercosmos 8* satellite (Fig. 2). In 1977–81 a number of probe devices and photometers (e.g. EMO-R2) (Fig. 3, 4) were launched aboard *Vertikal* rockets and *Intercosmos* satellites [Серафимов, 1979]. All probe and photometer devices and experiments were developed in cooperation with IKI.

Fig. 2. The first Bulgarian space device P1, launched on 1 December, 1972 onboard *Intercosmos 8*

For the Scientific Program of the first Bulgarian cosmonaut G. Ivanov and the Soviet cosmonaut N. Rukavishnikov for *Salyut 6* manned station in April, 1978 two instruments were created in cooperation with IKI: the trace spectrometric system *Spectrum 15* for Earth remote sensing (Fig. 6) and the photometric equipment DAGA for experiments in space physics (Fig. 7).

Fig. 3. The Bulgarian-Russian team that developed the probe device P2. From left to right: N. Mizov (BAS), V. Gubski (IKI), T. Ivanova (BAS), G. Gdalevich (IKI), St. Chapkanov (BAS)

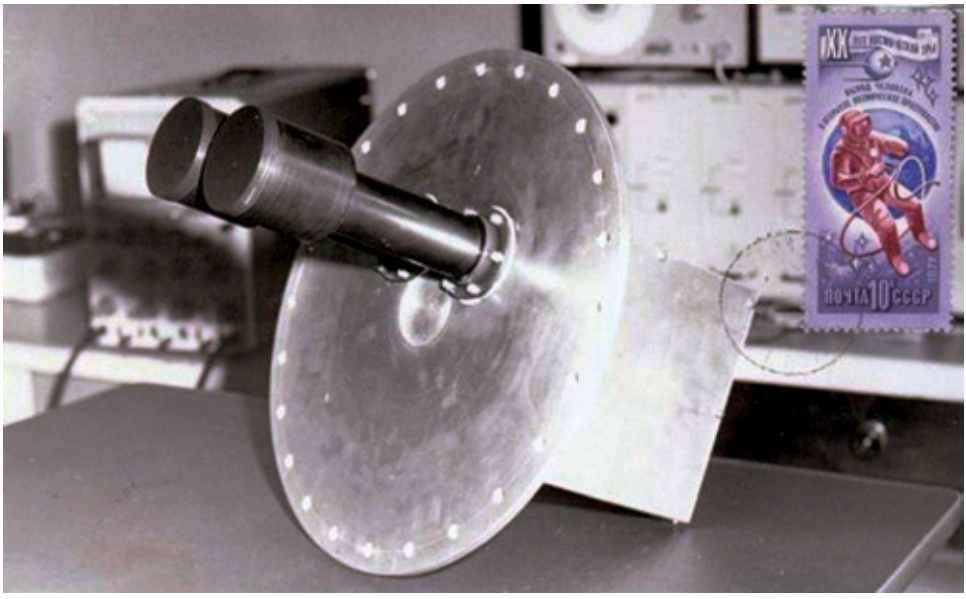


Fig. 4. The rocket photometer EMO-R2 measuring the vertical profiles of the red oxygen (6300 Å) emission

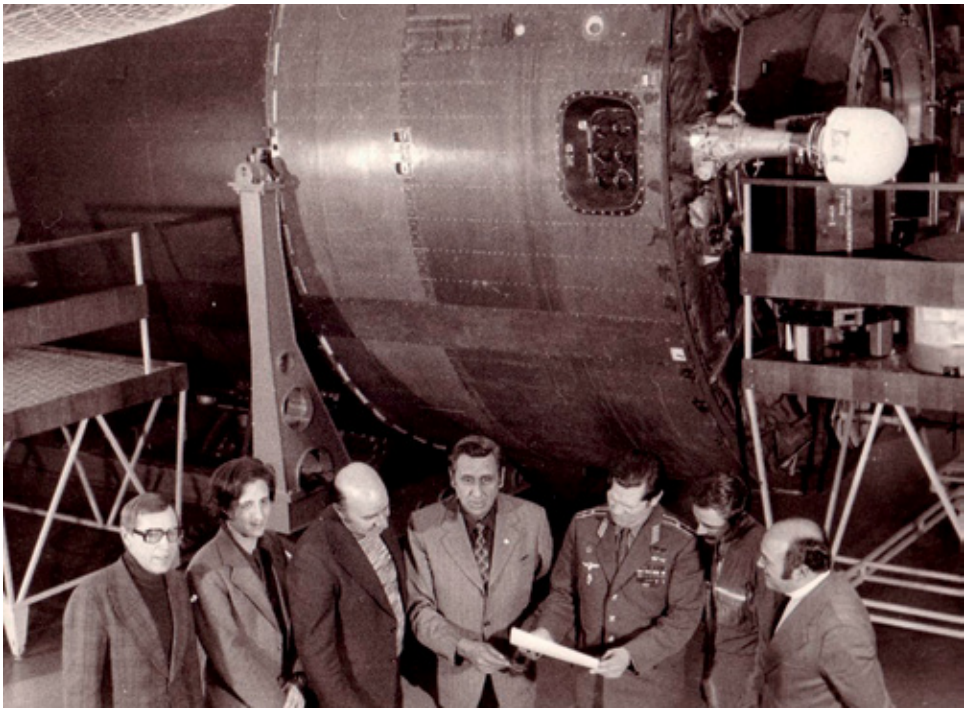


Fig. 5. The Bulgarian constructors of *Spectrum 15* (led by D. Mishev, in the centre) and of DAGA photometer (led by M. Gogoshev, first from the right) and Soviet specialists in discussion with the cosmonaut G. Ivanov

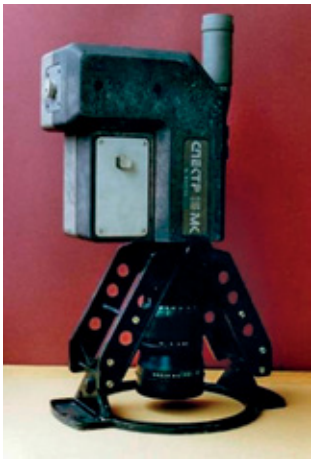


Fig. 6. Trace spectrometer *Spectrum 15* developed for the flight of G. Ivanov and N. Rukavishnikov on *Salyut 6*

Fig. 7. M. Gogoshev (Bulgaria) and cosmonauts V. Ryumin (USSR), G. Ivanov (Bulgaria), and A. Alexandrov (Bulgaria), during training with DAGA photometer for *Salyut 6* orbital station

Fig. 8. Bulgarian government meets the cosmonauts and leading specialists from both countries

Fig. 9. Bulgarian and Soviet space researchers celebrate together the launch of *Soyuz 33* with G. Ivanov and N. Rukavishnikov aboard

In the following years a series of trace spectrometric systems *Spectrum 15* were used aboard the space stations *Salyut 6* and *Salyut 7* and airborne laboratories [Мишев, 1985].

The flight of the first Bulgarian cosmonaut was a moment of national triumph in our country (Fig. 8, 9).

For the scientific program of the second Bulgarian cosmonaut A. Aleksandrov on *Mir* space station (June 1988) 12 scientific instruments and 40 Bulgarian-Russian experiments in space physics, Earth remote sensing, space biology and medicine, and material sciences were developed. Many of them were in cooperation with IKI. Some of the instruments were used for years aboard *Mir*. For example, a number of Russian and international cosmonauts in the period 1988–2001 worked with the multichannel spectrometric system *Spectrum 256* [Mishev et al., 1990; 1993], developed jointly by Bulgaria and IKI, which provided many images and spectrograms of the Earth surface (Fig. 10), analyzed by Bulgarian and Russian scientists [Butov, Loginov, 1995; Chekalina et al., 1993; Krezhova, 2002; Krezhova et al., 1998; Lazarev, Avakyan, 2001].

A peak in the Bulgarian space research was the National space program *Bulgaria-1300*, devoted to 1300th anniversary of the Bulgarian state. For the realization of the program two satellites were launched in 1981 with two fields of investigation: space physics and remote sensing of the Earth.

The first satellite *Intercosmos-Bulgaria-1300-I* (*IC-Bulgaria-1300)* for investigation of the ionosphere-magnetosphere interactions was launched on 07.08.1981. The *Meteor* type satellite launched in polar orbit, with 81.90 inclination and perigee/apogee 896/904 km carried aboard twelve Bulgarian-Soviet scientific instruments for measuring plasma parameters, particle fluxes, electric and magnetic fields and optical investigations. Most of those instruments and experiments were developed and conducted in cooperation with IKI. Figures 11–13 represent moments of the Bulgarian-Russian works on *Intercosmos-Bulgaria-1300-I*.

The second satellite *Meteor-Priroda* (*Bulgaria-1300-II*) for Earth remote sensing was launched with two scientific instruments aboard created also in cooperation with IKI. These were the multichannel spectrometric system SMP-32 and the high frequency radiometer RM-1.

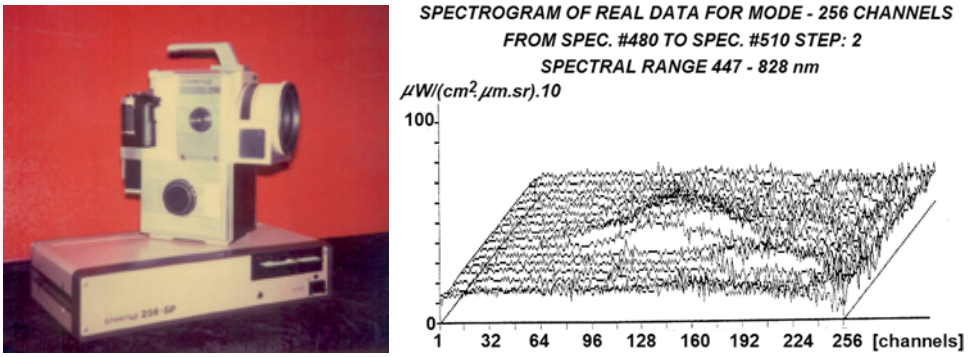


Fig. 10. The multichannel spectrometric system *Spectrum 256* and a spectrogram

Fig. 11. May 1979. A visit of the *Intercosmos* delegation in Bulgaria to discuss the space project *Intercosmos-Bulgaria-1300*

Fig. 12. A meeting in IKI for discussions on *Intercosmos-Bulgaria-1300.* IKI delegation led by Acad. R. Z. Sagdeev, Bulgarian delegation led by Acad. K. B. Serafimov

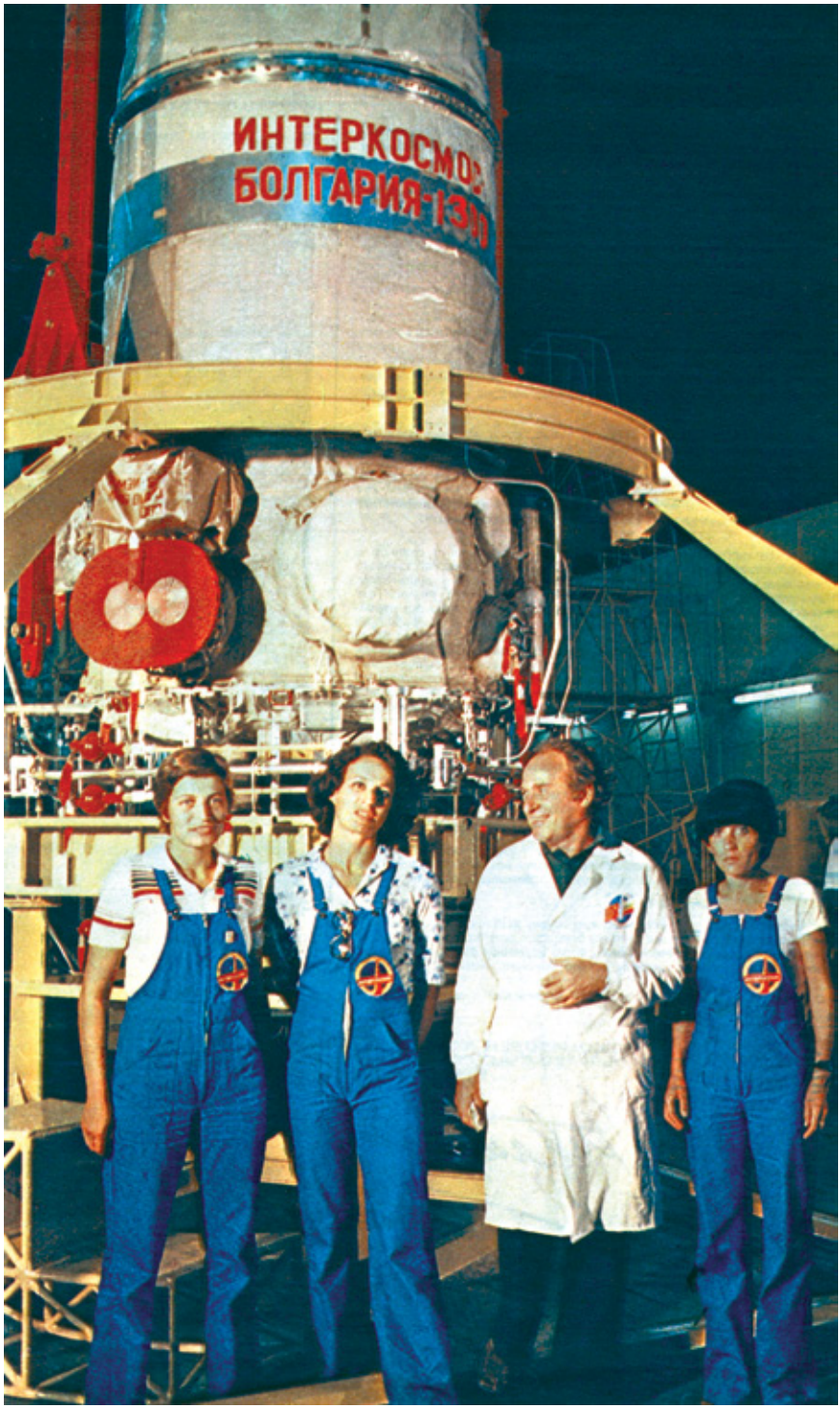


Fig. 13. Bulgarian and Soviet scientists during tests of the scientific complex on *Intercosmos-Bulgaria-1300-I* satellite

For more than 3 years of operation the *Intercosmos-Bulgaria-1300* provided many new scientific results for that time. Data analysis and interpretation was performed in cooperation of Bulgarian scientists with scientists from IKI and other Russian institutes. Some of the results obtained aboard *IC-Bulgaria-1300* are:

- Large database of precipitating particles events. Multiple inverted-V structures were identified and their parameters inferred from complex *in situ* measurements (Fig. 14) (e.g. [Антонова и др., 1991]).

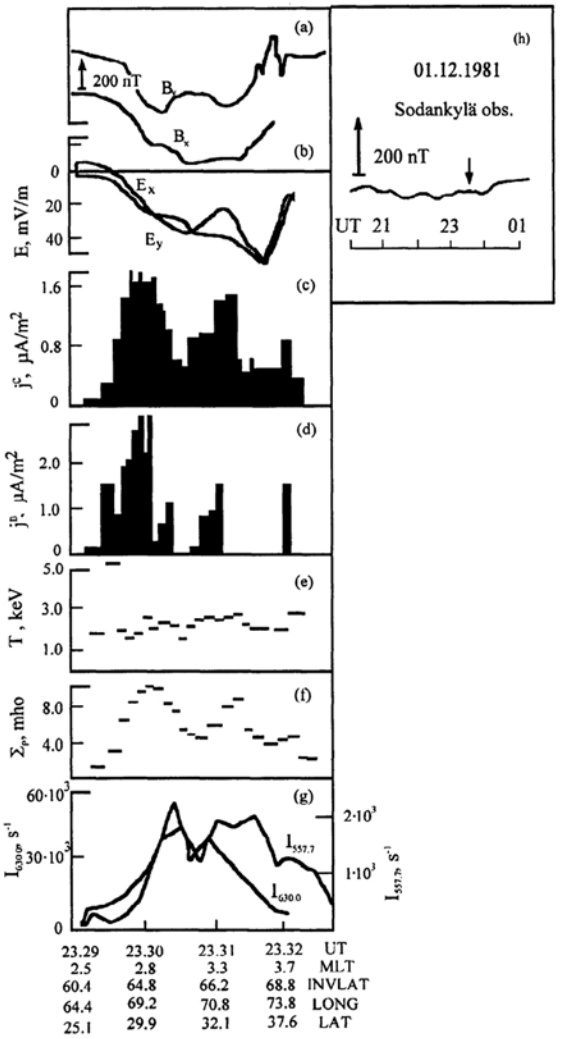


Fig. 14. An event consisting of three inverted-V events derived from observations by *Intercosmos-Bulgaria-1300* on December 1, 1981: (a) — Horizontal components of geomagnetic field disturbances; (b) — Horizontal components of the electric field; (c) — Field-aligned current density from precipitating electron flux data; (d) — Field-aligned current density from magnetometer data; (e) — Plasma sheet ion temperature; (f) — Height integrated ionospheric conductivity; (g) — Emissions of the upper ionosphere for 5577 Å and 6300 Å; (h) — Magnetogram for Sodankylä (from [Антонова и др., 1991])

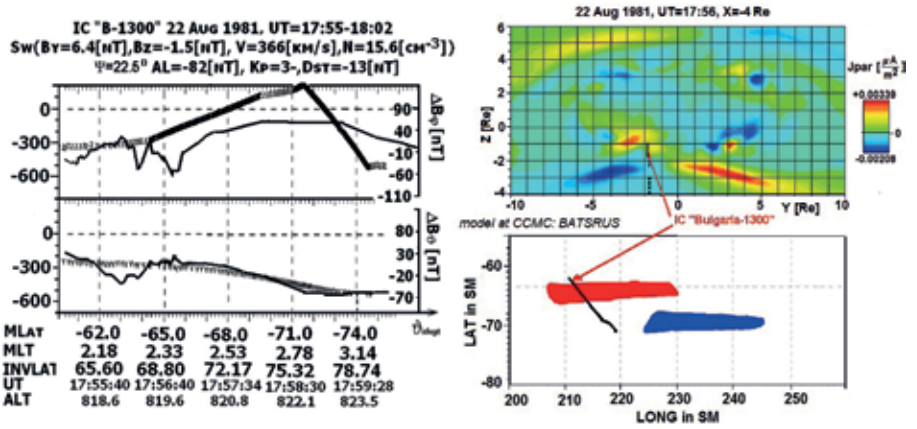


Fig. 15. Field-aligned currents measured on *Intercosmos-Bulgaria-1300* and modelled. Two components of the measured magnetic field (MF, after subtracting the IGRF MF) are shown (left). The model MF (calculated from Tsyganeko-2001 model) is plotted with symbols. X-axis is co-latitude, Y-axis for each panel denotes the MF-component amplitude (left for measured field, right for Tsyganeko model). Vertical dashed lines mark intervals of three degrees. The changes in the measured MF are more than 10 times greater than in the model. Projection to the magnetosphere (up) and to ionospheric heights (bottom) of the MHD up going (red) and down flowing (blue) currents in the vicinity of satellite path (right). That part of the orbit, on which Tsy-2001 model predicts downward currents, not seen in the data, do not map to the Region 1 current (from [Danov, Koleva, 2007])

- Numerous magnetic field measurements, which revealed small-scale structure of the field-aligned currents (FACs). The measured field-aligned currents are compared with those calculated by empirical and magnetohydrodynamic (MHD BATS-R-US) modelling (Fig. 15) [Аршинков и др., 1983, Данов и др.., 2006; Danov, Koleva, 2007].
- The three-axis stabilization of *IC-Bulgaria-1300* supplied unique possibility to measure three components of the electric field. The analysis of simultaneously measured electric and magnetic fields and the precipitating particles gave the possibility to conclude that the electrons are the carriers of the field-aligned currents producing aurora [Podgorny et al., 1988].
- Small-scale electromagnetic disturbances in the auroral region were demonstrated [Дубинин и др., 1985].
- Based on data from the *IC-Bulgaria-1300* satellite, the latitudinal distribution of oxygen and helium ions in the topside ionosphere was discussed for nighttime equinox at high solar activity. In such periods the helium ions are predominating at altitudes of 1000 km [Koleva, Kutiev, 1985].
- Mutual analysis of *IC-Bulgaria-1300* and *Dynamics Explore-B* satellites data shows that the area in the auroral latitudes with depleted neutral oxygen and helium density coincides with the maximums in the 1 keV electron flux and with the total energy flux in the range 1–15 keV [Dachev et al., 1985].
- Effects of small-scale plasma disturbances on the *IC-Bulgaria-1300* spacecraft potential were studied. In the auroral zone the potential variations correlate well with the increasing flux of energetic electrons. The observed variations

were explained by a secondary electron emission from the satellite surface [Balebanov et al., 1985]. The study of the subauroral electric field, based on data from *IC-Bulgaria-1300* and *Dynamics Explore-B* satellites revealed that two types of electric field could be observed: a polarization field, producing the polarization jets, and penetrating equatorwards of the auroral oval when the shielding of the oval is disrupted [Кутиев, Колева, 1989]. Auroral oval and polar cap boundaries and their locations under different geomagnetic conditions were studied [Gogoshev et al., 1987; Guineva, Stoeva, 1993] (Fig. 16).

Even today some Russian (I. Podgorny, A. Podgorny, E. Antonova) and Bulgarian (L. Bankov, D. Danov) scientists actively use the *Intercosmos-Bulgaria-1300* data in their research.

One of the most famous and successful Soviet projects was the realization of the Halley comet flyby by the *Vega* probes in 1986. One of the 14 scientific instruments aboard *Vega 1* and *Vega 2* spacecraft was the Three-Channel Spectrometer (TKS) (Fig. 17).

TKS was a joint development of Bulgaria, France, and the USSR under the leadership of Prof. M. Gogoshev, Prof. G. Morels, and Prof. V.A. Krasnopolsky [Gogoshev et al., 1985]. The investigation of the Halley comet by TKS was the first Bulgarian participation in an interplanetary space project.

During *Vega 2* flyby from 8th to 12th of March 1986, TKS measured more than 3000 spectra of the comet coma (Fig. 18). The Bulgarian team processed the data from the UV spectral channel [Werner et al., 1989a] and maps of the comet coma were reconstructed. The emissions of the species in the UV spectra were identified, parameters and production rates of six of them were determined and the dust density was estimated [Krasnopolski et al., 1986; Moreels et al., 1986, 1987; Stoeva et al., 2003]. At the reconstructed maps jet-structures, consisting of a mixture of cometary gas and dust, were identified and the gas/dust ratios were analyzed [Werner et al., 1989b]. The distribution of the neutrals emissions in the near nucleus region in sunward direction [Guineva, Werner, 2007; Guineva et al., 2006] and of the ions in the cometary tail [Guineva et al., 2003; Stoeva et al., 2005] were studied in detail. The dust distribution in the comet *Vega 2* trajectory plane was reconstructed using a tomographic algorithm. The jet-structure found is in very good agreement with the dust distribution measured along the trajectory by *in situ* dust measurements [Stoeva et al., 2005].

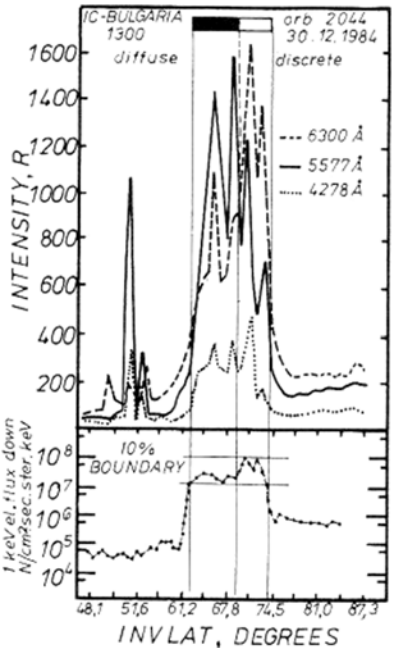


Fig. 16. A case of crossing the polar oval boundaries (the vertical lines) defined from optical and 1 keV electron flux data (from [Gogoshev et al., 1987])

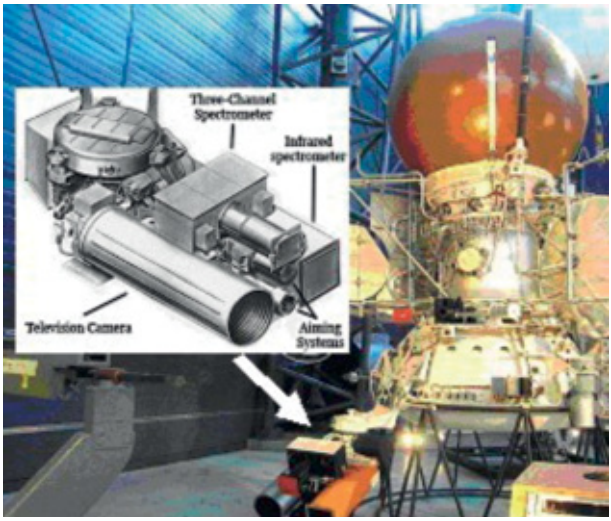


Fig. 17. The *Vega* probe with the TKS mounted on a steering platform

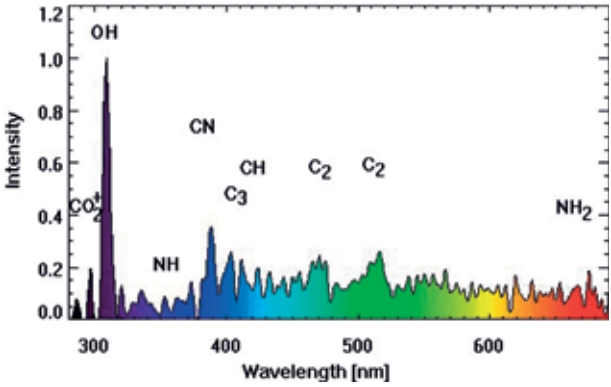


Fig. 18. More than 3000 spectra of the Halley comet coma were obtained by TKS

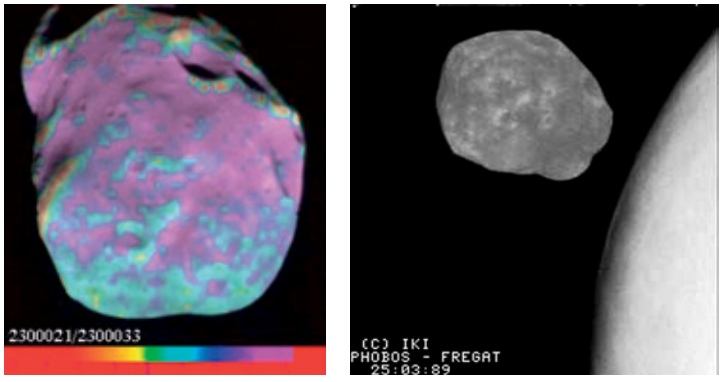


Fig. 19. Images of Mars-Phobos system provided by *VSK Fregat* aboard *Phobos 1* and *2* probes

The video spectrometric and navigation complex *VSK Fregat* was developed cooperatively by Bulgaria, IKI, and Germany for the *Phobos* mission. VSK combined a three-channel TV camera and a spectrometer. In 1989 aboard *Phobos 1* and *2* space probes *VSK Fregat* provided 37 unique images of Phobos (Fig. 19) from a distance of 190–1100 km. The data were used to update the three-dimensional model of Phobos, to provide improved determination of its density and orbital dynamics and to study Phobos' surface [Телевизионные..., 1994; Avanesov et al., 1989, 1990, 1991].

COOPERATION AFTER INTERCOSMOS

In the years after the INTERCOSMOS program the cooperation between Russian Academy of Sciences (which succeeded the USSR Academy of Sciences) and BAS in space research continues thanks to the efforts of the Russian and Bulgarian scientists. Examples are the joint experiments and results obtained in *Interball 1* and *2*, APEX, ACTIVNY, *Koronas F*, *Mars 96*, *Phobos Grunt Return* international space projects as well as a number of mutual investigations conducted on the International Space Station (ISS) and on *Bion* type of satellites.

The INTERBALL project

Acad. Galeev initiated the INTERBALL project at a large INTERCOSMOS meeting held in 1982 in Plovdiv, Bulgaria. Bulgarian scientists led 4 experiments included in the project developed together with Russian colleagues: one on the *Tail* probe — the Low Energy Plasma Composition Spectrometer (AMEI-2), — and three on the *Auroral* probe (aka *Interball Au*) — the Three-Axis Magnetic Field (IMAP-3), the DC Electric Field Intensity and ULF Waves (IESP-2), and the Auroral UV Emission Line Measurements (UVSIPS). Bulgarian teams participated in three more experiments: the Wave Complex, Electric and Magnetic Fields (KEM-3) aboard *Magion 4* and *5* subsatellites, and in the Fluxgate DC Magnetometer (FM-3I) aboard the *Tail* probe. The complex character of the *in situ* measurements gave the possibility to obtain a deeper understanding of the magnetospheric processes as the following examples show:

- Field aligned currents were identified in the central part of a cusp energetic particle event observed aboard *Interball 2* satellite at an altitude of $3R_E$ [Bochev, Kudela, 2005]. The source plasma of the multiple small-scale FACs measured aboard *Interball Au* during a complex storm event on 22–24 November, 1997 facilitated their relating to the traditional FAC regions 0, 1, and 2 [Koleva, Bochev, 2009] (Fig. 20).
- Ultra low frequency (ULF) waves and PC5 oscillations were studied on base of satellite and ground-based measurements. Extensive study of ULF fluctuations with frequency around 1.8 mHz gives ground to reconcile their physical nature with the surface wave mode model in contrast to the traditional interpretation in terms of magnetic field line resonances [Nenovski et al., 2007]. ULF wave activity at the magnetopause observed by the *Magion 4* subsatellite of the *Interball 1* spacecraft reveals the existence of narrow-band waves of frequency ~0.33 Hz. The proposed generation mechanism associates

these waves with the anisotropic ion fluxes registered just inside the magnetopause [Teodosiev et al., 2005].

- The orbit of *Interball 1* allowed investigating the plasmas in the high-latitude near-Earth outer magnetosphere and in the magnetotail lobes. Regions of mixed magnetosheath–plasma sheet population with the presence of ionospheric ions are frequently observed under northward interplanetary magnetic field with substantial horizontal component. A detailed analysis of plasma and magnetic field data (Fig. 21) allowed to conclude that the mixed regions are formed on double-reconnected filed lines [Koleva et al., 2006]. Observations in the near magnetotail lobes show that the lobes are populated with plasmas of various origin and properties. A ubiquitous picture in the lobes is the registration of 'clouds' of anisotropic electrons originating in the solar wind [Koleva, Smirnov, 2007].

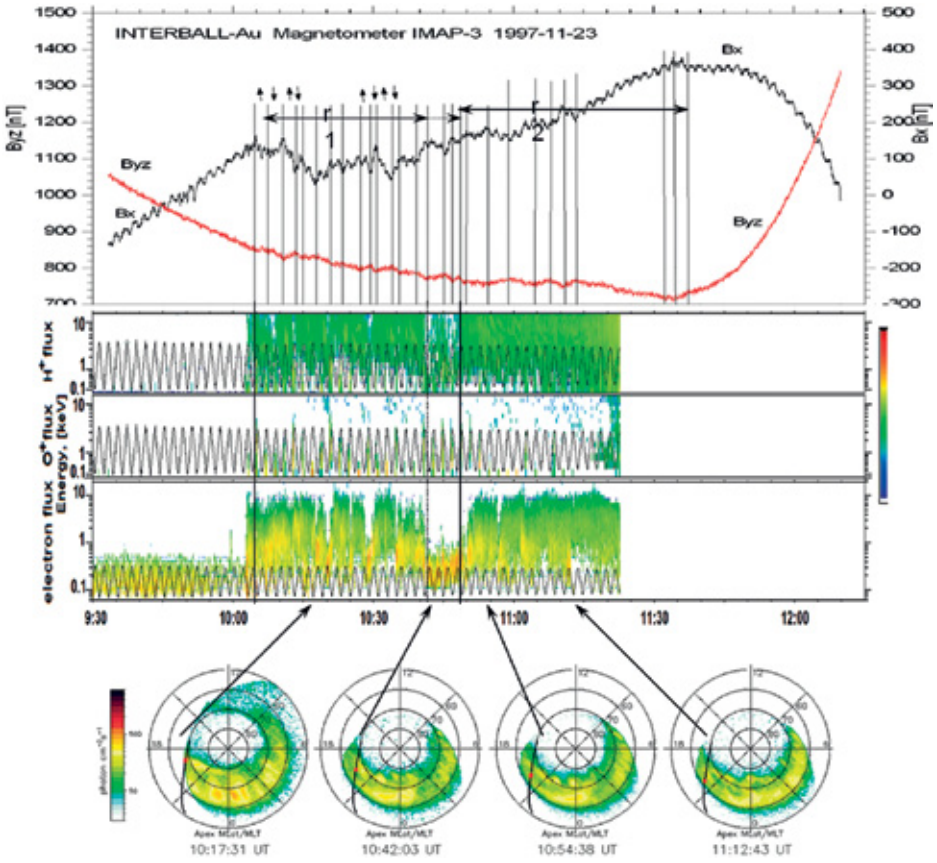


Fig. 20. Multiple small-scale FACs measured aboard *Interball Au* on 23 November 1997. On the panels from top to bottom: the *Byz* component of the magnetic field measured by IMAP-3, the vertical lines separate the small-scale current sheets; spectrogram of the proton flux measured by ION instrument; spectrogram of the oxygen flux (ION); spectrogram of the electron flux measured by ELECTRON instrument; UV images from *Polar* satellite with the projection of the *Interball Au* orbit, the red point denotes the the footprint corresponding to the time of the image (from [Koleva, Bochev, 2011])

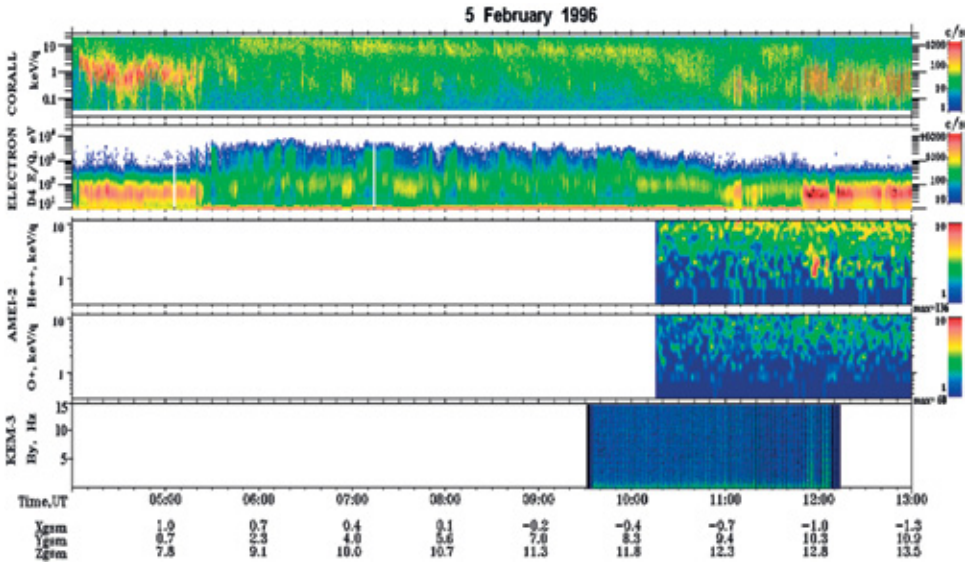


Fig. 21. Spectrograms of plasma measurements aboard *Interball Tail* and ULF waves measured simultaneously on *Magion 4* subsatellite on 5 February 1996 in the near-Earth magnetotail displaying the presence of a mixed plasma population. The ion and the electron spectra and the presence of He^+ and O^+ ions prove the different origin of the plasmas. At UT 11:08–11:10 and FTE event is identified (from [Koleva et al., 2006])

Nowadays

Since 2002 the Bulgarian-Russian scientific cooperation in space research is developed in the frame of the "Agreement on Fundamental Space Research between BAS and RAS". The Agreement was initiated by Acad. Zelenyi (Russia), Acad. Mishev (Bulgaria), and Prof. Getsov (Bulgaria) during the *Interball'2002* meeting in Sofia, Bulgaria. The joint Russian-Bulgarian Working Group on Fundamental Space Research meets every year (Fig. 22). For the 2014–2016 period the number of the joint projects is 33. They are in the field of investigations in the near-Earth space, planetary research, medical and biological investigations, astrophysics.

Nine of the joint projects are with IKI, here are the results of some of them:

- In the "Magnetosheath" project the interaction of the solar wind with the Earth magnetosphere is studied using model and experimental data. The magnetosheath-magnetosphere model, developed at the Institute of Mechanics, Sofia, Bulgaria, is used as a theoretical basis. It describes the interaction between the solar wind and the Earth's magnetosphere in a simplified gas-dynamic approximation and allows for a self-consistent description of the magnetosheath boundaries: the bow shock and the magnetopause. *Interball Tail* measurements are used as experimental data. The case studies performed show a pretty good agreement between the simulated and measured ion flux (e.g. [Dobreva et al., 2015] (Fig. 23).

Fig. 22. Meetings of the Russian-Bulgarian Working Group on Fundamental Space Research

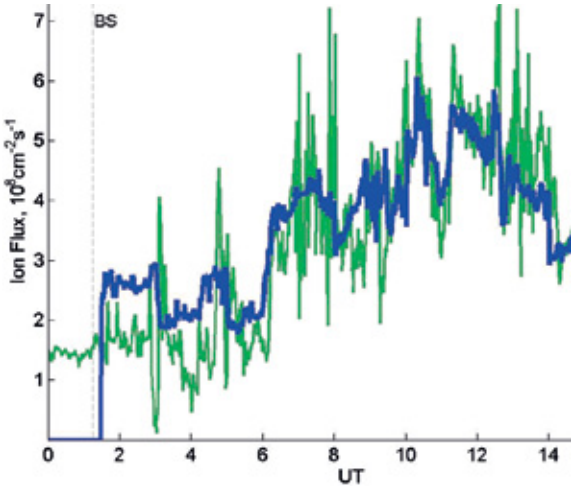


Fig. 23. Comparison between the numerically calculated (blue line) and the measured (green line) ion flux along the *Interball Tail* orbit. The dashed lines indicate the moments of bow shock (BS) and magnetopause (MP) crossings (from [Dobreva et al., 2015])

- The project "Magnetoplasma" is devoted to the study of the processes of magnetospheric plasma configurations formation by *Interball* and *Cluster* data. A special attention is paid to the plasma sheet boundary layer (PSBL). The multipoint *Cluster* measurements reveal that at the lobe-PS interface simultaneously exist field-aligned beamlets — a classical PSBL, and PS-like structures — classical "absence" of PSBL. This structure is interpreted as a result of the localization in Y direction of the flux tubes with beamlets and of the flux tubes with isotropic plasma (Fig. 24), which is a direct evidence that the PSBL is a spatial, not temporal structure [Grigorenko, Koleva, 2009].

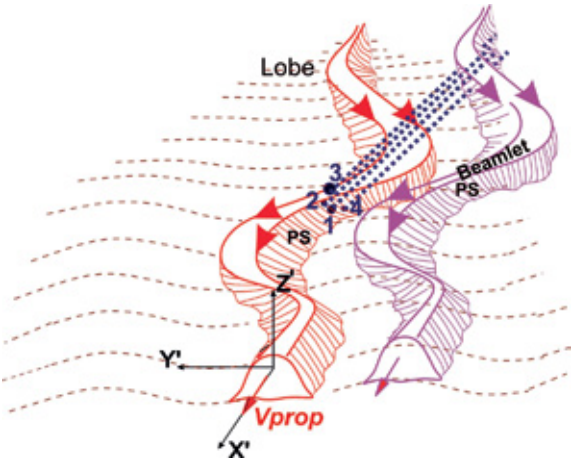


Fig. 24. A cartoon of the 3D-structure of the PS/lobe interface based on *Cluster* data: it contains of classical PSBL with beamlets and flux tubes of PS-like plasma, both localized in Y direction. A wave-like disturbance propagates earthwards (from [Grigorenko, Koleva, 2009])

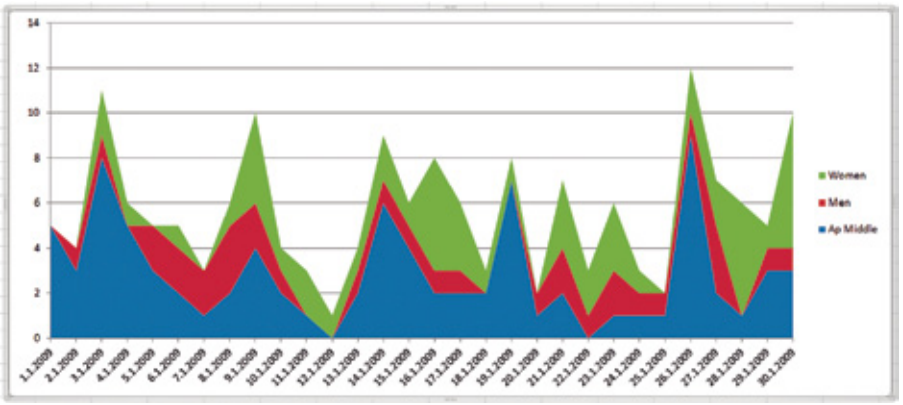


Fig. 25. Daily *Ap*-index for January 2009 and numbers of patients' hospitalized for ischemic cerebral infarction (from [Jordanova et al., 2012])

- Bulgarian and IKI scientists cooperate also in the "Heliobiology" project to investigate the geomagnetic activity influences on human health. The periodicities of cerebral infarctions, cerebral hemorrhage, and subarachnoid hemorrhage episodes, based on a large scale studies, resemble the periodicities found in the solar and geomagnetic activity [Jordanova et al., 2012] (Fig. 25). Experiments on synchronized monitoring of cardiac indices at rest, made simultaneously at three different latitudes, revealed that the variations of heart rates match the variations of the horizontal component of the geomagnetic field vector [Zenchenko et al., 2014].
- The "Interaction" is a part of the *Obstanovka* (Environment) project, which is current mission on the ISS led by IKI. It provides data for electromagnetic fields and the plasma-wave processes in the vicinity of large space objects (satellites and space stations). Bulgarian scientists participate with the Langmiur probe experiment for measuring the concentration and temperature of the thermal plasma and with equipment for measuring the body potential on the station [Киров и др., 2009; Kirov, 2010]. The instrumentation and first results form ISS are shown in Fig. 26.
- The "Wave-R" project. For the future *Resonance* mission (led by IKI) devoted to the investigation of the Earth's magnetosphere, the AMEF-WB instrumentation (Fig. 27) for measuring the electric and magnetic fields in the frequency range 0–1 MHz is under development in SRTI-BAS in partnership with IKI RAN and IZMIRAN. The AMEF-WB instruments will be installed on four high apogees satellites moving along the magnetic field lines in order to identify the processes and currents in the magnetic field tubes [Бойчев и др., 2012].
- In 2013 Acad. Zelenyi proposed a new cooperation between IKI and SRTI-BAS — a joint participation in the radiation environment investigations onboard different platforms of the *ExoMars* project, which is to be carried out by ESA and Roscosmos. The project has two launches foreseen in 2016* and 2020. The *ExoMars* program has been established to investigate the Martian environment and to demonstrate new technologies paving the way for a future

* Successfully launched on March 14, 2016 — *ed*.

Mars sample return mission in the 2020s. Launched in 2016, its first element, the *Trace Gas Orbiter* (TGO) satellite, will spend at least one Martian year orbiting the planet. The second stage of *ExoMars* includes a Surface Platform and a Rover on Mars, planned for launch in 2020. Two dosimeters and experiments are under development for these missions: 1) *Liulin-MO* for measuring radiation environment onboard the *ExoMars 2016* TGO, as a part of the Fine Resolution Epithermal Neutron Detector FREND (IKI RAN) (Fig. 28) and 2) *Liulin-ML* to study radiation environment on Mars surface as a part of the Active Detector of Neutrons and Gamma Rays ADRON-EM (IKI RAN) on the Surface Platform of the *ExoMars 2020* mission (Fig. 29). The objectives of the research are measurements of the ionizing radiation characteristics during the cruise phase, in Mars orbit and on Mars surface [Semkova et al., 2015]. Data obtained will be used to verify radiation environment models and to assess radiation risk to the crewmembers of future exploratory flights. The dosimeters and experiments are created in cooperation between SRTI-BAS, IKI RAN, and Institute for Biomedical Problems (IMBP) of the Russian Academy of Sciences.

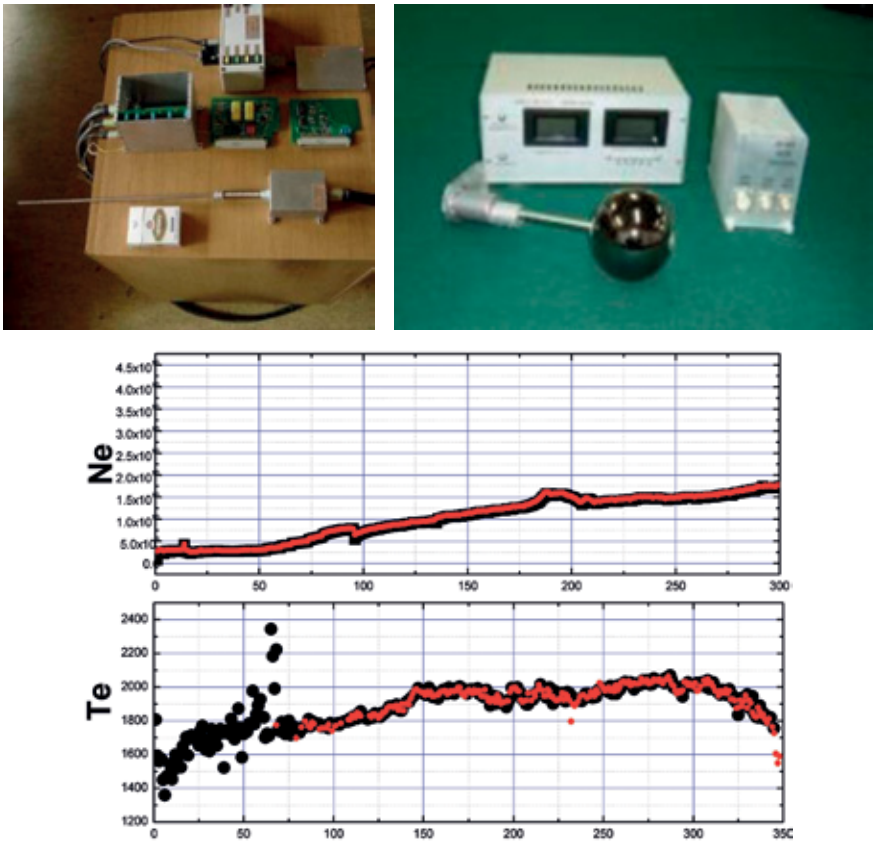


Fig. 26. Bulgarian equipment for *Obstanovka* project (aboard the ISS). An example of the concentration and temperature measurements with the Langmiur probe aboard the ISS

Fig. 27. Instrument AMEF-WB for measurement electric and magnetic fields in the frequency range 0–1 MHz of the *Resonance* project

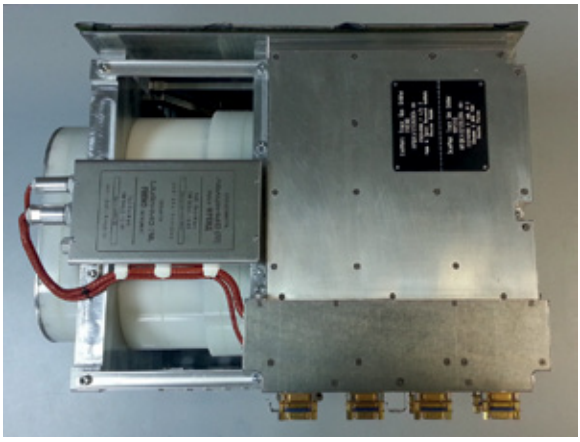


Fig. 28. The Fine Resolution Epithermal Neutron Detector FREND with *Liulin MO* dosimeter (on the top) for *ExoMars 2016* TGO

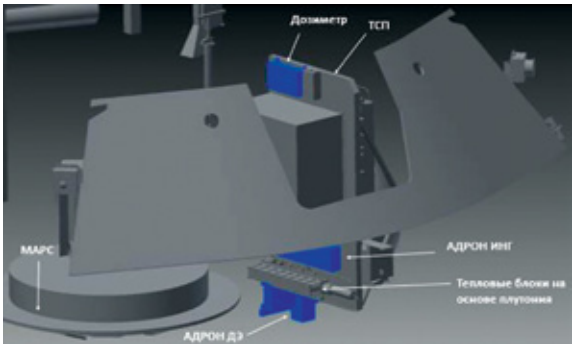


Fig. 29. Location of the active detector of neutrons and gamma rays ADRON and the dosimeter on the *ExoMars 2020* Surface Platform

50 YEARS OF FRIENDSHIP

Fifty years of scientific cooperation between Bulgaria and IKI are marked with a number of meetings and friendship – meetings of leading scientists, project teams, co-authors, and friends, meetings during conferences, working groups, and pre-launch tests, and long-lasting friendship between generations of directors of the institutes and researchers. Many scientific events were jointly organized and thousand collaborative papers presented. Figures 30–36 present pictures taken during a number of meetings and joyful moments of the Russian-Bulgarian space collaboration.

Fig. 30. Kiril Serafimov (in the middle) and Konstantin Gringauz (on the right) in early 1980s

Fig. 31. Roald Sagdeev and Kiril Serafimov play football in Stara Zagora, Bulgaria

Fig. 32. Dimitar Mishev (on the right) and Lev Zelenyi (in the middle), *Interball 2002* meeting in Sofia

Fig. 33. Some of those who were at the beginning of the Bulgarian-Russian space cooperation. Meeting after many years. From left to right: Valery Smirnov (IKI RAN), Tsvetan Dachev (SRTI-BAS), Tania Ivanova (SRTI-BAS), Genadyi Gdalevich (IKI RAN)

Fig. 34. During the meeting of the Bulgarian-Russian Working Group on Fundamental Space Research, Sofia, 2003

Fig. 35. Some of Russian and Bulgarian participants in COSPAR 2006 Assembly, Beijing

Fig. 36. Michail Mogilevsky (IKI RAN) and Boycho Boychev (SRTI-BAS), during the International Conference on Fundamental Space Research, Sunny Beach, Bulgaria, 2008

Fig. 37. IKI Lab. 546 in 1981 (courtesy A. Fedorov)

A few words about the personal cooperation and friendship between the authors of this paper and IKI colleagues.

It started in 1978, when we, together with Lab. 546 of the Space Plasma Physics Department led by Oleg Vaisberg, began the development of the Energy-Mass Analyzer of Ions (AMEI) for the *Intercosmos-Bulgaria-1300-I* satellite. It was our first participation in a space project and the knowledge and experience we got during joint discussions, developments, tests, calibrations, and data analysis with V. Smirnov, G. Zastenker, O. Vaisberg, A. Fedorov, A. Leibov, and other colleagues from the Space Plasma Physics Department were very valuable. In the years that followed, our common work with the Space Plasma Physics Department and Lab. 546 continued with the mutual work on the development and data analysis of the Low Energy Plasma Composition spectrometer (AMEI-2) for *Interball Tail* probe, and presently with a research based on *Interball* and *Cluster* data conducted together with E. Grigorenko (Fig. 37, 38).

Fig. 38. The Bulgarian part of the AMEI instrument team of the *Intercosmos-Bulgaria-1300*, Plesetsk, 1981

We remember warmly the joint work during *Intercosmos-Bulgaria-1300* and *Interball* with other IKI colleagues — I. Podgorny, V. Balebanov, E. Vasilyev, L. Pesotsky, T. Lesina, J. Dikareva, L. Chesalin.

Our first attempt to conduct Martian radiation environment measurements was onboard *Mars 96* mission. For *Mars 96* we developed the RADIUS-MD radiation complex together with IMBP, CNES (France), and IPNS-CEA (France, [Semkova et al., 1994]). The next attempt was on *Phobos Sample Return* mission, for which in cooperation with IMBP, Lavochkin Association, and NIRS (Japan) we developed the *Liulin-F* dosimetric instrument [Петров и др., 2011; Semkova et al., 2008]. The failures of these two fantastic scientific missions were a scientific and personal catastrophes for us also. After *Phobos Sample Return* disaster we were very disappointed, but the invitation of L. Zelenyi to join the *ExoMars* project and make radiation investigations onboard gave us again hope of realization of our long-lasting dream. Recently, following that invitation, we began collaborating with the IKI Nuclear Planetology Department, led by Igor Mitrofanov, on the development of the dosimeters and dosimetric experiments as a part of IKI neutron detectors for *ExoMars* TGO and *ExoMars* Surface Platform. Today (January 2016) we are analysing together with A. Malakhov from IKI RAN the data from the pre-launch tests at Baikonour of the *Liulin-MO* dosimeter of the FREND instrument aboard TGO, expecting the launch in March 2016. We have also good working relationships with L. Belyakova from the department of Quality Control Management and the colleagues from the Testing and Control Station of IKI RAN. In this project we cooperate also with our traditional partners in space radiation measurement experiments from IMBP.

Moments of our personal meetings with IKI friends we present in Figs. 39–43.

Fig. 39. Picture taken during last visit in Bulgaria of our unforgettable friend V. Smirnov. From left to right: Jordanka Semkova, Valery Smirnov, Rositza Koleva, Sofia, 2003

Fig. 40. Meetings of nice colleagues and friends are always very pleasant. From left to right: Elena Grigorenko, Natalia Boodkova, Rositza Koleva, Yuri Ermolaev, ISROSES conference, Varna, 2006

Fig. 41. Yuri Galperin and Rositza Koleva, Interball 2001 Symposium, Warsaw

Fig. 42. Collaboration and friendship are supported by regular inspiring discussions. From left to right: Lev Zelenyi, Jordanka Semkova, Yuri Ermolaev, Rositza Koleva, Irina Misetckaia (IMBP), Varna, 2006

Fig. 43. The first meeting in Bulgaria on *Liulin-MO* dosimeter of FREND instrument on *Exo-Mars 2016* TGO, Sofia, 2013. In the foreground: Alexey Malakhov and Maxim Mokrousov (IKI RAN), in the background — SRTI-BAS participants of the project

CONCLUSION

The 50-year-long partnership between IKI and Bulgaria in space research resulted in a number of space missions and projects, many new scientific methods, instruments, and experiments, new results in space physics, solar-terrestrial interactions, remote sensing of the Earth and planets, in many lessons learned, and in real friendship between generations of colleagues from both countries.

Let us work in the future together to extend what we reached and to get to new horizons.

Happy 50th anniversary, IKI!

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CHINA-RUSSIA JOINT MARS EXPLORATION PROGRAM YH-1

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INTRODUCTION

November 2004, an email received by Dr. Chi Wang from IKI. His friend Prof. Georgy N. Zastenker invited China to take the piggyback launch opportunity of *Phobos Sample Return* to the earth magnetosphere. Chi went to my office and ask me how should he reply. This is the beginning of *Yinghuo 1* (YH-1).

My first reaction was, why not we go to Mars with together with *Phobos Sample Return*? In 2004, China did not have any program for Mars. The lunar program was at the very beginning. CE-1 had just been approved and started. It was clear that there was almost nobody who dared to think about a mission to go to Mars. We then immediately organized a few small meetings to discuss the possibilities. The discussion were also carried out with our friends at IKI. The conclusion was that it may be possible, but we need a face-to-face meeting with the spacecraft system manager at Lavochkin Association. With the help of IKI we soon received the invitation from Lavochkin and went on the trip to Moscow.

In the beginning of 2005, in January, Moscow was dark and cold. Snow was packed on the side of the main road. The height was about one meter. We were arranged to stay in a hotel near the airport. The second day, we met with the president of Lavochkin Association Mr. Georgy Polischuck* and the chief designer of *Phobos Sample Return*, Mr. Maxim Martynov. We presented our proposal. It was a microsatellite to be released in the Martian orbit at the beginning, when *Phobos Sample Return* s/c would have been inserted to the Mars orbit. It should be an elliptical orbit that would then allow us to measure the Martian space environment from low altitudes to high, and possibly cross all the boundaries. The instruments aboard our s/c would be a flux-gate magnetometer, a particle detectors, which can measure both electrons and ions. None of previous missions, to the best of our knowledge, had done thorough measurements of both magnetic fields and plasma at the same time. The third instrument would be very interesting. We proposed a radio occultation measurement experiment with *Phobos Sample Return* to measure parameters of Martian ionosphere. The joint experiment would explore the Martian ionosphere profile at both noon and midnight local time. Both are extreme local time for ionosphere representing the highest and lowest ionization of the Martian atmosphere, and were never investigated before. Lavochkin was enthusiastic about our proposal. It was accepted, but the mass allocated for the s/c from the launch was only 110 kg.

After we returned back to Beijing, we sent a formal proposal to China National Space Administration (CNSA). The proposal was accepted in principle and we were required to do some detailed studies. This was done with the participation of Shanghai Academy of Space Technology (SAST). By the end of the year, the mission was formally approved.

In the following sections, I will introduce the details of the mission particularly on the science part, starting with brief review of the history of Mars space environment measurement. The following sections give the scientific objectives of the YH-1, its scientific payload, and describe briefly the development of the project.

* Until 2010 — *ed.*

A BRIEF DESCRIPTION OF THE MARTIAN SPACE ENVIRONMENT REVEALED BY HUMAN BEINGS

With the help of probes performing fly-bys over Mars, orbiters around the planet, and the landers on its surface, in 40 years human beings have obtained some fragmentary and preliminary knowledge on the Martian space environment [Nagy et al., 2004].

After the USSR experienced several failures, the United States used the window of November 1964, launched two probes (*Mariner 3* and *4*) to perform a close fly-by. *Mariner 3* failed, but *Mariner 4* became the mankind's first Mars probe to take pictures of the planet and its atmospheric features from a close distance. On 14 July 1964, *Mariner 4* flew over Mars at the distance of 9920 km from the surface, sent back 22 pictures of Mars, and revealed the surface feature of a large number of impact craters. The results of this exploration indicate that around Mars there is an atmosphere composed mainly of CO_2. The atmospheric pressure on the Martian surface was estimated in the range of 500–1000 Pa. *Mariner 4* has detected also a small number of features of the magnetic field on the Martian surface.

In November 1971, *Mariner 9* entered its orbit and became the mankind's first successful Martian orbiter. In its about 2-year-long operation, *Mariner 9* obtained a great deal of information about Mars, and explored the composition and pressure of the Martian atmosphere with higher precision. As its most important achievement, by means of satellite-ground occultation, it obtained the electron density profile of Martian ionosphere for the first time (Fig. 1).

Having arrived on Martian surface in July and September 1976, respectively, the landers of *Viking 1* and *2* have got more important findings. In the landing course, they have measured the atmospheric profiles of Mars (Fig. 2).

The exploration data indicated that the Martian atmosphere can be divided into 3 layers, namely low, intermediate, and high layers. The high-layer atmosphere is located above 110 km, also called the hot layer. It is heated by solar ultraviolet rays. Upward from the height of about 120 km, the hot layer begins to be ionized, and it is the Martian ionosphere, as shown in the first diagram. The electrons in the ionosphere are mainly contributed by CO_2. As their energies mainly come from the solar ultraviolet radiation, so the electron density in the ionosphere varies with the solar activity.

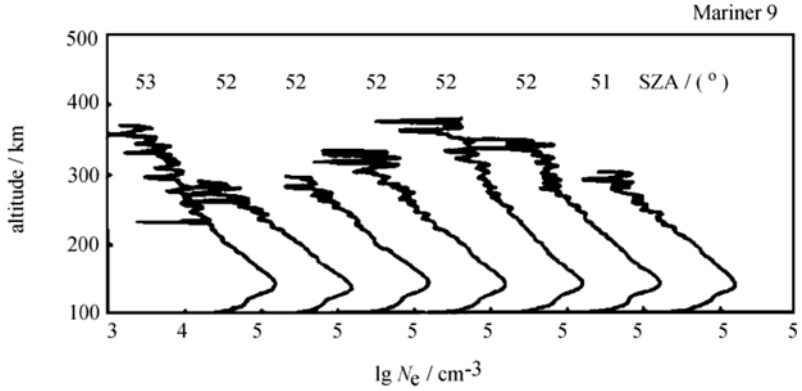

Fig. 1. The electron density profile of Martian ionosphere measured by using the satellite-ground occultation technique and *Mariner 9*

Accordingly, we can infer that the region of maximum ionospheric electron densities should be in the sky above the local noon on the sub-solar side. But this suggestion is to be verified by observation data. Now, it is not yet known whether the ionosphere exists above the midnight region of the anti-solar side of Mars.

The *Mars Global Surveyor* (MGS), launched in 1996 by the USA and inserted into its orbit in Sep. 1997, carried out very successful exploration program. Up to November 2006, MGS had operated for 10 years in the orbit around Mars, and obtained the global magnetic field distribution of the planet (Fig. 3).

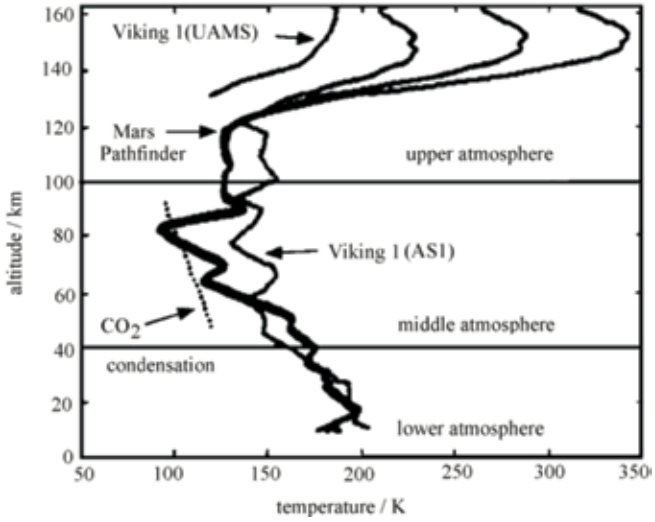

Fig. 2. The atmospheric profiles of Mars measured during the landing courses of the landers of *Viking* and *Mars Pathfinder*

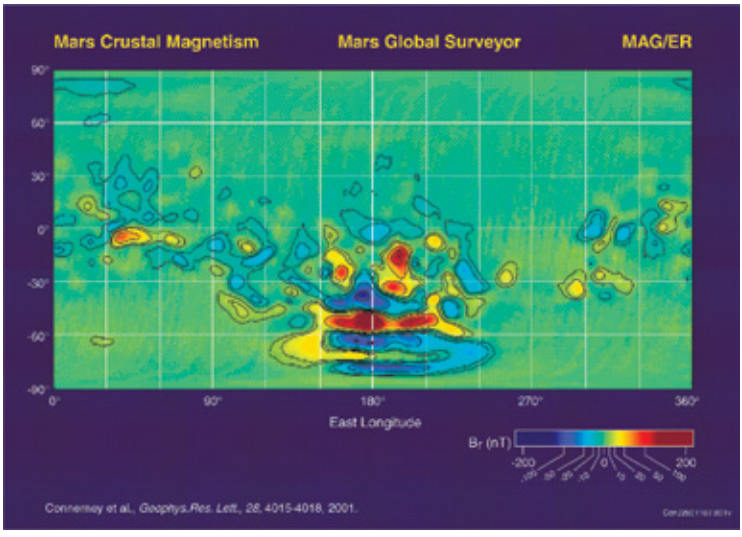

Fig. 3. The global magnetic field distribution of Mars measured by MGS

It shows that unlike Earth, Mars has no intrinsic magnetic field, and its observed magnetic field distribution is caused mainly by the remnant magnetism of rocks. In some regions these magnetic fields are rather strong, reaching 1600 nT. Such complex magnetic field structure can strongly influence the global structure of Martian ionosphere and its dynamical processes. Hence, Mars may have an ionospheric structure more complex than all other planets. To a certain extent, the Martian remnant magnetism changed the structure of Martian ionosphere. Then, Martian ionospheric plasma, surface remnant magnetic field, and the magnetic field induced by solar wind probably may interact with each other. At the same time, rather rapid rotation of Mars makes the structure of magnetic field even more complicated [Acuña et al., 1998, 1999].

The Soviet *Phobos 2* probe [Sagdeev, Zakharov, 1989; Zakharov, 1992], that was launched in July 1988 and entered orbit in March 1989, was the most successful Mars exploration program of the USSR. Because of its comprehensive payload, which included detectors of magnetic fields, particles, and electrons, *Phobos 2* managed to make important discoveries even in its not-too-long lifetime of only 3 months. According to the observed data of *Phobos 2*, it was roughly estimated that the average escape rate of the oxygen ions in the magnetic tail of Mars can reach $2 \cdot 10^{25}$ s^{-1}, namely 0.5 kg/s. In addition to the escape of other components, the total escape rate of ions will be 1 kg/s at least. According to this rate, in a period shorter than 10^8 years, all oxygen in the Martian atmosphere will escape out, and in $4.5 \cdot 10^9$ years Mars will lose the amount of water enough to make a layer 1-meter thick.

The plasma detector package on *Mars Express* probe of the European Space Agency has also made significant advances in our knowledge about the planet. It detected the solar wind-driven escape of Martian ions, acceleration by the field-aligned electric field, the escape rate of Martian ions, etc.

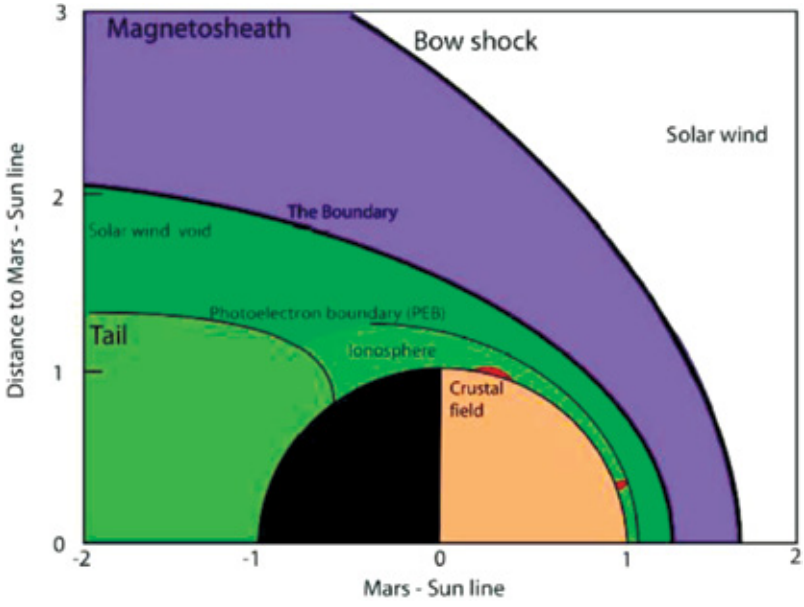

Fig. 4. The macroscopic space environment of Mars

Mars Express discovered that the solar wind penetrates directly into the high-layer atmosphere at the subsolar point, and that this phenomenon is related with the magnetic anomaly on the Martian surface [Lundin et al., 2004]. Its updated measurements on the escape rate of Martian ions indicate that water on Mars may exist in the form of underground ice [Barabash et al., 2007]. *Mars Express* made new measurements of the escape rate of oxygen ions, and obtained a result less than that of *Phobos 2*.

Extending upward from the Martian ionosphere to the interacting region with the solar wind and comparing space environment characteristics around the Earth with those of other planets, using the fragmentary exploration results available now, we can build a general macroscopic concept about the space environment around Mars.

First, neutral components of the escaping Martian atmosphere are ionized by solar UV-radiation or high-energy precipitating electrons, and form the ionosphere. Because of the very weak intrinsic magnetic field of Mars (less than 5 nT), thermal plasma in the Martian ionosphere will interact directly with the solar wind.

As the conducting ionosphere is situated in the moving magnetic field of the solar wind, the electric current is produced in the ionosphere, and it causes in turn the induced magnetic field. This magnetic field does not let the solar wind plasma and magnetic field to penetrate lower than several hundred kilometers over the Martian surface. Thus blocked solar wind decelerates and is deflected, forming a bow shock in the upstream of Mars. The region between the bow shock and the ionosphere is the magnetosheath. The limited observations revealed that the blockage of the solar wind happens at the very low positions near the subsolar point, and that the height of the bow shock wave is about 1700 km (about 0.5 Martian radius). The macroscopic space environment of Mars is shown in the Fig. 4.

SCIENTIFIC OBJECTIVES OF YH-1

Considering the insufficient human exploration on Martian space environment and fully using the merit of the large elliptical orbit of YH-1, the scientific objectives of YH-1 were determined as follows:

1. To detect and measure Martian space magnetic field, ionosphere, particle distribution and their variations

By using the magnetometer, the distribution and structure of Martian space magnetic field, as well as their variability with the solar wind may be detected. With the plasma detector package (including the electron analyzer and ion analyzer) and magnetometer, the Martian bow shock, magnetosheath, magnetic field pile-up region, the ionospheric particle distribution and its response to the solar wind disturbances, as well as variabilities may be explored.

It was proposed to use satellite-satellite occultation observation to study the inversion of the electron density distribution of the Martian ionosphere. It would be performed using transmission signal of the Russian *Phobos Sample Return* probe, and the satellite-ground occultation observation would be also made by using the downlink telemetry signal of YH-1. Particularly, the satellite-satellite occultation observations in the ionospheric region at about noon, while the zenith angle of the Sun is less

than 43° and in the region about midnight, while the zenith angle of the sun is greater than 138°, would be made. Thus, we could study the features of these extreme ionospheric regions and the generation mechanism of the sun-backward Martian ionosphere.

Comparing these data with other, we may obtain the long-term ionospheric/atmospheric data over the equatorial regions near the Martian dawn and evening sides by the satellite-ground occultation observations. Besides, we could understand the behavior of the Martian global ionosphere, including the effects of the magnetic field, solar activity, the interaction with the solar wind, dust storm, etc. In addition, by referring to the plasma and magnetic field data gathered by Russian *Phobos Sample Return* probe, the two-point joint explorations of the Martian space magnetic field and particle distribution can be accomplished.

2. To estimate the escape rate of Martian atmospheric ions

The plasma detector package would be used to detect the escape rate of Martian atmospheric ions. Together with the data on magnetic field, physical processes of the atmospheric erosion, and the transportation mechanism, as well as the effect of the interaction between the solar wind and the Martian atmosphere on the loss of Martian water would be studied.

In the Martian ionosphere, ions are transported from the lower to the upper layer and then escape. These mechanisms are closely related to Martian atmospheric erosion and water loss. To study the effects of the solar wind on the heating and driving off of the Martian atmosphere is of important significance to understand the evolution of the Martian atmospheric environment and the Marian atmospheric erosion. The study of ion escape is helpful to understand the main evolutionary characteristics of the Martian crustal environment in the past 4.5 billion years.

3. To explore Martian topography, landform and dust storms

With light and small optical camera aboard YH-1, the explorations of the Martian large-scale topography, landform, and dust storms would be carried out, and the first group of Chinese observational data on Martian topography, landform, and dust storms would be obtained. Then we could study the driving mechanisms of the formation and evolution of the asymmetrical Martian topography, the topographic features of the Martian surface and its evolution, the origin and geologic evolution of Mars, as a clue to evolutions of other Earth-like planets, as well as the origin of Martian dust storms and their effects on the Martian ionosphere and space environment.

4. To detect Martian gravity field

The available models of Martian gravity field are mainly based on the orbital and altimetry data of the *Mars Global Surveyor* and small amount of data from *Mars Express* and *Mars Odyssey*. But because of their polar orbits, the derived high-order zonal harmonic terms of the gravity field are mixed with the equally even or odd low-or-

der zonal harmonic coefficients, therefore it is difficult to separate them from each other — hence, so-called lumped phenomenon exists.

YH-1 would have had an approximately equatorial (its orbit inclination is less than 5°) and highly eccentrical orbit. Different combinations of zonal harmonic terms would have led to different orbit disturbances, if the orbital data of YH-1 had been analyzed together with the orbital data of the probes with different orbital inclinations and eccentricities. Then even terms and odd terms, high-order terms and low-order terms could be fairly separated to improve the accuracy of the Martial gravity models. Especially for low-order terms and gravity field near the equatorial plane, YH-1 would have played an important role. For examples, the three Martian principal moments of inertia (A, B, C) and the Martian tidal parameters could be derived and used for the inversion and study of the Martian interior structure. By observing the on-orbit YH-1 one year through, the accumulated orbital data could be used to study the exchange between the Martian atmosphere and the ice cap (about 1/4 of the atmosphere participates in this process), and to compare, test, and put constraints on Martian atmospheric circulation models.

PAYLOAD OF YH-1

The main scientific objectives of the YH-1 Mars probe were the detection and study of the Martian space environment. Hence, for the choice of its payload, the main considerations were the measurements of the Martian space magnetic field parameters, as well as plasma energy and mass spectra.

Table 1. Engineering parameters of the scientific payloads of YH-1

Device Name	Weight [kg]	Size [mm]	Power Consumption [W]	Technical Specification and Function
Plasma package	3.5±0.5		12±1.6	0.02–10 keV Measurements of the directivity, energy spectrum, and composition of Martian space particles, plasma distribution, ion escape
Ion analyzer I	0.6±0.1	132×72×91		
Ion analyzer II	0.6±0.1	132×72×91		
Electron analyzer	0.6±0.1	132×72×81		
Electron box	1.7±0.2	200×200×50		
Occultation receiver	⩽3.5		⩽18	Ionosphere occultation observations at Martian noon and midnight, electron density distribution
Antenna	⩽1.5	860×560×40		
Electronics box	2.0±0.2	200×180×70		
Optical imager	<1.5	100×100×150		Optical imaging of Mars, dust storm observation, required spatial resolution <500 m
Magnetometer	2.5±0.1		7±0.2	0.01 nT resolution, 3 components, measurements of the Martian space magnetic field and its structure
Electronics box	2.0±0.1	270×210×60		
Detectors A, B	0.256, 0.235	120×60×50		
Total	11.3			

Among the chosen instruments, the plasma detector package was one of the most advanced plasma detectors in the world. They were adaptive to the spin or 3-axis stabilized satellite platforms, suitable for detection of the angular distribution and energy spectrum of space plasmas, as well as the ion mass. The detection accuracy of the high-precision fluxgate magnetometer was 0.01 nT, reaching the advanced level of world fluxgate magnetometers. The satellite-satellite occultation receiver in cooperation with the Russian *Phobos Sample Return* probe would be used mainly to detect the ionospheric electron densities at Martian noon and midnight, expecting to fill up the gaps of Mars ionosphere explorations. The light and small optical imager would take moderate-resolution images of Martian surface features along with global images.

Main parameters and technical specifications of the above-mentioned payload are summarized in the Table 1.

1. Plasma Detector Package

According to the observed data of several previous spacecraft, such as *Phobos 2* and *Mars Express*, the main ionized species in space around the Martian magnetosphere are H+,O+,O+, CO+, etc. The particle energies are mainly concentrated in the range from 22 eV to several keV [Barabash et al., 2007; Lundin et al., 2004]. In order to meet the above scientific objectives, the plasma detector package had to satisfy the following requirements:

- energy range: $\leqslant$0.02 keV, $\geqslant$10 keV;
- number of mass groups: $\geqslant$6;
- time resolution: 8 s.

The plasma detector package consisted of 4 parts: the ion analyzer I, ion analyzer II, electron analyzer and electronics box. The two ion analyzers were symmetrically installed outside the cabin, responsible for the energy, angle, and composition measurements of ion component. The electron analyzer was installed outside the cabin, responsible for the energy and angle measurements of electrons. The electronics box was put inside the cabin, and consisted of two parts, namely the circuit board of the data processing unit of ion analyzers, and the circuit board of the data processing unit of the electron analyzer. The specifications of the plasma detector package are listed in Table 2.

Table 2. Specifications of the plasma package of YH-1

Name	Electron	Ion I	Ion II
Energy [keV]	0.02–10		
Energy resolution [%]	15		
Mass resolution [M/ΔM]	none	6 mass groups	
Angular resolution [°]	9×15	15×360	
Field of view [°]	9×90	90×360	
Temporal resolution [s]	8		

2. Fluxgate magnetometer

Its main function was to measure the magnetic field in the Martian space environment. As the intrinsic magnetic field of Martian globe is very small, so the interaction between the planet Mars and the solar wind is very different from the interaction between the Earth and the solar wind. Therefore, the induced magnetosphere caused by the interaction between Mars and the solar wind differs fundamentally from the terrestrial magnetosphere in both scale and structure.

The magnetometer consisted of: magnetometer detector A, detector B and electronics box. In order to improve the measuring accuracy and reduce the interference of the satellite's remnant magnetism on the sensors, two 3-axis high-accuracy magnetometer detectors (the magnetometer detectors A and B) were installed on the satellite. By using the difference of their installation positions and a suitable data processing, the interference of the satellite's remnant magnetism could be eliminated.

Magnetometer parameters:

- mechanical perpendicularity of the 3 axes: $\leqslant 2''$;
- spectrum noise level at 1 Hz: $\leqslant 0.01$ nT·Hz$^{-1/2}$;
- total noise in 10 Hz bandwidth: $\leqslant 0.1$ nT(rms);
- resolution: $\leqslant 0.01$ nT.

The fluxgate magnetometer consisted of the 3-axis fluxgate sensor and electronic circuitry. The sensor consisted of a secondary coil surrounding an inner primary coil, wound around a magnetic core.

3. Occultation receiver

The principle of the radio occultation observation of the Martian ionosphere was to take the ultra-high frequency beacon signal (833 MHz/416.5 MHz) of the Russian *Phobos Sample Return* probe as the radio source of the occultation observation, to receive this signal by the occultation receiver installed on YH-1 and record the carrier phases L_1 and L_2 and the amplitude, when the radio signal was occulted by the Martian ionosphere. Electron density profile and total electron content of the Martian ionosphere would have been derived on the Earth after processing;

Occultation receiver included antenna and electronics box. The parameters:

- sensitivity: $\leqslant -145$ dBW;
- measuring accuracy of carrier phases: 1/100 cycle (0.02 m);
- sampling rate: 10 Hz;
- antenna polarization: linear polarization;
- operating frequencies: 833 MHz, 416.5 MHz

By VLBI observations the accurate positions of the YH-1 probe and the precise orbit of the Russian *Phobos Sample Return* probe could be obtained. On the ground, based on the measured carrier phases L_1 and L_2 at the two frequencies, the slant total electron content (TEC) along the propagation path of radio waves could be obtained, the bending angle α can be derived from TEC, then by the Abel transform the refraction indices could be derived, and finally the electron density profile would be obtained from refraction indices.

4. Optical imager

The optical imager consisted of optical lenses and electronic system. It would have started its operation after the spacecraft had entered the designed orbit. It could take pictures of two-satellite separation and Martian surface in multiple kinds of modes, and transmitted image data to the data management subsystem. The main technical specifications of the optical imager were:

- effective pixels: $\geqslant 4 \cdot 10^6$;
- imaging requirements: Mars basically fills up the field of view when Mars is at 10^4 km distance, and the pixel resolution at peri-martian distance is better than 0.5 km;
- image buffer storage: over 10 frames of fully resolved pictures;
- the signal-to-noise ratio: $\geqslant 30$ dB.

The optical imager was a high-performance miniaturized imaging equipment for dynamical objects, hence the high-resolution imaging device and an integral synthesized design of the optical, structural, and electronic system was adopted, to meet scientific objectives of the acquirement and monitor of high-resolution images.

DEVELOPMENT OF YH-1

From the government approval to the launch window of 2009, there were only 3 years. The engineering team in China worked very hard. SAST was the system leader of the development, while National Space Science Center (NSSC, called Center for Space Science and Applied Research, CSSAR, at that time) was the user and made science payload and also the ground operation center.

The main difficulty for us, both SAST and NSSC, were the low temperatures YH-1 may encounter on its intended large elliptical orbit. The s/c could run into the shadow of the Sun around apo-Martian, which may last for 3 hours. Accordingly, the s/c temperature could decrease 30 degrees lower than on the sunlit side. For instruments outside of the s/c, like the sensor of FGM, the temperature could go down to −180 °C.

In order to test the s/c design, SAST built a new facility for this special low temperature test. Fortunately, the design was approved. After this uncertainty removed, the development speed increased. Finally, we had everything ready for shipping to Moscow by April 2009.

June 18, 2009, YH-1 s/c arrived to Moscow. It participated in the joint test. All figures showed that YH-1 was ready for launch. Middle of September, we were informed that *Phobos Sample Return* was delayed and cannot be launched within the next launch window to Mars. YH-1 was then shipped back to China. The next launch window was scheduled for November 2011.

To keep a spacecraft in storage is not simple task. After YH-1 returned to China, we did a lot to increase the reliability mainly by keeping all electronic systems in the working status. January 2011, YH-1 was shipped to Moscow again. Until its launch, YH-1 did not have any problem during tests. It was then shipped to Baikonur launch site in Oct. 2011.

At 4:16 9 November, 2011, *Phobos Sample Return* and YH-1 were launched by *Zenith-2SB* from Baikonur and soon reached the low earth orbit. From the first orbit

telemetry, YH-1's data were perfect. Unfortunately, *Phobos Sample Return* cannot ignite its engine and leave the low earth orbit. It re-entried the Earth atmosphere in January 2012.

FINAL REMARKS

YH-1 was the first Chinese Mars exploration program. Under the frame of China-Russia cooperation, we obtained an opportunity to carry out the exploration of Martian space environment from large elliptical equatorial orbit. During its development, we built a very good relations with the Russian scientists and engineers. Unfortunately, the mission failed during the departure from the Earth orbit to Mars. As another example of a unsuccessful human space exploration, we experienced not only the depress and sorrowful feelings of failure, but also the feeling that Mars is so far from human beings and so still is a mystery beneath the curtain.

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PLASMA ERUPTIONS FROM THE EARTH TO THE STARS — PERSONAL JOURNEY OF COLLABORATION WITH THE IKI

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In order to understand eruptions of the collisionless plasmas of the Universe — from magnetospheres to stellar atmospheres and beyond — it is important to take into account collective nonlinear dynamics of charged particles and their interaction with the self-generated electromagnetic turbulence. I am happy that I had a chance to collaborate closely on these issues with scientists of one of the worldwide leading space research centres, of IKI. In addition to our common theoretical investigations of the nonlinear particle dynamics, plasma turbulence, and eruptions we worked together on space missions like *Interball*, *Geotail*, *Cluster*, and *Roy* to explore space plasmas in the Earth's magnetosphere. Now we are preparing a new generation of missions to the Sun, *Solar Orbiter* and *Interhelioprobe*, which started with the INTERHELIOS proposal developed by German and Russian scientists together. This is a logical next step towards understanding eruptions in the Universe. Obviously there are commonalities of magnetospheric and solar eruptions, but also differences if one looks closer at the physical processes involved. I review a few of the results we obtained together during years of a fruitful collaboration with IKI and its scientists.

PROLOGUE

First of all, my heartiest congratulations to IKI, the Space Research Institute of the Russian Academy of Sciences, on the occasion of its 50th anniversary! During this half of a century IKI scientists, engineers, and technicians turned the institute into one of the leading space research centres in the world!

In the early 1980s I met IKI scientists for the first time. It was during one of the famous international workshops on plasma astrophysics organized by IKI together with the Georgian Academy of Sciences. That time it took place in Telavi, the main city of Kakheti, from where Greater Caucasus Mountain Range can be seen. There I became acquainted with several Soviet researchers who worked at the forefront of their fields: on strong plasma turbulence and collapse, on collisionless shocks and magnetic reconnection, to name a few. That time R. Z. Sagdeev, one of the founders of the quasi-linear theory of weak plasma turbulence, was the director of the IKI. A. A. Galeev, his former PhD student, was the head of IKI's space plasma department. A. A. Galeev himself already worked closely together with the next generation of plasma physicists. Several of them were at the Telavi meeting. For instance, L. M. Zelenyi who just in 1976 published a paper together with A. A. Galeev about the possibility of spontaneous reconnection instabilities, which could cause geomagnetic substorms. It was impossible to underestimate the value of this intriguing finding if it could be confirmed.

Note that in the 1970s the realm of magnetic reconnection was still very much disputed. J. Dungey had started this controversial discussion in 1961, when he suggested that the magnetosphere of the Earth taps the interplanetary magnetic field by

magnetic reconnection. The gained energy they would then be released in the Earth's magnetotail, again by magnetic reconnection. The second reconnection could accelerate charged particles towards the Earth, powering the aurorae (Fig. 1).

Indeed, using IMP-1 measurements N. Ness (1965) discovered a finite normal magnetic field component in the direction perpendicular to the mid-plane of the geotail. B. Coppi and co-workers calculated in 1966 the properties of a collisionless plasma, tail-tearing instability, which might be behind the observed eruptions called substorms (Fig. 2).

The [Coppi et al., 1966] idea was that tail current-sheet tearing could be due to inverse Landau damping on the electrons. Spatial scale and growth rate of such collisionless "electron tearing mode" instability would be, however, very small. K. Schindler (1974) suggested a faster growing ion tearing mode instability due to an inverse Landau-damping on ions. In fact, thermal ions meander across the tail mid-plane on so called Speiser-orbits while thermal electrons stay gyrotropic (Fig. 3).

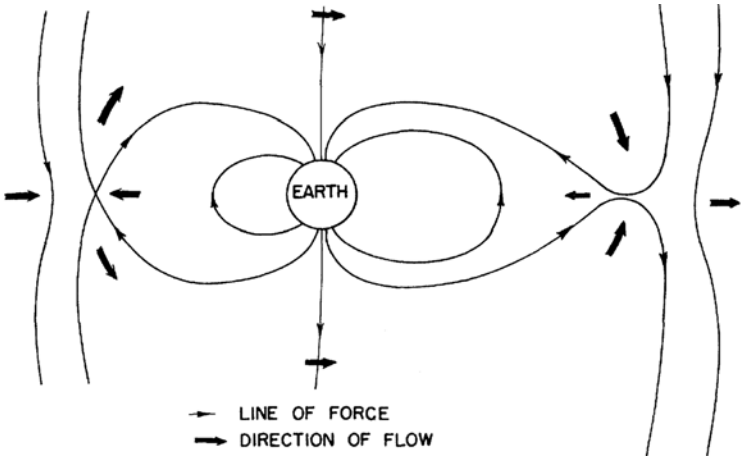

Fig 1. Reconnection at the day- and nightside of the earth's magnetosphere (from [Dungey, 1961])

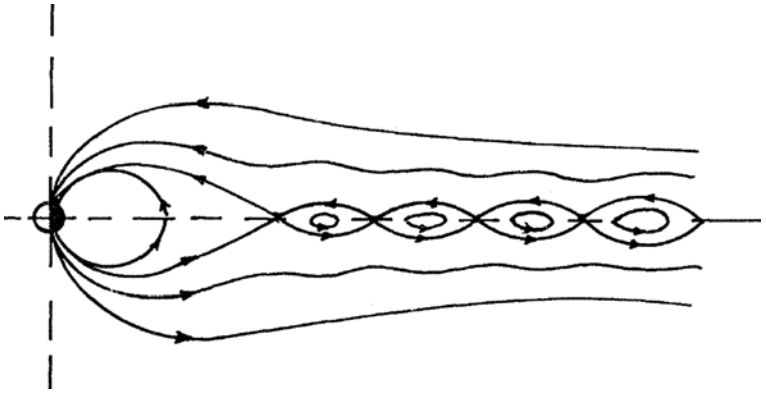

Fig. 2. Tearing mode instability in the Earth's magnetotail due to electron Landau damping [Coppi et al., 1966]

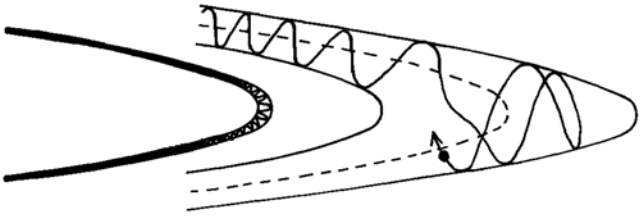

Fig. 3. Electrons (left) stay gyroscopic while ions meander across the magnetotail current sheet, possibly allowing an ion tearing mode instability [Schindler, 1974]

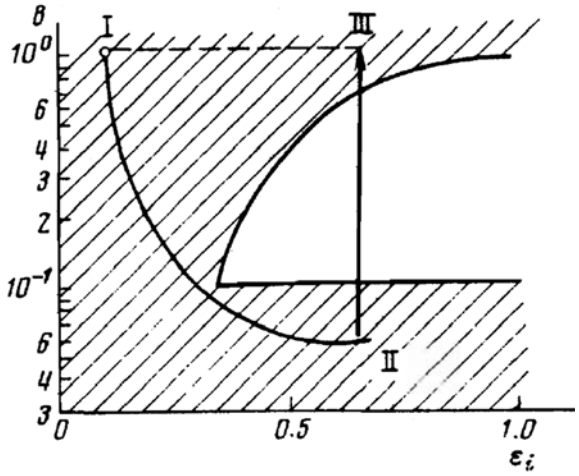

Fig. 4. Schematics of a substorm scenario in current sheet thickness epsilon = *RhoI/L* while B denotes the normal to the sheet magnetic-field component [Galeev, Zelenyi, 1976]

After K. Schindler's suggestion of an ion tearing mode instability, A. A. Galeev and L. M. Zelenyi in 1976 found, however, that electrons, which stay gyrotropic, can stabilize the tearing mode and inhibit its growth. In the parameter space spanned by the tail current sheet thickness (normalized by the thermal-temperature ion Larmor radius) and the normal to the sheet magnetic field component (normalized to the ambient field strength) they, however, seemed to have found a gap for an instability. The existence of such gap would lead to a substorm scenario as illustrated by Fig. 4.

During a substorm growth phase the tail stretches, remaining in a stable equilibrium (from point I to point II in Fig. 4). After reaching a threshold an ion tearing instability would take place causing a substorm (white gap from II to III in Fig. 4). Finally, during the substorm recovery phase the tail would return to a metastable state (from point III back to point I in the Figure). In 1982 B. Lembege and R. Pellat estimated the energy needed to compress the gyrotropic electron gas alone (left orbit in Fig. 3). They concluded that in a 2D configuration stabilizing influence of the magnetized electrons prevails. They argued that, therefore, in a magnetic field typical for the tail fast ion tearing mode instability cannot take place. And the reason would be that energy needed to compress the electron gas exceeds the free energy available on their flux tube via inverse Landau damping of growing ion tearing mode instability.

After [Lembege, Pellat, 1982] it was, therefore, still not clear what destabilizes the Earth's magnetotail. Hence, no first-principle prediction was possible of the substorm onsets. Still, the conditions had to be found for which the incompressibility of the electron gas is broken and the reconnection electric field is balanced in collisionless plasmas. For example, electrons could be scattered out of their adiabaticity by resonant interactions with plasma waves and turbulence while turbulent, so-called "anomalous", resistivity could balance the DC electric fields of reconnection. Indeed, one could expect that the tail plasma is turbulent with all the excess of free energy, e.g., in the current sheet, prone to excite plasma instabilities. In my home institute, the Heinrich-Hertz ("Central") Institute for Solar-Terrestrial Physics (ZISTP) we analysed, e.g., whether unstable lower hybrid waves could do this job [Büchner, Lehmann, 1984].

A unique chance arose to investigate directly the magnetospheric plasma turbulence: the international space mission *Interball*. The *Interball* science program was led by IKI scientists, first by A. A. Galeev and later by L. M. Zelenyi. My German colleague H. R. Lehmann agreed with IKI a German participation in this project, which was supplying the electronics for an instrument able to measure electron and ion flow fluctuations. The optimum configuration for all the *Interball* instruments was ventilated during a workshop "Plasma Processes in the Magnetosphere", organized in 1982 by the Bulgarian Academy of Sciences in Stara Zagora. The title page of the workshop proceedings nicely illustrated the name of the envisioned space mission: it depicted an artist's view of an erupting 3D tail-tearing instability, which might form at its non-linear stage ball-like "plasmoid" structures between reconnection regions (Fig. 5).

Fig. 5. Title page of in the proceedings of the 1982 workshop on "Plasma Processes in the Magnetosphere" held in Stara Zagora, Bulgaria (left). It depicts an artist's view at the consequences of magnetic reconnection in the Earth's magnetotail: plasmoids ("balls") formed between reconnection regions (right)

The fluctuation instrument, my institute was going to contribute to the *Interball* mission, was supposed to help determining the modes of the space plasma turbulence. Can the turbulence trigger large scale instabilities of the tail? Does it suffice to balance the electric field of collisionless magnetic reconnection? In order to configure the fluctuation instruments properly, the relevant frequencies had to be estimated as well as the amplitudes of the expected modes of turbulence. I reviewed the plasma instabilities prone to turbulence. Assuming weak turbulence I estimated quasi-linearly saturation level of the turbulence following the Ansatz developed by A. A. Vedenov together with E. P. Velikhov and R.Z Sagdeev (see, e.g., [Vedenov et al., 1961]). This way I estimated a corresponding "anomalous" electrical resistivity and whether it suffices to trigger reconnection and balance the electric field in collisionless, but turbulent plasmas.

After my talk in Stara Zagora I continued to discuss these questions with L. M. Zelenyi as well as with S. I. Klimov and the members of his IKI-based wave research group like S. Savin, S. Romanov and M. Nozdrachev. IKI colleagues had already run wave packages, e.g., on the *Prognoz 8* single-spacecraft predecessor of INTERBALL. Together we looked at these observations, but could not find evidence for enhanced turbulence prior to substorm onsets (see, e.g., [Klimov et al., 1986] and the monograph by [Zelenyi, Büchner, 1988]). On the other hand, we could narrow down the frequency ranges, which had to be covered. Based on these findings, we continued to prepare at ZISTP in Berlin / Potsdam our ion- and electron-flux-fluctuation instrument IFPE/I as part of the wave-analyser ASPI on the *Interball Tail* probe [Klimov et al., 1987].

CAN MAGNETOSPHERIC PLASMA ERUPTIONS BE DUE TO CHAOTIC PARTICLE MOTION?

In parallel we continued to explore alternatives for collisionless reconnection-related eruptions in the Earth's magnetotail. What could release electron incompressibility? What could scatter particles in the velocity space breaking down the adiabaticity of their motion? The adiabaticity of particle motion can break down, if they quickly encounter inhomogeneous magnetic fields.

Tracing particle orbits and investigating the conservation of adiabatic invariants of motion by means of Poincare-surfaces of section I found conditions for which the quasi-adiabaticity of the particles meandering across the tail-midplane is broken causing deterministic chaos [Büchner, 1986]. Corresponding quasi-adiabatic invariant of motion is related to the fast meandering is broken when separatrices are reached in the velocity space, which divide topologically different types of motion. During separatrix crossing the quasi-adiabatic integrals of motion jump. The amount of these jumps does critically depend on the phase of particle motion, by which the orbits approach the separatrix. Depending on this phase the trajectories can even diverge exponentially such orbits are deterministically chaotic.

Together with L. M. Zelenyi we estimated these jumps and their consequences for a chaotization of the charged particles' motion in the tail-like magnetic field configurations [Büchner, Zelenyi, 1986]. The adiabaticity of the particle motion breaks down close to the midplane of the tail, where the field line curvature is the strongest. As a quantitative criterion we introduced the now famous "kappa"-parameter. The dimensionless "kappa" related the maximum local curvature of the magnetic field

to the minimum Larmor radius of particles under consideration. For a closer interaction between us and to investigate the consequences of chaotic particle motion for tail eruptions I went to stay at IKI for three month.

Already before, in 1984 R. Z. Sagdeev had convinced G. M. Zaslavsky to move from Siberia and join IKI in Moscow. G. M. Zaslavsky is the founder of a strong school in nonlinear dynamics and Hamiltonian chaos. Among other important results he introduced the notion of a separatrix map for theoretical studies of Hamiltonian chaos. We applied his theory to study the nonlinear properties of particle dynamics. During my three-month-stay at IKI we extensively exchanged our thoughts already with the next generation of non-linear-dynamics and chaos researchers, who had already followed on G. M. Zaslavsky, like A. I. Neistadt and A. A. Chernikov, later D. L. Vainchtein. Finally, we succeeded to derive theoretically the conditions for the onset of chaotic particle scattering in the magnetotail [Büchner, Zelenyi, 1989]; [Vainchtein et al., 2005]).

After finding an appropriate mathematical model of the chaotic electron pitch-angle scattering we used it to calculated the consequences for a possible sheet tearing and eruption after the removal of electron compressibility. The key to the onset of collisionless plasma eruptions are strongly curved magnetic fields. We derived the conditions for substorm onsets by fast ion-tearing mode instability, which should occur as soon as the thermal electrons become chaotic [Büchner, Zelenyi, 1987a] and found first observational evidence for our new approach to the old problem of magnetotail stability and substorm onset [Büchner, Zelenyi, 1987b]. Later more observational support of our predictions was obtained, see, e.g., [Pulkkinen et al., 1992] and references therein.

Together with the IKI and the Abastumani Astrophysical Observatory in Georgia led by J. Lominadze, strongly supported by the European Space Agency and the Academy of Sciences of the German Democratic Republic, we prepared and organized in 1988 in Potsdam an international workshop in the framework of the famous Varenna-Abastumani School of Plasma Astrophysics. The workshop focused on the actual theories and observations of collisionless magnetic reconnection in space and in the laboratory. Among other pioneers in the field J. W. Dungey was present. In Potsdam for the first time he drew the attention of the space plasma community at non-gyrotropic electrons causing off-diagonal elements of the pressure tensor in reconnection regions, which may balance the electric fields of reconnection even without turbulence [Dungey, 1989]. This idea was later quantitatively developed by M. Hesse, another participant of the Potsdam meeting.

During my stay at IKI in Moscow I enjoyed meeting scientists from the West, who regularly visited the Institute. For example I met there M. Ashour-Abdalla from the University of California Los Angeles (UCLA). She was very interested in our results about transition from regular to chaotic particle motion in the magnetotail. We started a fruitful collaboration with her to investigate the consequences of the nonlinear ion scattering in the magnetosphere carrying out that time numerically very expensive multi-particle calculations. For the academic year 1990–1991, just after the German uniting, M. Ashour-Abdalla invited me as a guest professor at the UCLA to use further her powerful mini-supercomputer. That time we had already discovered the separatrix tentacle effect [Büchner, Zelenyi, 1990]. It appeared to be due to modulation of the correlated chaotic scattering as I could later prove at the UCLA [Büchner, 1991].

Already together with M. Ashour-Abdalla we could show that correlation-modulated chaotic scattering causes the formation of beamlets and other structures in the ion flows of the geotail (see, e.g., [Ashour-Abdalla et al., 1991, 1993]). After that M. Ashour-Abdalla and L. M. Zelenyi continued to calculate ion test-particle trajectories in the Earth's magnetosphere using, e.g. a Tsyganenko-empirical model of the global magnetospheric field or the fields obtained by global MHD-simulations, calling this method "Large Scale Kinetics" (LSK), and compared these results with spacecraft observations of distribution functions.

But my interest was more to dwell on the factors determining the onset of plasma eruptions by taking into account electron physics. It could be, e.g., that finite magnetic guide field present in the Earth's magnetotail could influence the stability of the tail.

In order to understand better the role, which a shear of the magnetic fields can play, we had already investigated the influence of a guide field on particle chaotization in the magnetotail [Büchner, Zelenyi, 1991]. That time our collaboration was joined by the IKI PhD students M. Kuznetsova, D. Zogin and B. Savenkov. While we investigated with D. Zogin the quasi-adiabatic ion acceleration in the magnetotail [Büchner et al., 1990] and with B. Savenkov the influence of a reconnection related neutral line on transition between regular and chaotic charged particle motion [Savenkov et al., 1991] we started to investigate theoretically with M. Kuznetsova the influence of a finite shear magnetic field on the stability of collisionless magneto-plasmas in tail-like configurations. We found the growth rate of an oblique tearing mode instability, which would form winding flux ropes instead of plasmoids in the Earth's magnetotail depending on the strength of the shearing (guide-) magnetic field component [Büchner et al., 1991].

So, I was curious to understand the macroscopic consequences of chaotic particle scattering and turbulence for eruptions of collisionless plasmas in a self-consistent way. Hence, I started to solve Vlasov equations of collisionless plasmas together with the field equations by solving them numerically, because a self-consistent analytical solution for the macroscopic (in)stability of real systems cannot be found in practice. Instead I started to utilize particle-in-cell (PIC) codes and such, directly solving Vlasov equations, to investigate nonlinear and nonlocal feedback of chaotically scattered particles and self-generated plasma turbulence on macroscopic plasma stability and possible onset of eruptions.

SELF-CONSISTENT NUMERICAL SIMULATIONS OF ERUPTIONS, INTERBALL, CLUSTER, AND THE TSSSP GROUP

During a guest professorship at the UCLA 1990–1991 for me an opportunity arose to develop self-consistent kinetic simulations of space plasma eruptions back home in Germany. In 1992 G. Haerendel of the (Garching-based) Max-Planck-Institute for Extraterrestrial Physics (MPE) founded a new external department ("Außenstellle") of the MPE, to which he invited me to launch there my Max-Planck-"Theory and Simulation of Solar System Plasmas" (TSSSP) group. The TSSSP group was soon joined by the late J.-P. Kuska, who developed for us the self-consistent, fully kinetic relativistic PIC code GISMO, and by the late H. Wiechen, who had graduated with K. Schindler in Bochum. While H. Wiechen carried out large scale MHD simulations of the global consequences of plasma eruptions, B. Nikutowski continued to compare our findings with space observations and to prepare the coming experiments.

Exciting space missions were expected to be launched soon: the IKI-led multi-spacecraft mission *Interball*, the multi-point mission ESA *Cluster* in 1995 and 1996, and the German EQUATOR-S mission of G. Haerendel in 1997. German Space Agency (DARA, later DLR) financially supported the continuation of our collaboration with IKI on *Interball*. This enabled us to invite IKI scientists to Berlin and to help, e.g., developing the *Interball* orbit analysis tool of V. Prokhorenko. Being granted project support by the European Union we could start the EMSNET network to support in particular also *Interball* science work, the development of data analysis tools and related activities of Eastern European space scientists helping them to bridge gaps in their financial support after the economical breakdown in their countries.

Meanwhile, we ourselves used PIC and MHD codes on newly obtained access to fast computers for simulation of different scenarios of substorm eruptions. Together with IKI scientists we had earlier found that a finite magnetic guide-field (-shear) might delay the onset of tail eruptions [Kuznetsova et al., 1996]. By means of PIC simulations we verified this and could show, in addition, that despite a finite magnetic guide field substorms can nevertheless be triggered by a local suppression of the cross-sheet magnetic field [Pritchett, Büchner, 1995]. Describing microscopic chaotization effects via transport coefficients, which we introduced into MHD models, we modeled the evolution of large-scale magnetotail reconfigurations in the mid-tail [Büchner, Otto, 1995] as well as in the near-Earth tail, closer to the dipolar field of the inner magnetosphere [Wiechen et al., 1997]. First, however, the cross-tail magnetic field component has to be essentially suppressed, as it indeed, can happen via redirection of the convective plasma flows in the near-Earth magnetotail.

On August 3, 1995, the *Interball-Tail* spacecraft was launched from Plesetsk together with a Czech sub-satellite *Magion*. After the commissioning phase we could together with our IKI colleagues and international collaborators, directly look for the turbulence in the tail using data of the international instrument suite ASPI [Klimov et al. 1997]. In this collaboration we obtained important new insights into the properties of the collisionless space plasma turbulence (e.g., [Büchner et al., 1998a, c; Nikutowski et al., 1996, 1998, 1999; Savin et al., 1997, 1998a, b, 1999] — but no conclusive answer to the question, whether the turbulence level in the tail suffices to cause substorm eruptions.

In 1996 G. Haerendel's plans failed to develop the Berlin external department of the MPE into a new Max-Planck-Institute for Solar System Research (MPS) and the "MPE-Aussenstelle" (external department) Berlin was closed. Before that happened I had already been invited by Sir I. Axford to move the TSSSP-group from Berlin to the Max-Planck-Institute for Aeronomy (MPAe) in Katlenburg-Lindau, which a few years later, in 2003, itself became the Max-Planck-Institute for Solar System Research (MPS). By that time the MPAe had already had an excellent track-record of successful international scientific collaboration, including IKI scientists and supplying crucial instrumentation to major space-plasma related missions like the Japanese GEOTAIL project and the ESA's *Cluster* mission.

Along this way and together, e.g., with A.A. Petrukovich of IKI, we combined the *Geotail* observations with those of *Interball*, e.g., by tracking the propagation of a reconnection pulse from the tail to auroral breakups [Petrukovich et al., 1998]. With another colleague from Moscow, A. Teselkin, we investigated the consequences of particle acceleration by reconnection, predicting the formation of multiple "lima-bean", as they were called by L. Frank, distributions [Büchner, Teselkin, 1996]. Note that these

distributions for electrons later were called "crescent-shaped" distributions. With J.-P. Kuska we also predicted the formation of cup-like structured ion flows [Büchner, Kuska, 1996]. Both were looked for as remote signatures for reconnection utilizing energetic particle observations of *Geotail* [Zong et al., 1999] using results of the RAPID instrument [Wilken et al., 2001] onboard *Cluster* [Büchner et al., 1998d].

ESA multipoint space mission *Cluster* was first proposed in November 1982. Four identical spacecraft were supposed to give the community a first chance to distinguish spatial and temporal variations in space plasmas by means of independent and instantaneous multi-point measurements. The first attempt to lift off *Cluster* was scheduled for the year of take-off of the second *Interball* (aka *Interball-Auroral*) probe, i.e. for 1996. In combination with four *Interball* satellites a success of the scheduled first *Cluster* launch would have enabled not only multi-point, but also the first multi-scale space plasma observations. Unfortunately the first ever *Ariane 5* rocket launch with four *Cluster* spacecraft aboard failed during its ascent from Kourou, French Guiana, on 4 June 1996. Fortunately, however, a new take-off was financed by the agencies, using two Russian *Soyuz-Fregat* rockets. Four *Cluster* spacecraft were finally successfully launched by two sets of two satellites on July 16 and on August 9, 2000, when two Russian rockets took off from Baikonur, Kazakhstan. In 2015 the *Cluster* mission celebrated its first 15 years in orbit, it was one of the ESA missions that generated the highest amounts of scientific publications! We contributed to them as soon as we arrived at Katlenburg-Lindau in 1997, continuing at the same time our collaboration with IKI scientists. EQUATOR-S, unfortunately, failed soon after its launch.

In 1998 Brittnacher et al. had re-examined the stabilization of the ion tearing mode instability looking for the missing free energy needed to compress the electron gas. They also analyzed the consequences of pitch-angle scattering and spatial diffusion using a finite element discretization directly incorporating particle orbits in the analysis of possible kinetic instabilities of current sheets. They confirmed that in two-dimensional geometries the pitch angle scattering alone does not allow an ion tearing mode instability. If so, only the slow electron tearing mode instability of [Coppi et al., 1966] would remain and only in the case that the normal magnetic field component across the sheet is essentially removed. All these investigations did not rule out, however, the eruptions due to enhanced turbulence, nonlinear instabilities and such, which take place in three-dimensional configurations.

I addressed these question, e.g., by developing a theory of three-dimensional kinetic reconnection [Büchner et al., 1998a]. Using PIC codes we succeeded to simulate direct transition from small scale turbulence to reconnection and the formation of large scale coherent structures [Büchner et al., 1998b]. In particular, we established a coupling between major global wave instabilities of the Earth's magnetotail current sheet and three-dimensional tearing (e.g., [Büchner, Kuska, 1997; Büchner, 1998]). We found that a sausage-mode instability of the tail current sheet can cause bulk-plasma oscillations of the plasma sheet (Fig. 6 shows the cover page of "Analysis Methods for Multi-Spacecraft Data" of 1998, which uses our results to illustrate the opportunities of four-point measurements [Büchner et al., 1998b]). We could show that such sausage-mode instability would directly couple into three-dimensional magnetotail reconnection, possibly causing substorm eruptions and forming 3D plasmoids with magnetic nulls and spiraling field lines embedding them [Büchner, Kuska, 1999]. The magnetic structure of kinetic 3D null-point reconnection made it even to the cover page of 1999 book "Plasma Astrophysics and Space Physics", edited by J. Büchner,

Sir I. Axford, E. Marsch, and V. Vasyliunas (see Fig. 7), which combined contributions of participants of the VII[th] International Conference on Plasma Astrophysics that took place in 1998 at the MPAe in Katlenburg-Lindau. There among others E. Parker was present, who very early, ten years ago, in 1988 had sent us a letter recognizing the importance of our findings about the non-linear particle dynamics for the understanding of collisionless magnetic reconnection. Our results about the structure of three-dimensional collisionless reconnection became part of the IKI's proposal of a multi-satellite-tomography oriented space mission *Roy* ([Galperin et al., 1999], see Fig. 8).

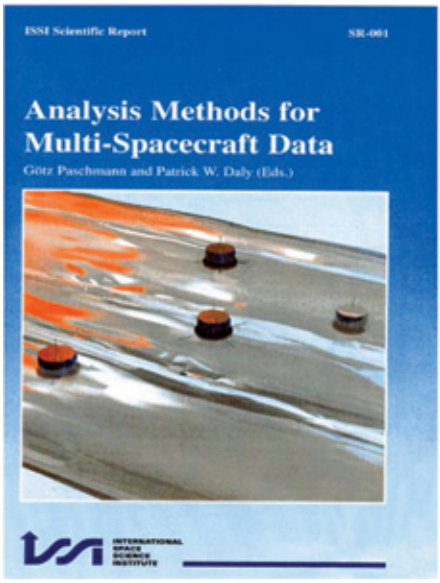

Fig. 6. TSSSP PIC-code GISMO simulation results about a magnetotail sausage-mode flapping prior to substorm onsets, used for the title page of the ESA report "Analysis Methods for Multi-Spacecraft Data" (see also [Büchner et al., 1998b])

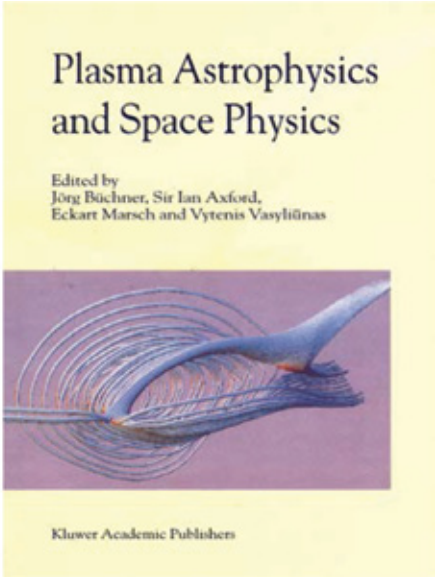

Fig. 7. GISMO simulations results of three-dimensional kinetic magnetic reconnection revealed the structure of 3D plasmoid magnetic fields as illustrated on the title page of our 1999 book "Plasma Astrophysics and Space Physics"

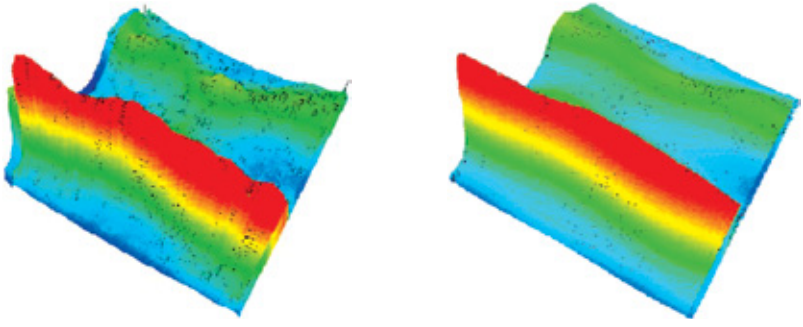

Fig. 8. Vlasov-code simulated (left) and tomographically reconstructed collisionless space-plasma current-sheet density structure — in preparation of a future *Roy* space mission (right, from [Zelenyi et al., 2000])

While we so far relied on PIC codes, it was desirable to resolve better phase space resonances by directly solving Vlasov equations. In 1999 Th. Wiegelmann, who graduated with K. Schindler in Bochum, joined the TSSSP group. He developed our first numerical code, which directly solved Vlasov equations. Using this Vlasov-code we could reliably study the coupling between the self-generated turbulence of kinetically unstable current sheets and reconnection through them [Wiegelmann, Büchner, 2000]. Together with the IKI and the group of V. E. Kunitsyn of Lomonosov Moscow State University (MSU) we used our code to simulate the presumable structure of current sheets in collisionless space plasmas (Fig. 8, left) and how it would look like, if reconstructed tomographically by observations of the planned *Roy* space mission (see Fig. 8, right). I. Silin of that MSU group later joined the TSSSP group at the MPAe. Together with him we continued our collaboration, when L. M. Zelenyi joined the TSSSP-group after being granted a prestigious Humboldt-fellowship [Silin et al., 2002]. Meanwhile, I. Silin had MPI-parallelized our Vlasov-code. This allowed us to calculate the anomalous resistivity due to lower hybrid turbulence in the magnetosphere. If parametrized by an effective "collision rate" the latter appeared to be in the lower hybrid frequency range. Later we could confirm this prediction by *Cluster* observations [Silin et al., 2005]. In those years we also closely collaborated with S. Savin of IKI on the determination of the thickness of space plasma current sheets prone to reconnection — like at the Earth's magnetopause. In 2004 his former undergraduate student E. Panov joined us for a PhD project to investigate the properties of current sheets as the outer boundaries of the magnetosphere. For this project E. Panov successfully used simultaneous observations by the four *Cluster* satellites to determine the thickness of the magnetopause current sheets (e.g., [Panov et al., 2007, 2008]).

ERUPTIONS — FROM THE EARTH TO THE SUN AND STARS

Is it possible to generalize the knowledge obtained about turbulence, reconnection, and eruptions in the Earth's magnetosphere to the Sun and other astrophysical objects?

In 1859 Lord Carrington published for the first time the conjecture that geomagnetic eruptions might be related to eruptions at the Sun. Meanwhile this relation is empirically confirmed and a new research field has emerged — that of the physics of "Space Weather" — to investigate it in its details. With this respect R. G. Giovanelli proposed already in 1946 that solar flares might be magnetic discharges in the chromosphere of the Sun — the process later called magnetic reconnection! This was well before J. Dungey in his [1961] paper suggested that magnetic reconnection is the mechanism of interaction between the solar wind and magnetospheres.

What are the commonalities and the differences between reconnection in the solar corona and in the magnetosphere?

First of all, solar coronal magnetic field is much stronger and more complex than that of the Earth. The coronal plasma-beta, the ratio of plasma to magnetic energy, is much smaller than unity, while in the magnetosphere equilibria often require a balance of magnetic and plasma pressure. The solar magnetic field is generated by dynamo processes below the surface of the Sun, while at the Earth's magnetopause solar wind and ionospheric plasmas interact, carrying magnetic fluxes frozen in the plasma flows. Magnetospheric guide fields are of the order of or smaller than the reconnecting magnetic fields, while in the solar corona a strong external magnetic (guide-) field dominates.

Second, with regard to the plasma processes charged particles of the solar corona also interact via turbulence rather than via their direct binary collisions — as in magnetospheres. The collission-based magnetic Reynolds numbers for eruption-relevant processes are even larger than in the magnetospheres, up to an order of magnitude 10^{12}. A resistive tearing instability would therefore be way too slow to explain flare eruptions. This was pointed out by E. Priest already in first textbooks. Hence, it is even more important to worry about turbulent transport in the solar atmosphere and for the understanding of the reason of eruptions. Plasma conditions and parameters are, however, different.

Hence, besides commonalities, there are also major differences. The magnetic structures, in which solar flares and geomagnetic eruptions take place, for example, are very different. The coronal field is much more complex than planetary magnetic fields. According to remote optical observations and interpreting, observed bright stripes as tracers of magnetic fields, coronal magnetic field is essentially three-dimensional. Since neither currents nor magnetic fields in the solar corona can be measured directly, methods had to be derived locating coronal current sheets using the information obtained by utilizing the Zeeman-effect for estimating the photospheric magnetic fluxes [Büchner, 2006].

In order to take into account specifics of the coronal magneto-plasmas one need to apply adjusted numerical simulation tools, which can cope with strong magnetic fluxes, their emergence through the photosphere and with the collisionless character of the plasmas. Developing such tools, we found out, e.g., that bright points in the corona are formed in places, where magnetically confined plasmas collide [Santos et al., 2008]. For data driven corona simulations one should use the magnetic fields, which initially extrapolate to the corona out of the observed photospheric magnetic fluxes [Otto et al., 2007]. To the lowest order the structure of the very complex coronal magnetic field can be described by a superposition of the fields of a multitude of sources breaking through the solar surface. The photosphere forms, therefore, a multiply connected "magnetic carpet" [Title, Schrijver, 1998]. The corresponding coronal magnetic field can be described, e.g., by a multitude of three-dimensional "domes", related to different source regions of the magnetic flux. These "domes" are divided by a skeleton of quasi-separatrix layers [MacLean et al., 2009]. Other that the three-dimensional reconnection in the magnetosphere for a typical quadrupolar photospheric magnetic field the main (parallel) reconnection electric field would extend far away from a magnetic null than being concentrated at X-line regions [Santos et al., 2011a], see Fig. 9 depicting our result on the cover page of the *Astronomy and Astrophysics*, Vol. 525, Jan. 2011. Note that according to the theory many null points should exist in the solar atmosphere, they are the joints of the magnetic skeleton.

It is still an open question, however, what triggers eruptive reconnection in the skeleton.

Generally speaking, most of the hypotheses about the onset of solar eruptions assume that in the course of stable magnetic field configurations' evolution a critical point can be reached, at which equilibrium is lost and an eruptive instability takes place (e.g. [Schindler et al., 1983; Forbes, Isenberg, 1991]). A well-known candidate for such instability is that of a lateral kink — also called "torus instability" ([Gold, Hoyle, 1960]; for a recent revival see, e.g., [Aulanier et al., 2010] or [Török, Kliem, 2015] and references therein). In order to verify this hypothesis we recently carried out corona simulations driven by observational data.

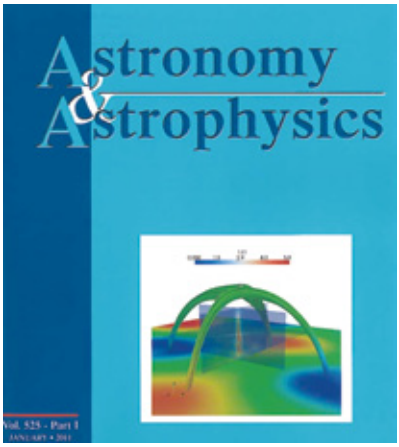

Fig. 9. Reconnection region below a three-dimensional magnetic null-point in the solar corona [Santos et al., 2011a]

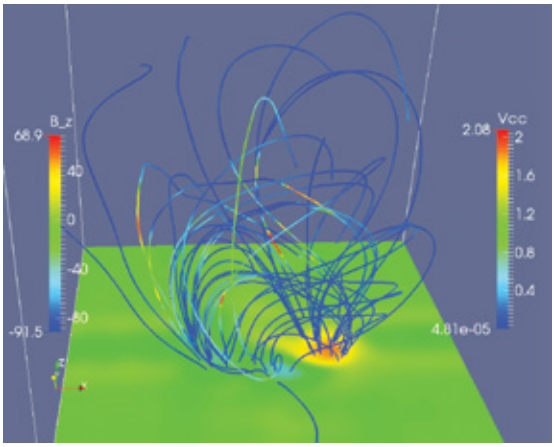

Fig. 10. Flaring loop solar magnetic field. The field lines are colored according to current carrier drift speeds, red corresponds to drifts in excess of the threshold of kinetic instabilities causing anomalous resistivity and reconnection [Skala et al., 2015]

In order to describe the corona above active regions as large as $(200\ \mathrm{Mm})^3$ and larger we used our heavily parallelized GOEMHD3 code. We started the simulations with the observed photospheric magnetic field and plasma motion [Skala et al., 2015]. In Fig. 10 one can see that in the evolving magnetic field above active regions of the Sun the current carrier velocity (V_{cc}) varies. In the Figure red-colored are regions along field lines where the V_{cc} exceeds the threshold for kinetic plasma instabilities causing anomalous (turbulent) resistivity allowing reconnection.

If one wants to take into account these plasma instabilities and turbulence, technically unobservable at the Sun, one has to develop theoretical models valid for the characteristic parameters of the coronal plasma, which is dominated by a strong external guide magnetic field. Hence, to the lowest order one-dimensional current instabilities will be excited in places, where the current-carrier velocity V_{cc} exceeds the threshold of micro-instabilities. We identified these locations by means of global solar MHD simulations, as shown, e.g. in Fig. 10, where in the red-color-indicated field regions strong plasma turbulence is expected to be generated. We investigated the properties of this strong turbulence taking into account also highly nonlinear wave-particle interactions by means of a high-resolution Vlasov-code, which would discretize Vlasov equations by means of a conservative, practically noiseless scheme to grasp the instabilities and their consequences correctly. For this sake I invited N. Elkina to join the TSSSP group after she got her PhD at Moscow Keldysh Institute of Applied Mathematics — part of which is located in the same building as the IKI. Applying the new, practically numerically noiseless Vlasov-code [Elkina, Büchner, 2006] to the solar coronal plasma we obtained the anomalous resistivity, which in solar conditions would be due to strongly nonlinear effects like formation of phase space holes and double layers [Büchner, Elkina, 2006]. To understand their macroscopic consequences we added sub-grid-scale (SGS) terms to the MHD equations. The effective (anomalous) resistivity was parametrized by a quasi-collision frequency, which

appeared to be of the order rather of the ion plasma frequency than of the order of the lower hybrid frequency typical for the magnetospheric plasma [Silin et al., 2005].

We also obtained the threshold in terms of the relative drift velocity of the current carrying particles in terms of the macroscopic MHD variables. Using these microphysical results in our corona simulations we obtained an outbreak of solar eruptions right in time as they were observed. Hence, as in the magnetosphere, microphysical plasma processes seem to be behind large scale eruptions just of different nature due to the different plasma and magnetic field conditions.

Solar eruptions release not only accumulated magnetic energy but also magnetic helicity as it was found by *in situ* observations of coronal mass ejections in the solar wind [Yang et al., 2013]. We earlier had already found, however, that the magnetic helicity is approximately conserved in the course of collisionless (kinetic) magnetic reconnection [Wiegelmann, Büchner, 2002]. Now that we were able to simulate eruptions in the corona we found out that the also accumulated magnetic helicity of the corona can suddenly locally drop [Santos et al., 2011b]. Calculations of the relative helicity evolution based on solar observations suggest that even a critical amount of accumulated helicity has to be reached before an eruption [Yang et al., 2013].

Similar to the plasma sheet of the Earth's magnetosphere we also obtained the formation of flux ropes in the solar corona. In particular, they are formed around the current sheet trailing coronal mass ejections [Barta et al., 2011a]. Other than in the magnetosphere, however, solar corona simulations revealed a whole chain of flux ropes at a variety of scale sizes, formed by cascading reconnection. Optical [Nishizuka et al., 2009] and radio [Barta et al., 2011b] observations confirmed these theoretical predictions.

Based on the experience obtained earlier, partially together with IKI scientists, in the magnetosphere we investigated the acceleration of particles in strongly curved and reconnecting magnetic fields of the solar corona. This allowed us to explain localized bright structures observed in the chromosphere of the Sun and magnetically connected to the plasma trailing coronal mass ejections [Guo et al., 2010; Zhou et al., 2015].

Detailed quantitave verification of these and other theoretical predictions requires, however, observations which lead beyond the abilities of observations of the existing solar space telescopes aboard actual missions SOHO, SDO, and STEREO.

Plasma eruptions are observed also in planetary magnetospheres and near-Earth small bodies of our Solar System. Here we don't have the place for the comparison with eruptions near the Earth and at Sun.

Plasma eruptions are meanwhile claimed to be observed also in exoplanetary systems. They were first discussed to take place at "hot Jupiters" on close-in orbits, which can actively interact with their central stars (see, e.g., [Shkolnik et al., 2003]). Such eruptions could, indeed, be due to direct magnetic interactions, releasing accumulating magnetic energy in huge interplanetary flares (e.g. [Preusse et al., 2007] and references therein).

SUMMARY AND FUTURE PROSPECTS

Plasma eruptions, which release accumulated magnetic energy, are common phenomena throughout the whole plasma Universe. First conjectured for the Sun [Giovanelli, 1946] they meanwhile have been *in situ* investigated in the magnetospheres of the Solar

System and in the laboratory, possibly also in exoplanetary systems. After a "cartoon" phase (in the 1960s) theories of the underlying reconnection process were developed passing through a "dark age of magnetospheric physics" [Axford, 1994]. Leaving behind misleading qualitative concepts, increasingly quantitative, based on high-resolution in space and time observations, multi-spacecraft *in situ* observations are interpreted using numerical solutions, more and more sophisticated mathematical models, and self-consistent kinetic plasma simulations. Numerical simulations are needed since the still local multi-spacecraft *in situ* observations as well as remote imaging alone cannot draw a complete picture. Complex, non-local and non-linear space plasma dynamics leading to plasma eruptions cannot be described mathematically by just locally solving linearized equations. Numerical simulations bridge the gap between analytical first principle based theories and their consequences for the complex non-local and strongly non-linear plasmas of the magnetosphere. Increasingly appropriate numerical simulations are needed to interpret spacecraft observations obtained in the magnetosphere by missions like IMP, ISEE, *Interball*, *Cluster*, and now also MMS.

The co-founded by M. Ashour-Abdalla series of International Space Plasma Simulation schools (ISSS) played an important role in distributing numerical code and training young scientists. Now a further improvement of the numerical simulation techniques is required to describe the microscopic plasma processes together with their macroscopic system evolution in order to interpret already existing data as well as to prepare the next generation of solar space observatories *Solar Orbiter*, *Solar Probe Plus*, and *Interhelioprobe*, of planetary magnetospheres (JUICE), of extrasolar planets (PLATO) and of the space plasma turbulence if the THOR mission will be decided in 2017.

The understanding of plasma eruptions in the Universe, in galaxies, at stars, in magnetospheres, and in the laboratory — of their commonalities and of their specifics in dependence on configurations, plasma and field parameters — is crucial and of fundamental importance for our understanding of the dynamics of the complex plasma systems surrounding us. Their investigation needs high resolution, well-coordinated multi-point and multi-channel (particles and fields, covering a broad frequency spectrum) space observations as well as improved (algorithms and hardware) numerical simulation models. All this requires the combined efforts of internationally collaborating researchers, to bring together critical amounts of human and technological resources.

In 1997, when I moved the TSSSP group to the MPAe (which later became the MPS) that institute had already a good track record of successful collaboration with IKI, e.g., by the common investigation of the comet Halley by the *Giotto* and VEGA missions in 1985. That time in the MPAe discussions were started about a common solar space observational INTERHELIOS (see, e.g., [Axford et al., 1998]) and a new multi-spacecraft mission *Roy* to the magnetosphere (see, e.g., [Galperin et al., 1999]). Out of the INTERHELIOS project later the out-of-ecliptic ESA mission *Solar Orbiter* was developed (to be launched in 2018) and its Russian pendent, two *Interhelioprobe* spacecraft (planned to be launched in end of the 2020s). With the coming remote observations of the Sun from outside the ecliptic and *in situ* observations close to the base of the solar corona the loose ends can now be brought together. For this sake, however, more theoretical investigations are necessary to narrow down the existing hypotheses by critical observations of distinguishable observables and signatures. While advanced observations of magnetospheric eruptions allow more and

more quantitative investigations, the quantitative investigation of solar plasma eruptions has just started. For them new types of numerical simulations have to be developed as an eminent research tool helping to transfer plasma-physical concepts to other space and astrophysical objects.

My experience of collaborating with scientists from Russia, the USA, and other countries convinced me how necessary international collaboration on these difficult issues is and how fruitful it can be. On the occasion of 50th anniversary of IKI I wish all of us, in particular the next generation of scientists, a chance for a continuation of a peaceful scientific collaboration, across the borders and despite of political differences as the German Chancellor A. Merkel told L. M. Zelenyi and me, when we met at the occasion of the 25th anniversary of the "Falling Walls" of the 9th of November 1989 in 2014 in Berlin.

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FIFTY YEARS OF SUBSTORM RESEARCH AND ITS PROSPECTS

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INTRODUCTION

After Akasofu had defined the substorm in 1964 on the basis a great number of all-sky images taken at high latitudes, its main ingredients have been revealed: (1) the growth phase, owed to an erosion of magnetic flux from the front-side magnetosphere and transport into the tail, connected with field stretching and plasma sheet thinning; (2) the sudden onset of strong magnetic disturbances resulting from the appearance of a large-scale current system, the so-called substorm current wedge, (3) the liberation of stored energy by reconnection in the near-earth tail, (4) the earthward transportation of energy by flow bursts, accompanied by downtail ejections of "plasmoids". This development of insights into the basic ingredients of a substorm was supported by increasingly sophisticated numerical simulations. Some fundamental problems are still under dispute: Where and how is the substorm triggered, by reconnection in the mid-tail or by instability at the inner edge of the tail? What is the generator of the substorm current wedge? How do flow bursts cope with the rising plasma pressure as the flux tube volume is shrinking? How do plasma and magnetic flux enter into the magnetosphere? How does all of this account for the morphology and dynamics of the substorm aurora? With the evolving exploration of the Solar System one has also discovered the signatures of substorms in the magnetospheres of the outer planets. While we can expect that the still open questions will soon be answered, a great challenge for future research is to understand seemingly similar events in stellar atmospheres as, for instance, during solar flares.

This is neither a research nor a review paper. It is a brief overview of the basic ingredients of what has been named "substorm" by S.-I. Akasofu 50 years ago. The substorm is the transformation of state that the magnetosphere undergoes, when open magnetic flux, eroded from the frontside and transported into the tail, returns into the closed field-line magnetosphere. "Open" and "closed" refers to the Earth's magnetic field being connected to the interplanetary field or not. This overview does not discuss the process of frontside reconnection but begins with the storage of the eroded magnetic flux in the tail, the so-called growth phase. This happens under stretching and compression of the magnetic field. The next step is the liberation of a substantial fraction, not necessarily all at once, of the flux added to the tail. It involves the onset of reconnection at a typical distance of $20R_E$ in the tail, the generation of so-called flow bursts, which transport the reconnected flux earthward, and the ejection of plasmoids in the anti-sunward direction. The first sign of it has been named the breakup phase. Inside the magnetosphere, it is connected with a dramatic onset of aurora and electron (and proton) precipitation, which expands poleward. The still existing great dispute and area of research concern the relation between what happens in the tail and what is observed at low altitudes. Particle precipitation is only one side of the earthward energy transport, the other side is the downflow of electromagnetic energy. It is connected with the appearance of a large-scale current system, the substorm current wedge, its ionospheric leg being the auroral electrojet, and the entry of magnetic flux deeper into the dipolar magnetosphere. The physical nature of the generator of this current system is another of the presently intensely discussed and unsolved problems.

In this paper, I will characterize the main ingredients of the substorm process with the assistance of some famous cartoons and other intuitively comprehensible illustrations. This implies, of course, a very personal selection leading to the unavoidable suppression of many complementary results and interpretations. The paper ends with short summaries of our present state of understanding and a look into future research.

THREE ASPECTS OF THE SUBSTORM

I characterize the substorm by three of its main aspects, the auroral manifestation, the cycle of magnetic flux transport, and the related plasma convection and low altitudes. Figure 1 was derived by Akasofu (1964) from a large number of all-sky images taken during various phases of a substorm and is thus a synopsis of the typical morphology of the aurora. Since the aurora is essentially only caused by electron precipitation, the arcs are traces of sheets of upward field-aligned currents. A decisive observation is that the substorm begins abruptly with the first brightening at or adjacent to the most equatorward located arc. This arc has moved into this location from higher latitudes during the preceding growth phase (see next section). The figure also exhibits the fast poleward expansion of the aurora in the midnight sector, whereby the most poleward arc is continuous, while behind the aurora has broken up into more erratic structures.

The substorm is a consequence of a cyclic transport of magnetic flux starting with reconnection at the dayside magnetopause, most efficiently when the magnetic field carried by the solar wind has a strong component antiparallel to that of the magnetosphere. The solar wind drags and stretches the field into the tail, which is thus loaded with magnetic energy. Eventually reconnection takes place in the central current sheet of the tail at about $20R_E$ and restores the loss of closed magnetic flux from the frontside. This is sketched in Fig. 2 as viewed in the noon-midnight meridian plane. However, returning the magnetic field is a three-dimensional process and involves transportation around the morning and evening sides of the magnetosphere. This is sketch in the inset of this figure. This sequence of events has first been proposed by J. W. Dungey (1961).

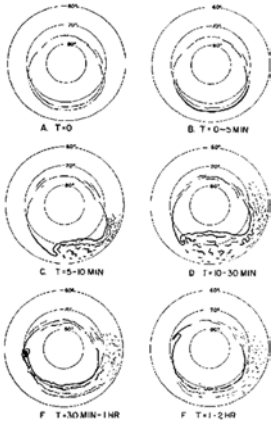

Fig. 1

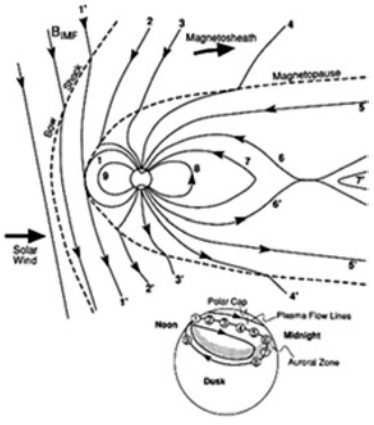

Fig. 2

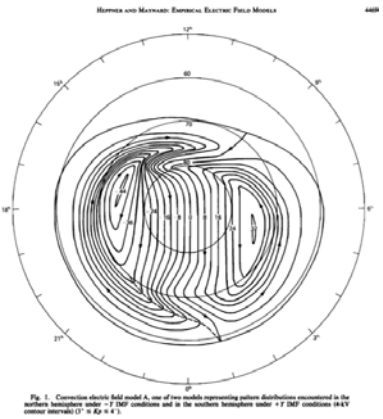

Fig. 3

The consequence of this cyclic magnetic transport in the inner magnetosphere is a convection of plasma and field, first across the polar cap under expansion of its size, until tail reconnection leads to entry into the outer near-dipolar magnetosphere and sunward convection along the auroral oval. However, since near Earth the magnetic field is nearly incompressible, any motion across the polar cap is accompanied by return flow as shown by the potential contours in Fig. 3. These are instantaneous flow lines or equipotential contours, but not traces of the actual transport of plasma and its frozen-in magnetic flux, since the convection electric field is strongly varying during a substorm. The figure from paper [Heppner, Maynard, 1987] contains a synopsis of that convection pattern during a substorm for certain conditions of the interplanetary magnetic field assembled from many electric field measurements on a low-orbiting satellite.

THE GROWTH PHASE

When for a somewhat extended period the southward component of the interplanetary field allows substantial flux transport from the front into the tail, the polar cap expands and its lower boundary in the midnight sector is pushing equatorward. This is marked by an auroral arc, the so-called growth-phase arc, which actually traces the deflection of the equatorward flow of the polar cap into two sunward flow channels along the polar cap boundary. Figure 4 [Haerendel, 2015a] shows this situation in a cartoon depicting the 3D connection between polar cap convection and tail field. The green circles and arrows mark the direction of the electric currents, while the blue arrows mark the flow vectors. The equatorward motion of the polar cap boundary is a consequence of the loss of closed, but highly stretched magnetic field from the central tail. As a consequence, the current sheet, which separates the northern from the southern tail lobe, becomes increasingly narrower. This is shown in Fig. 5 taken from [McPherron et al. 1973]. A thin current sheet is the condition for the eventual onset of reconnection in the collisionless plasma of the tail.

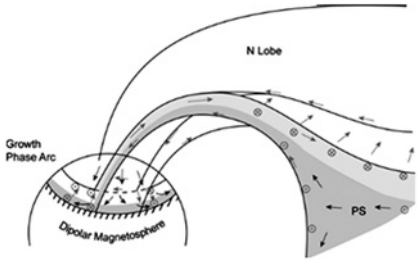

Fig. 4

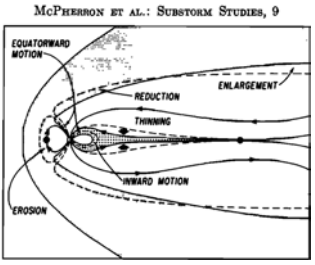

Fig. 5

SUBSTORM ONSET IN TAIL AND IONOSPHERE

Starting with the famous paper [Hones, 1979] it slowly emerged that after sufficient thinning of the plasma and currents sheets in the tail reconnection suddenly starts somewhere near $20R_E$. On the one hand, open magnetic field assembled in the tail during the growth phase is re-converted into closed field and returns into the magnetosphere, on the other hand, an equivalent of flux is ejected into the antisolar direction, often forming partially closed plasmoids. This is visualized in Fig. 6 from paper [Hones, 1979]. The formation of plasmoids and their ejection were first observed by Japan's *Geotail* mission [Nishida et al., 1997]. Needless to say that subsequent *in situ* measurements (e.g. [Mozer et al., 2002]) and numerical simulations (e.g. [Nagai, 2006; Shay et al., 1998]) have greatly elaborated the physics of this process. V. Angelopoulos [Angelopoulos et al., 1992] observed the consequence of that in form of flow bursts (Bursty Bulk Flows, or BBFs), which transport the reconnected field and hot plasma earthward. For more detailed exploration of nature and timing of these flows in relation to the visible manifestations in the ionosphere the dedicated five-spacecraft THEMIS mission (short for Time History of Events and Macroscale Interactions during Substorms) has been created [Angelopoulos, 2008]. An important feature of these flow bursts is the strong steepening of the magnetic field vector, the so-called dipolarization front. It is the result of the relaxation of the field after reconnection and the transfer of shear stress into plasma acceleration. Figure 7 shows an example of the sequential passage of a flow burst as experienced by the instruments on four of the THEMIS spacecraft at various distances along the tail [Runov et al., 2011]. The figure to the left shows the positions of the spacecraft inside the field geometry and the right figure contains the vertical component of the magnetic field.

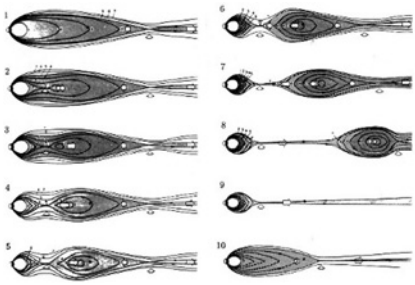

Fig. 6

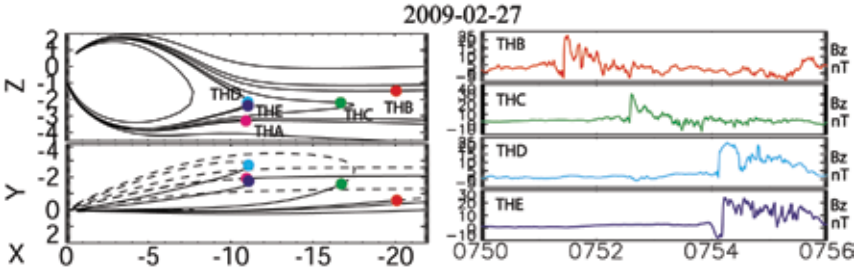

Fig. 7

Onset of a substorm in the tail is undoubtedly the onset of a somewhat extended phase of reconnection, in contrast to a transient event, called *pseudo-breakup*. Onset in the ionosphere is defined by the sudden brightening of the most equatorward arc followed by poleward expansion. This expansion occurs in multiple steps, each one lasting for one or two minutes, starting with the formation of a new arc on the poleward side of the previous arc, the so-called *breakup arc*, which then fades and moves equatorward. This has first been documented in paper [Oguti, 1973] and is shown in Fig. 8 as the temporal sequence of the latitudinal brightness distribution observed with a meridian scanning photometer. The equatorward progressing traces are signatures of arcs related to the entry of new magnetic flux into the near-dipolar magnetosphere. M. G. Henderson [Henderson et al., 1994] related the arcs to the upward current region flanking a flow channel. Figure 9 from paper [Haerendel, 2015b] shows an example of the transformation of a breakup arc in the course of two minutes. It also shows that the newly forming arc is highly structured by short lasting narrow rays. A wavy structure with fast, mostly eastward motions characterizes also the first appearance of the breakup arc.

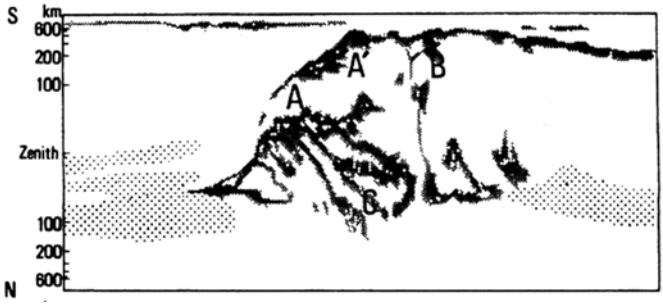

Fig. 8

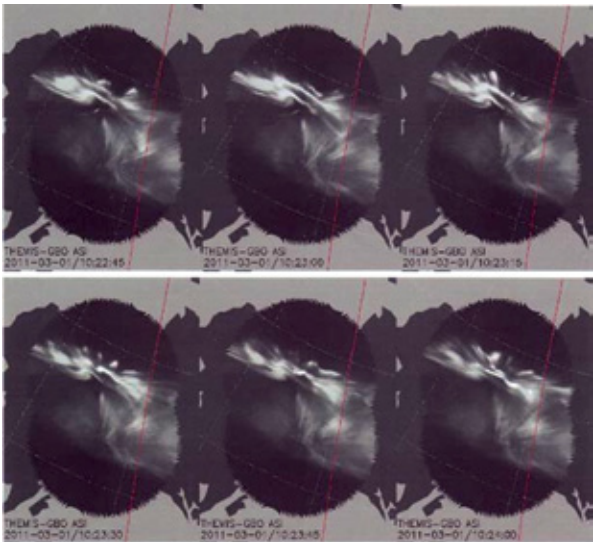

Fig. 9

A matter of present days' controversy is whether the initial brightening is caused by the arrival of the first flow burst at the outer edge of the dipolar magnetosphere or whether it is caused by an instability. Inspired by the visual impression, processes such as ballooning instability or current sheet collapse have been proposed. The author of the paper [Haerendel 2015b] has discussed the various ideas with himself leaning towards the latter proposal. Arguments based on the relative timing of the onset of the ionospheric signatures and the appearance of flow bursts at the inner edge of the tail have not yet led to a clear solution of the controversy. A compromise may be that instability of the near-Earth edge of the tail current sheet as well as onset of reconnection $10R_E$ further outward commence spontaneously, when the current sheet has become sufficiently thin, i.e. of the order of the proton inertial length or gyroradius. The relative timing of the two processes may differ by a few minutes in either direction. Since travel time from the X-line to the inner edge of the tail also takes a few minutes, one would have an explanation for the contradicting answers obtained by timing arguments (see for instance [Mende et al., 2011]).

THE SUBSTORM CURRENT WEDGE

The appearance of the *auroral* or *westward electrojet* (AEJ) after substorm onset coincident with characteristic magnetic perturbations thousands of kilometres equatorward of the aurora led [McPherron et al., 1973] to postulate the existence of a large-scale current system called *substorm current wedge*. The cartoon summarizing these observations but containing also an interpretation is shown as Fig. 10. Downward field-aligned currents on the morning side and upward field-aligned currents on the evening side connected by the AEJ are consistent with auroral and magnetic observations. Interpretation was the suggestion that the field-aligned currents originate from a rerouting of the westward current in the tail at its inner edge. The controversy about this concept filled at least the last decade of the last century. Meanwhile it has become accepted that there must be a generator acting inside the current wedge at the tail/magnetosphere interface, because this is the source of energy and momentum flux into the polar ionosphere responsible for the aurora as well as the equatorward progression of the magnetic flux returning from the tail.

An obvious candidate for the current generator is braking of the flow bursts by the increasing magnetic field at the inner edge of the tail [Haerendel, 1992]. Pursuing this concept in various ways by observation, theory and simulation has shown that flow braking would work the right way, but the magnitude of the generated current would be too low in order to explain the observed strength of the AEJ [Birn et al., 1999]. At the time of writing there are two ways out of this dilemma. J. Birn and M. Hesse [Birn, Hesse, 2013] found by numerically simulating the earthward motion of flux tubes of low entropy, called *magnetic bubbles*, that vortices are forming at the outer magnetospheric boundary under partial reflection of the flow, which could carry the required amount of total current. This is shown in Fig. 11.

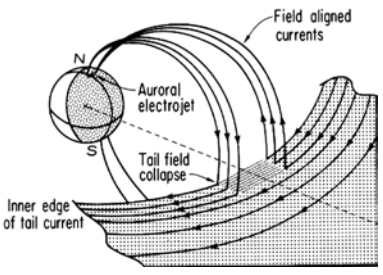

Fig. 10

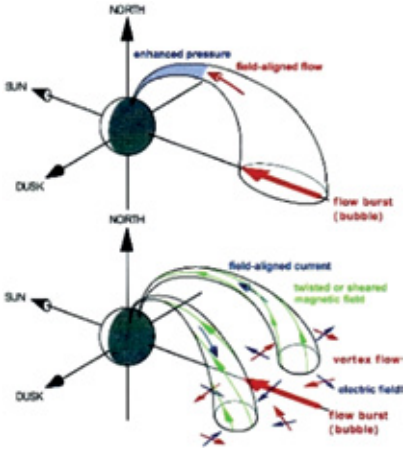

Fig. 11

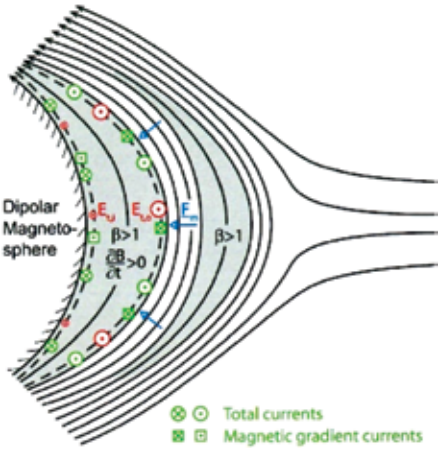

Fig. 12

Another view is that of the author [Haerendel 2009, 2015c] who maintains that flow energy is not only insufficient but is mostly fed into the highly structured breakup arc shown in Fig. 9 and does not lead to formation of a strong westward current. He proposes instead that the current is generated at the interface of the high magnetic pressure and high plasma pressure on the earthward side, when the flow bursts have agglomerated at the outer magnetospheric boundary (Fig. 12). Although the pressure gradient current flows in the wrong direction, it is not relevant for transferring momentum to the ionosphere, because it is divergence-free. It is the magnetic gradient current in the boundary layer between low- and high-beta plasma, which has the required eastward direction and can feed the field-aligned currents. The energy is supplied by the internal energy of the ions.

DO WE UNDERSTAND THE SUBSTORM?

By 1979 most of the fundamental facts were known about the substorm, but understanding developed slowly. Decades of lively discussions followed, mostly focussing on cause, location, and timing of the substorm onset. At the same time *in situ* exploration and remote sensing aided by theory and numerical simulations added new insights into the detailed physical processes. Great progress was achieved by the availability of multi-point measurements owed to ESA's *Cluster* and NASA's THEMIS missions. The value of the latter was greatly augmented by the THEMIS ground-based network of all-sky cameras in Canada and Alaska. All the same there are still a few, but rather fundamental open problems of two or more spacecraft, such as:

- the causal sequence of substorm onset,
- the breakup processes,
- the nature of the generator inside the substorm current wedge,
- plasma entry into the dipolar magnetosphere.

The reason for the lack of a unified understanding of these issues, in spite of the existence of a great many ideas and apparent solutions, is twofold. On the one

hand, conjugacy of simultaneous ground-based or low-altitude satellite observations and measurements in the tail or outer magnetosphere are rare and often non-conclusive. The Keplerian laws make obtaining conjugate constellations of two or more spacecraft awfully difficult. On the other hand, numerical treatments of the substorm are not yet capable of properly incorporating all facets of solar wind energy input, the internal distribution, and the processing on the way to and inside the ionosphere. The demands on storage and processing speed are still too high.

We can thus conclude that although the substorm is basically understood, there is still urgent need for further elucidation of some critical issues. This needs continued scientific engagement and public support including invention and realization of new methods and new missions such as the recently launched Magnetospheric Multiscale (MMS) mission (NASA).

PROSPECTS

The universe is full of objects, in or around which plasma processes are taking place similar to those of a magnetospheric substorm. However, the environmental parameters differ greatly and transfer of the near-Earth processes to these situations are not at all straight forward. Since in most cases information about such processes on distant objects is carried by electromagnetic radiation (radio waves and X-rays), mostly generated by nonlinear plasma processes and electron bremsstrahlung, there is great need for better understanding of the electron acceleration processes even still in the Earth's environment and attempts to transfer their fundamental physical mechanisms to these object. By drawing conclusions on the expected outcome and manifestation through electromagnetic emissions, one can at least obtain consistency checks. After all, basic microphysical processes are sufficiently stringent to avoid mere speculation.

There are only three important acceleration processes at hand, (1) *Fermi or stochastic acceleration*, greatly explored for shock waves; (2) *reconnection and energization* in the outflow or inside magnetic islands; and (3) *auroral or field-parallel acceleration*. The latter is preferentially realized in strong magnetic fields near the stellar object, whereas the two other processes play in the higher beta outer realms. In comparison with the first two processes, the auroral acceleration is little explored. More theoretical work and *in situ* exploration by multiple satellite missions at the relevant altitudes are certainly needed.

The easiest transfer of plasma processes explored near Earth is achieved in the context of planetary magnetospheres. Much work has already been done and is planned for the not too distant future. However, there is still much need to better understand the specificities of reconnection and auroral acceleration in these magnetospheres, as for instance caused by fast planetary rotation.

More difficult is the application to the Sun with its much denser atmosphere. The spatial and temporal scales are therefore so small that their resolution by optical observation will remain impossible for a long time, and *in situ* measurements are at best feasible in the outermost corona. On the other hand, owing to the high density and temperature there are many means of diagnostics which can at least provide consistency checks of the results predicted by theoretical application of concepts derived from substorm physics.

Basically the substorm or flare as a general notion involves the working of two processes operating after the build-up of stored magnetic energy, namely reconnec-

tion and auroral acceleration. The first requires understanding of the storage and its configuration leading to release by reconnection, the second requires understanding of the further energy transport towards the stellar object and its conversion into magnetic shear stresses. In general, field parallel acceleration of electrons (and ions) is enabled by the release of magnetic shear stresses. Even without preceding reconnection, strong magnetic shear stresses can be set up in the interaction of two differently rotating objects, like accretions disks and neutron stars or plasma overflows from Roche lobes into the magnetosphere of white dwarfs. Such objects are prone to make use of the auroral acceleration process as an efficient means of energy dissipation.

In conclusion I would like to voice the opinion that substorm exploration still has great need for further support by space agencies and governments for many years to come in order to clarify the remaining fundamental questions about its operation. This is not only needed for the sake of deeper understanding the Earth's plasma environment and its impact on human activities and technology in space (space weather), but also for furthering our understanding of the high-energy events on distant stellar objects, which carry much information on dramatic, but invisible internal reconfiguration processes.

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SOME VIEWS ON THE FUTURE EXPLORATION OF THE SOLAR SYSTEM

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WHAT IS MEANT BY SPACE EXPLORATION?

Space exploration is a double-faced activity:

1. It aims at answering fundamental scientific questions

- How did the Sun's family of planets and minor bodies originate?
- How did the Solar System evolve to its current diverse state?
- Why did the terrestrial planets differentiate, and what led the Earth to its present state?
- How did life begin and evolve on Earth, and has it appeared and evolved elsewhere in the Solar System?
- Also exploration would like to find evidence of past or present life.

2. It aims at extending human presence in deep space and eventually on other bodies than Earth:

- Develop exploration technologies, infrastructures, and capacities (life systems, maintenance of crew health, utilization of local resources, orbital operations).
- Increase opportunities for astronauts to engage in exploration.
- Implement manned missions to the Moon, asteroids and Mars, eventually leading to short or long duration settlements.

But also space exploration aims at:

- Satisfying the public interest, including providing virtual experiences and contributing to the cultural development.
- Creating opportunities to educate and inspire young people.

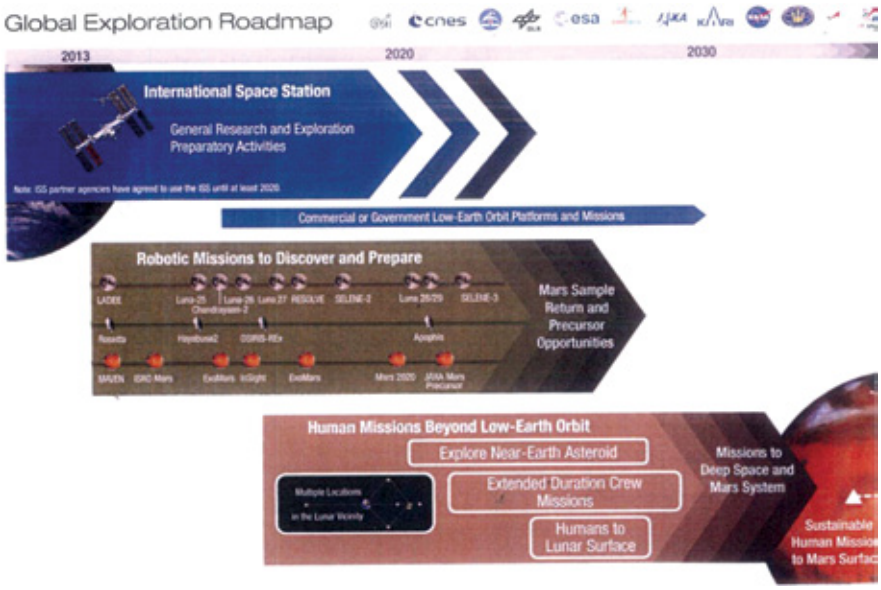
Space exploration is hugely popular (one billion calls on Internet in three weeks after *Pathfinder* landing on Mars).

Space exploration should be used to create a symbol of international cooperation in the use of science and technology for solving major problems for mankind.

However, the most visible, public-loved, and symbolic domain of space activities, the exploration, both manned and automated, encounters programmatic uncertainties.

The ISS is supposed to be abandoned in the 2020s. American attempts to a Moon return have been stopped. The mission to an asteroid, chosen by the Obama administration, could very well be cancelled by a new U.S. president*.

* Written in December, 2015 — *ed.*



Icon	Capability name	Description
	NASA *Orion*	Crew vehicle capable of delivering a crew to exploration destinations and back to Earth
	NASA Space Launch System (SLS)	Launch vehicle with the capability to deliver cargo or crew beyond low-Earth orbit. Initial capacity evolves with advanced boosters and an upper stage to enable increasingly complex missions with further evolution to support crewed Mars missions
	Cryogenic Propulsion Stage (CPS)	Included in SLS evolution plans, an in-space propulsion capability utilizing cryogenic hydrogen and oxygen as propellants. Could provide additional performance for missions to the lunar vicinity, lunar surface, or Mars. Mission durations will require long-duration storage of cryogenic propellants
	ROSCOSMOS Next Generation Space Launch Vehicle	Launch vehicle with the capability to deliver cargo or crew beyond low-Earth orbit. The next generation space launch vehicle and the next generation spacecraft together constitute the Russian Piloted System
	ROSCOSMOS Next Generation Spacecraft	Crew vehicle capable of delivering a crew to exploration destinations and back to Earth

HOW ARE WE ORGANIZED?

A measure of international coordination has been built up with the start in 2007 of the participation of 14 space Agencies to a group called The International Space Exploration Coordination Group (ISECG).

ISECG has developed a Global Exploration Roadmap which creates a framework for interagency discussions in three areas (Australia, China, Canada, Germany, India, Italy, Japan, Russia, South Korea, Ukraine, United Kingdom, United States, ESA):

- Common goals and objectives.
- A large range human exploration strategy.
- Coordination of activities preparatory to exploration.

As of today, the ISECG roadmap envisions three steps:

- First: a mini station in cislunar space (Lagrange Earth-Moon L_2).
- Second: men landing on the Moon in the 2020s.
- Third: human missions to Mars**,** as a long term ultimate goal.

The input to ISECG is mainly provided by the United States and the European nations, with a minimal presence of China and Russia: the Russian contribution is conspicuously low.

WHAT IS BEING PLANNED?

The lack of international thinking or even coordination is obvious today at all levels in space exploration.

Robotic

- A multiplicity of lunar missions takes place, Japan, China, India are preparing or have already flown their own spacecraft. South Korea, Brazil, and even European countries Germany, UK, Italy, despite being part of the European Space Agency were talking of their own missions to the Moon before the 2008 economic crisis. India launched very recently a mission to Mars and China intends to follow suite. All these efforts are basically intended to demonstrate technological know-how.

Manned

- The ISS, a glaring example of real cooperation and a superb success in management and technology, has no clear future, despite a past investment estimated above one hundred billion dollars. It nearly escaped abandonment by its major contributor, NASA, was prolonged provisionally to 2020 and fights now for a suspended sentence.
- The Chinese space station, which has been announced to be built in the 2020s, has yet to be integrated in an international cooperative scenario.


LRO (2009)
SELENE 2
SELENE 3
Luna-25
Luna-26
Luna-28
Chandrayaan-2
Luna-27
Luna-29
LADEE
MAVEN
ExoMars 2018
Lander/Rover
Orbiter
Sample Return
Mars Express (2003)
ExoMars 2016
MER (2003)
InSight
Mars 2020
ISRO Mars Orbiter Mission
MRO (2005)
Curiosity (2011)
Mars Precursor Mission
Post ExoMars Mission
NEOSSat (Asteroid Finder Mission)
GAIA (Asteroid Characterization)
Marco Polo-R
Hayabusa2
Rosetta (2004)
Apophis
OSIRIS-REx
2012
2013
2014
2015
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2017
2018
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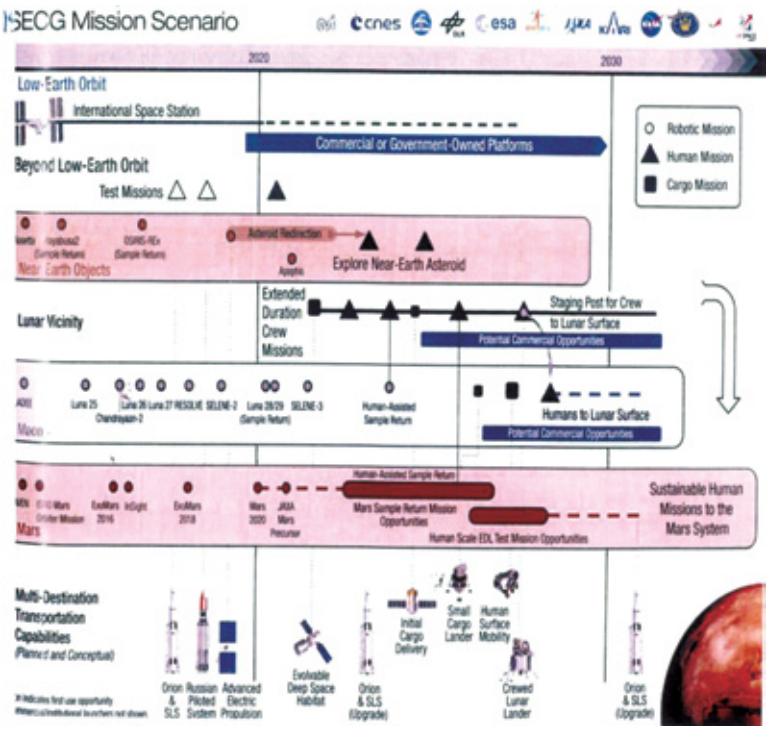

SECG Mission Scenario
2020
2030
Low-Earth Orbit
International Space Station
Commercial or Government-Owned Platforms
Beyond Low-Earth Orbit
Test Missions
Robotic Mission
Human Mission
Cargo Mission
Asteroid Redirection
Explore Near-Earth Asteroid
Near Earth Objects
Lunar Vicinity
Extended Duration Crew Missions
Staging Post for Crew to Lunar Surface
Potential Commercial Opportunities
Humans to Lunar Surface
Potential Commercial Opportunities
Human-Assisted Sample Return
Mars Sample Return Mission Opportunities
Human Scale EDL Test Mission Opportunities
Sustainable Human Missions to the Mars System
Mars
Multi-Destination Transportation Capabilities
(Planned and Conceptual)
Orion & SLS
Russian Piloted System
Advanced Electric Propulsion
Evolvable Deep Space Habitat
Orion & SLS (Upgrade)
Initial Cargo Delivery
Small Cargo Lander
Human Surface Mobility
Crewed Lunar Lander
Orion & SLS (Upgrade)

BASIC TECHNICAL TRENDS

Technical evolution since 1960

Propulsion:
- Not changed basically: an old launcher is a good launcher.
- Still with liquid hydrogen.
- Apparition of electric thrusters (proven in missions).
- Emergence of hybrid engines.
- Nuclear abandoned.

Subsystems:
- Power supply improved by one order of magnitude.
- Materials introduction of carbon fibers.
- Miniaturization: micro mechanical electronics systems (mems).

Enormous increase of performance of electronic components following Moore's law: *the performance of components increases exponentially with a two year constant*.

A few ideas for robotic missions

- The ESTEC Mini Mex CDF Study has shown in 2010 that the application of available technology could provide a gain in mass by a factor of 2 in the *Mars Express* mission, which would improve from 630 kg to 300. Such a mass is compatible with a piggyback mission to Mars with *Soyuz*.
- A Martian network could be established with 50 kg probes comprising each an EDL system and a 10 kg Net-lander style station launched from GTO. Total mass of one probe with fuel and cruise vehicle 125 kg.
- Complete mapping of the Moon at a 25 cm resolution. It would be obtained through a constellation of 8 nanosat carrying a 15 cm aperture telescope orbited at 50 km of altitude for 6 months. Data would be retrieved by a relay at L_2. The nanosats would be similar to the *Dove* satellites of the San Francisco company *Planet Labs*. These satellites equipped with a 10 cm diameter optics, weigh 5 kg each for a cost of 10,000 dollars. 71 *Doves* have already been launched.

A possible method for obtaining entry into Venus atmosphere. The *Vamp* system

- Developed by *Northrop Grumman Aerospace*.
- Semi-buoyant flying wing.
- Lifting entry subsonic at 95 km altitude.
- Still fully buoyant at 55–52 km.
- Solar powered propellers make it flying aircraft for exploring region 52–65 km altitude.
- Could be used for Mars and Titan.

A possible method for obtaining mobility: The *Archimedes* system

- Developed by University of German Army, Munich.
- Balloon 10 m diameter inflated before entry.
- Floats in atmosphere.
- To be tested in 2018.
- Could be used for Mars and Venus.

BASIC POLITICAL CHOICES

If space exploration is for many an inspiring goal, a growing preoccupation worries political leaders. Humankind is confronted today with threats to our survival on a habitable planet.

- The squandering of the natural resources, available only in finite quantities has to be replaced by a responsible management, in order to avoid dangerous shortages in food, water, energy, minerals, etc. These perils have to be fought by mobilizing science, including space tools.
- The growing trends towards solving the tensions resulting from scarcities could lead to the use of mass destruction weapons. There is a lack of unifying goals with which to build a lasting peace based on international partnership. However, global partnerships would be essential for establishing consensus and trust.

A symbol of world government is needed

Space and particularly space exploration could and should be used as this wanted symbol of the success of science and technology in understanding the world and helping humankind to achieve an improved standard of living, to solve major geopolitical issues, and provide a better destiny to all.

Remember that for hundreds of millions of people, the view from space made it possible to see and begin to recognize our own Earth as a planet from a new and previously impossible perspective. And we know since *Apollo XI* in 1969, that the public recognizes the significance and symbolism of space exploration. See the recent enthusiasm for the European comet lander *Philae* has shown.

A new attitude: Internationalize and share knowledge and means

The nations most advanced in space technology would help, work with, and participate in the lunar missions of others less knowledgeable (and the private sector), buying data, supplying scientific instruments, and providing technical assistance where appropriate.

This approach would be a return to the spirit of the International Geophysical Year 1957–58.

This tradition can be revived. It was a product of the scientific community and this community today is flourishing.

I urge partners who have not been active in ISECG to move forward and promote the basic idea that the exploration of the Solar System should be conceived as an endeavor of all mankind, coordination being replaced by cooperation.

The challenge: Exploring the Solar System in the 2020–2050 time range

- Multiple players: competition of cooperation?
- Transition to mems and nems.

Innovative avenue has to be invented:
- Multiply launch opportunities.
- Increase mobility on the surface of planets.
- Share information, efforts, and risks by increasing international cooperation, organizing joint R&D projects, and undertake joint missions.

A ROADMAP TO THE MOON

The Moon is a stepping stone into the Solar System and today is considered as a primary objective by many spacefaring nations. It is magnificent to imagine all of them working together, i.e. China, Europe, Japan, Russia, and the United States going to the Moon, this time truly "for all mankind".

The objective is not to go to the Moon, but to go to the Moon TOGETHER. This would be the Apollo *of the 21st century!*

Under an international council, structures would exist to regroup certain partners for specific tasks: R&D, operations, common realizations as mobile or fixed laboratories.

Which types of propulsion, which vehicles, which telecommunication and localization networks, all these questions are open to discussion. For instance, joint ventures could provide the facilities in low-Earth orbit and the fleet of mini shuttles operating between Earth and the orbital relays.

Some nations could form subgroups for the construction of their own facilities on the Moon, on one or many sites, not excluding some healthy competition.

Robotic missions: the robotic village

Conceived and studied by the International Lunar Exploration Working Group (ILEWG) the village is an umbrella coordinating, regrouping, and completing the various robotic missions to the Moon. It presents a phased approach, with orbital reconnaissance, small landers, a network of landers for science.

The village provides the opportunity to create an international structure and to test the type of governance needed for future more ambitious ventures as the International Lunar Base (ILB).

Possible International Cooperation for the Lunar Robotic Village

A. *R&D.* A number of specific products have to be continuously evolved as long as technology advances, for the needs of exploration components, instruments, systems, the burden of which could be shared between partners outside national and industrial restrictions. A fund could be created by "equal" partners for sustaining an R&D joint program.
B. *Operations.* Agreements could be shared between the various Deep Space Networks for not only a participation of all national facilities to the partner's missions.
C. *Assets.* A significant cooperation would be the joint development of "planetary" facilities under integrated management, such as:

- Geostationary telecommunication network and navigation/localization network (GPS style) around the Moon and Mars.
- International automatic stations on the Moon or Mars.
- International mobile laboratories on the Moon and Mars.
- Planetary Internet.

D. *Partnerships in missions.* Possible joint ventures (such as sample return missions) could be agreed upon, with distribution of major tasks or systems among the participating partners.

Man on the Moon

Two major steps would have to be implemented:

R&D would be the essential feature of the activity in the next ten years, maybe not in propulsion, but in what is called astronautics: orbital manoeuvres, automatic RV and docking, fuel management, use of non-classical trajectories. The future resides in the use of well-proved man rated launchers as *Soyuz* for the transportation of all crews to low-Earth orbit. Large structures would be robotically assembled in orbit, waiting to be occupied by astronauts for further trips. The ISS would be used as a relay in the whole system and kept alive instead of being deorbited. Its relationship with the Chinese mission *Tiangong* would occupy the center of the manned exploration program.

The R&D program would be a totally international program, managed by an international team, sharing data and overall information among members.

Establishment of an International manned Lunar Base (ILB)

A first step could be, as studied by ISECG, a mini station at L_2.

A series of crewed missions using both the Russian piloted system and the NASA *Orion* have been defined. Key mission activities include:

- Advancing deep space human space flight operations and techniques, including staging operations.

- Conducting high priority science benefiting from human presence, including human-assisted lunar sample return.
- Testing technologies and subsystems benefitting from the deep space environment.
- Characterizing human health and performance in a deep space environment.

A single launch of the SLS could deliver the Evolvable Deep Space Habitat to L_2. Using advanced solar electric propulsion, the habitat could be relocated to other locations in the lunar vicinity.

Functionality can be added to the habitat as mission requirements dictate, to include specific science equipment, servicing systems, additional docking ports, or fully closed-loop life support system elements. The crew would visit the habitat for stays of up 90 days in order to test life support systems, perform crew health maintenance studies and drive reductions in the supply chain.

In preparation for surface access missions, functionality could be added to the Evolvable Deep Space Habitat so it may also serve as a staging post to access the lunar surface facilities assets.

A minimal effort: Interoperability

Large multinational exploration missions will require agencies to accept and manage interdependency at different levels: architecture, mission, infrastructures, and systems. The nature of human exploration beyond low-Earth orbit will necessitate acceptance of, and commitment to, a level of interdependency that is beyond our current experience and that will increase interoperability across the architecture.

Agencies participating in the Interagency Operations Advisory Group (IOAG), Space Frequency Coordination Group (SFCG), and the Consultative Committee for Space Data Systems (CCSDS) have collaborated on establishing data communications and mission operations architectures, coordinating spectrum for space communications and technical standards for cross-support.

These teams have developed service catalog and technical standards, which respond to the anticipated needs of future exploration missions. These services and standards will enable highly internetworked mission operations and facilitate the integration of new partners into complex human space exploration missions.

Onboard systems standards are equally important. Initiatives such the International Docking System Standard and Onboard Interface Standards are essential for fostering onboard interoperability. Work on such standards continues.

The International manned Lunar Base (ILB)

The ILB will be the *integrated project of equal partners*, including a planning agreed upon by all, free circulation of technical knowledge, exchange of personnel, and above all sharing of the crucial responsibilities in the domains of development, management and program direction**.**

On the 24th of April 2008, in Beijing, China, under the leadership of the Center for Strategic and International Studies (CSIS, based in Washington, DC), and

the Chinese Society for Astronautics (CSA), the first "Global Space Development Summit" took place.

The summit was attended by a wide variety of space professionals from all around the world. Indeed, fifteen countries, six embassies, six space agencies, three elected representatives, and nine non-profit and international organizations participated in this event.

The summit issued a "Beijing declaration", which states:

We propose a collaborative international space program with the concrete goal of establishing a permanent international research and science station along the line of the successful international of Antarctica on the surface of the Moon by the year 2025.

This proposal met with no success, but it has not lost relevance.

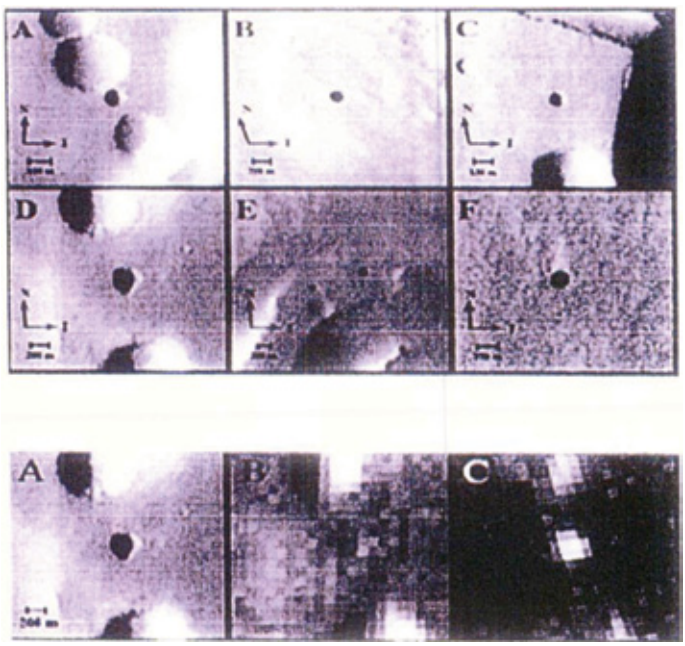
A ROADMAP TO MARS

Manned mission to Mars

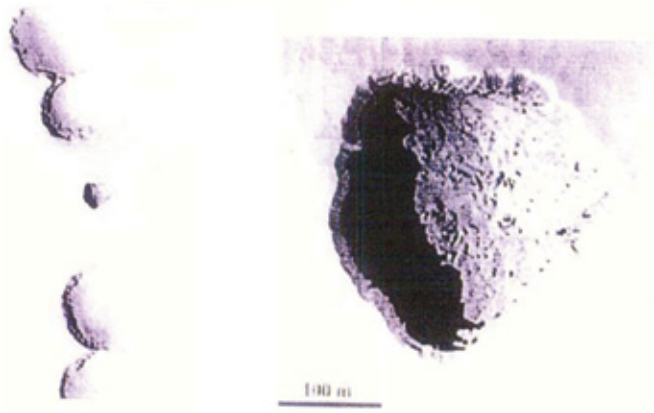
It is suggested to consider, as a starting point for planning, the ultimate objective of the global exploration, which would be the *establishment of permanent manned bases on the Moon and Mars*.

Extended lifetime for men on the Moon and Mars is only sustainable, if safety against hazards is provided.

The Martian surface experiences a range of significant hazards such as micrometeorid bombardment, solar flares, UV radiation, high-energy particles from space, intense dust storms, and extreme temperature variations.



Holes on the surface of Mars in Ascraeus Mons



Zoom on the preceding hole

Habitat in natural caves created by volcanic activity could provide major elements of protection. Lava tubes have recently been discovered both on the Moon and on Mars, but they have not been described with accuracy. Their existence nevertheless offers a unifying concept for occupancy, first on the Moon, then on Mars.

The Moon appears as a necessary preliminary step. Heavy equipment, as the nuclear electricity generator, ISRU tools, and all life support systems also require long duration testing on the Moon, as the major activity of the ILB.

Lava tubes are created by low-viscosity basaltic flow from a non-explosive volcanos.

- Very frequent on Earth (diameter 15 meters, length m to km).
- On the Moon, discovered by *Selene* (2009) in Marius Hills, Mare Tranquilitatis, and Mare Ingenii (diameter 50 meters, depth 50 to 100 meters).
- On Mars, present on Ascrea Montes.

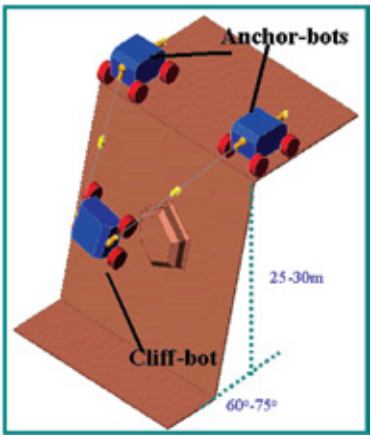
Another roadmap

It is proposed to go beyond the "first steps" of the present ISECG Roadmap and elaborate the steps of another Roadmap built on the exploration of lunar and Martian caves and the simultaneous development of the technology needed for the appropriation of such terrains.

Two types of research programs should be envisioned.

1. High resolution orbital mapping of suspected tube locations (imagery, thermal infrared detection, ground penetrating radars) followed by *in situ* robotic inspection.
2. Access to the cave and base construction.

Access is the specific problem of the cave as settlement: earth movers, bulldozers, heavy vehicles will have to be used for building an easy way of descending and ascending a height of the order of 100 m. Escalators, elevators, cliffbots and all the needed machinery will have to be developed for the lunar phase of the exploration, around lunar caves.



Configuration of Cliff-bot System

An early prototype of Cliffbot being tested at JPL in Pasadena, Calif., several years before its deployment to the Arctic for cold-weather testing. Credit NASA/JPL

Inside the cave will be deployed inflatable structures of large dimensions for habitability. Again the development of such techniques will take place on the Moon as one of the major objectives of the ILB.

Identification and qualification of caves from the orbit:

- Increase in number of missions and performances of instruments:
  - Multiwaveband mapping of volcanic terrains at 20 cm resolution.
  - Thermal IR detection and observations at 1 m resolution including oblique imaging.
  - Ground penetrating radar (1 to 5 MHz).
- Creation of a World Data Center for coordination of programmes.

...and by ground-based instruments:

- Vehicles
  - Inflatable rovers.
  - Planes.
  - Cliff-bots.
  - Cable deployment.

- Instruments:
- GPR.
- Muon topography.

Drawing of a Martian base below the Tartarus Colles arch (by Manchu for the association PLANETE MARS). Courtesy of Alian Souchier

A new roadmap

- From now to 2020, elaboration of an international frame and efforts for acceptance by space agencies.
- From 2020 to 2030: the mapping phase with satellites (and maybe Mars airplanes and rovers) carrying detection missions. Simultaneously, implementation of the R&D program.
- From 2030 to 2040: the implementation of the International Lunar base and the development on the Moon of the heavy machinery needed for the Martian caves.
- Around 2060, human mission to Mars and beginning of the establishment of an International Mars Base in caves.

Since the nature of the whole venture is basically international, a first move would be for ISECG to consider planetary cave dwelling as a potentially interesting concept and, therefore, to introduce it in the options for the future roadmap.

CONCLUSION

- We are in the 21st century.
- Space remains a symbol of mankind's achievements.
- But competition has to be replaced by cooperation.
- Imagination and creativity are needed for:
  - Introducing new concepts of missions.
  - Organizing international programs.

We are confronted with a choice.

- Explore the Solar System by separate nations or groups of nations on a competitive basis,
- ...or proceed on a cooperative mode with all nations enjoying a venture of united mankind.

The second option, which is of course our favorite, will be hard to implement, and this is why the whole scientific community should work on it, as it did in 1954–55 when it convinced the governments of the USSR and the USA to accept space as a major feature of the International Geophysical Year.

I urge the scientific community gathered today in Moscow to take the opportunity of this anniversary to start thinking about a new approach to the challenge of exploration of the Solar System.

Our IKI friends could take an initiative, following their great tradition of scientific cooperation. Remember than in 1980, under the leadership of Roald Zinnurovich Sagdeev, the international mission to comet Halley, VEGA, was opened to scientists of many nations and was followed by a slate of international planetary missions.

My friends, I urge you to resurrect this spirit!

> "IKI also fulfilled an important but unadvertised rule in the space programme, that of its public face". *Brian Harvey*
>
> Harvey, Brian, Zakutnyaya, Olga. Russian Space Probes: Scientific Discoveries and Future Missions. Springer Praxis Books, 2011, XXIX, 514 p.

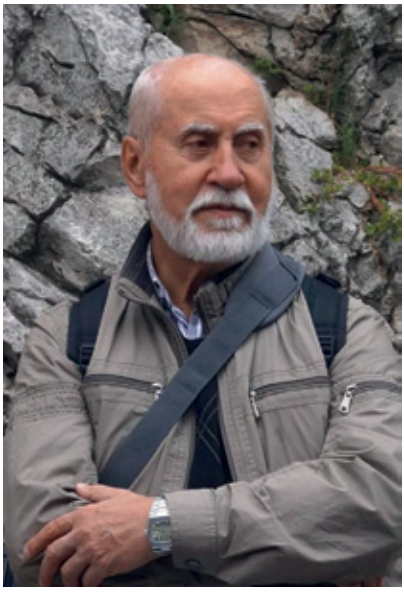
Although founded as a semi-classified organization, IKI soon acquired more or less prominent public face, since Soviet space program was a matter of national and international pride. The Institute was very much engaged with media relations and public outreach activities. It even had its own Press service group (a rare case for scientific institute at that time), within the Department of Scientific and Technical Information, organized in 1968 as "Print and Publication Group".

Its first head **Yuri Ivanovich Zaitsev** (since 1980 also the head of the Department) was also a pioneer of space exploration. A naval officer, he was transferred to Strategic Missile Forces in 1958, when they were just forming. In 1963 he was transferred to the Interdepartmental Council for Space Research at the Academy of Sciences (headed by M. Keldysh), and in 1968 he was enlisted to IKI's staff.

Since then, he became a true chronicler of space exploration with more than 10 popular books and 3500 articles on space research and rocketry and numerous public lectures under the aegis of "Znanie" Society (an organization for scientific promotion in the USSR). He was a member of the Union of Journalists of Russia, and a true journalist by vocation, wholly devoted to space and space science.

To our great sorrow, Yuri Ivanovich passed in March, 2016 a months after the 50th anniversary of IKI, whose birth, blossoming, and revival he witnessed and wrote up. Here we publish several articles, which he authored, as a tribute to his memory and also an insight into the history of the Institute and space exploration in our country.

We express our deep gratitude to the publishers who permitted to use the articles for non-commercial academic edition.



Yuri I. Zaitsev 26.04.1937–05.03.2016

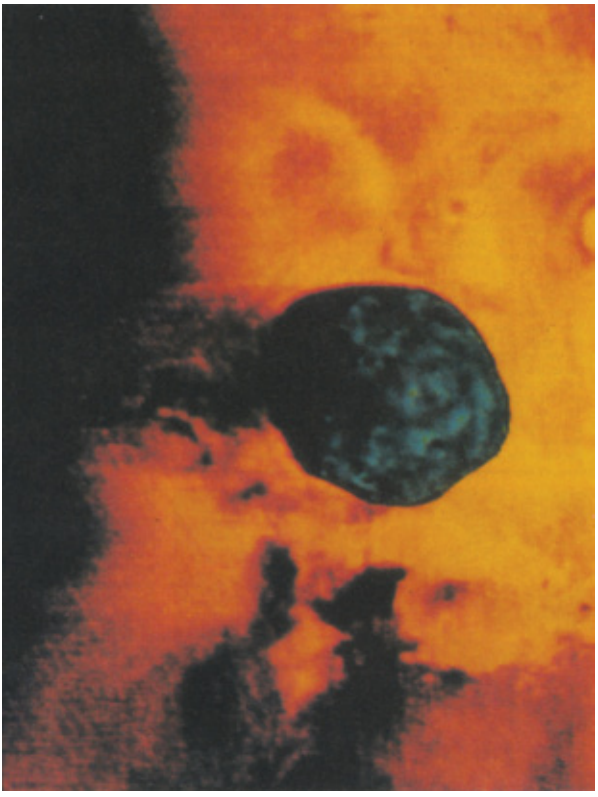
THE RED PLANET IN A NEW LIGHT*

Yuri Zaitsev

Photos of Phobos, the first heat images of Mars and traces of the planet's leaking atmosphere have all come from a Soviet space mission that, earlier this year, some said was a failure

OUR most recent odyssey to Mars began in July 1988, with the launch of two spacecraft called *Phobos* (*1* and *2*), and ended in March 1989, when ground controllers lost touch with the second craft. The international project involved 14 countries and the European Space Agency. It was the first flight designed especially to study one of the rocky minor bodies of the Solar System. Most of these orbit the Sun as "asteroids", between the orbits of Mars and Jupiter. But Mars has two small moons that are probably asteroids captured by the planet. The space mission was intended to investigate the larger of the two, Phobos — hence its name.

The results from the Phobos mission came in three stages. The first were observations made as the spacecraft travelled between Earth and Mars; the second comprised observations and measurements of Mars; and the third, the observations of the moon Phobos itself.



Credits: Novosti

* Originally published in *New Scientist*, 1679, 26 August, 1989, Pp.52-56 (https://www.newscientist.com/article/mg12316793-900-the-red-planet-in-a-new-light/). We preserved the style of the original publication, however, we do not include some illustrations, which can be found in the original. Note, that in the original Yuri Zaitsev is by mistake named a head of the Institute of Space Research at the USSR Academy of Sciences — *ed*.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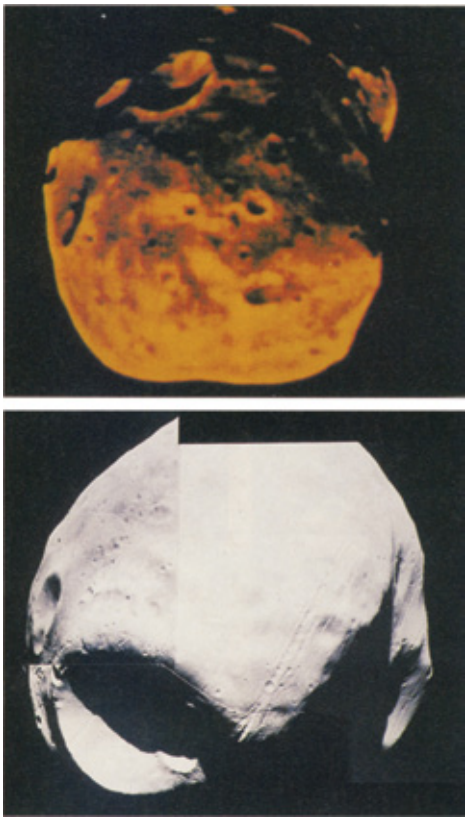


The resolution of the cameras onboard *Phobos-2* has given us the most detailed pictures of the surface of Phobos (left and top). Previous missions had revealed only major features, such as the Stickney crater (above from the Viking Orbiter). Credits: Novosti; NASA/SPL

Unfortunately, the Phobos mission did not carry out its programme in full. Early in September 1988, ground controllers lost contact with Phobos-1 after sending it an incorrect command. This switched off the orientation system of *Phobos-1*, and its solar panels stopped facing the Sun. With the onboard systems starved of power, the probe could not respond to any commands sent from the Earth.

After the loss of the first probe, the controllers took additional measures to make Phobos 2 more foolproof. They decided to correct its trajectory on the way to Mars only once, instead of twice as originally planned, even though this would increase the height of its orbit over the planet's surface and produce fewer scientific results.

On 29 January 1989, 200 days after its launch, Phobos-2 went into a highly elongated elliptical orbit above Mars's equator. Subsequent corrections gradually transformed the orbit into a circle around Mars, 350 kilometres above the orbit of Phobos. The planners chose to make these complex manoeuvres because they had only very scant information about the orbit of Phobos around the planet. All the data had been culled from observations from Earth during the short periods when the faint Martian satellite was visible, and also from the information supplied by three American spacecraft back in 1971 and 1976.

First Phobos-2 observed Mars, its atmosphere and space near the planet when in the elliptical "parking orbit". It carried on observing Mars for a further three days in this orbit. Then, with the probe at a distance of between 860 and 1130 kilometres from Phobos, it began the first television session of the Martian moon.

The spacecraft obtained nine television pictures of Phobos. The controllers needed this information to update their knowledge of the precise positions of Phobos and the space probe, in order to bring them closer together. When the distance between Phobos and the probe had diminished to between 320 and 440 kilometres, the spacecraft took more television images. These pictures were used not only for checking the position of Phobos but also for identifying the shape and details of its terrain.

On 21 March, the probe took up an orbit in which it kept pace with the Martian satellite, swinging between 400 kilometres further out from Mars than Phobos and

200 kilometres closer in. During this period, the probe completed one more television picture-taking session. At the same time, the controllers were preparing to put the probe on the side of Phobos not facing Mars, at a distance of 35 kilometres. Once there, the spacecraft was to have begun an entirely novel phase of its flight, moving along with the moon and making elaborate manoeuvres over its surface. According to the plan, the spacecraft would move in to hover only 50 metres above the Martian satellite. From here it would investigate the surface by bombarding it with lasers and beams of ions. The probe would then have lowered two landing modules — one fixed and the other mobile — onto the surface of Phobos.

But, unexpectedly, on 27 March, radio contact with the probe was lost. Roald Kremnev, the chief designer at the G. N. Babakin Research and Testing Station that built the probe, says that until that point the data from Phobos-2 indicated that all systems were in full working order. We do not have any information yet on the causes of the failure. Mission controllers will reach their final conclusions after processing all the information received during attempts to regain contact with the craft.

Despite the early termination of the mission, the staff of the Institute of Space Research and many foreign colleagues who prepared and participated in the investigations do not see it as a failure. The probe's instruments have collected new data on the activity of the Sun and interplanetary gas (see Box), the surface and magnetic field of Mars, and Phobos.

One unquestionable achievement has been the measurement of ionised gas – plasma – in the vicinity of Mars. Phobos-2 carried instruments to study magnetic fields, electric and magnetic waves, and other phenomena associated with plasma. It measured the magnetic field with two magnetometers, one from Austria and the Soviet Union and the other built by East Germany and the Soviet Union, and the plasma waves with an analyser that was developed by Czechoslovakia and the European Space Agency. Investigation of plasma waves can reveal what happens as the "solar wind" of charged particles from the Sun sweeps past a planet and interacts with its magnetosphere — the region where its magnetism dominates the solar wind.

The first investigations of the Martian magnetosphere were carried out between 1971 and 1974 by the probes Mars-2, Mars-3 and Mars-5. These observations indicated that Mars has a magnetic field, although very weak. They determined the shape and size of the magnetosphere including a long "tail" stretching away from the planet. These studies were limited, however, both by the instruments on board and by the orbits of the craft. The American craft, Mariner-9 and Vikings 1 and 2, had no instruments at all for such studies.

The weak magnetic field of Mars means that the solar wind must reach the planet's upper atmospheric layers before being stopped by the magnetic field. As a result, the magnetosphere is formed in a region where the solar wind is interacting simultaneously with both the planet's magnetic field and its atmosphere. In consequence, the Martian magnetosphere must differ substantially both from that of the Earth, where the stronger magnetic field stops the solar wind before it hits the atmosphere, and also from that of Venus. Venus has no magnetism of its own and its magnetosphere is formed by the solar wind disrupting the planet's ionosphere.

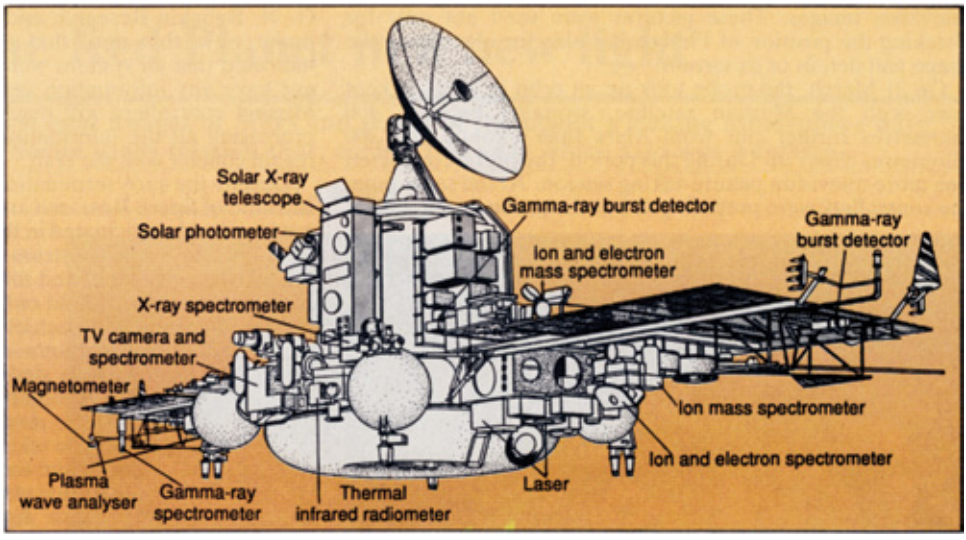
During its complicated loops around Mars, Phobos-2 was able to investigate the Martian magnetosphere, and its tail, in detail. The spacecraft found that the Martian magnetosphere, like that of the Earth, has distinct structures, such as a magnetopause (the boundary of the magnetosphere), a plasma layer in the tail, and a shock wave

in the flow of the solar wind in front of the magnetosphere. It was also able to discern some other, finer structural details of the Martian magnetosphere.

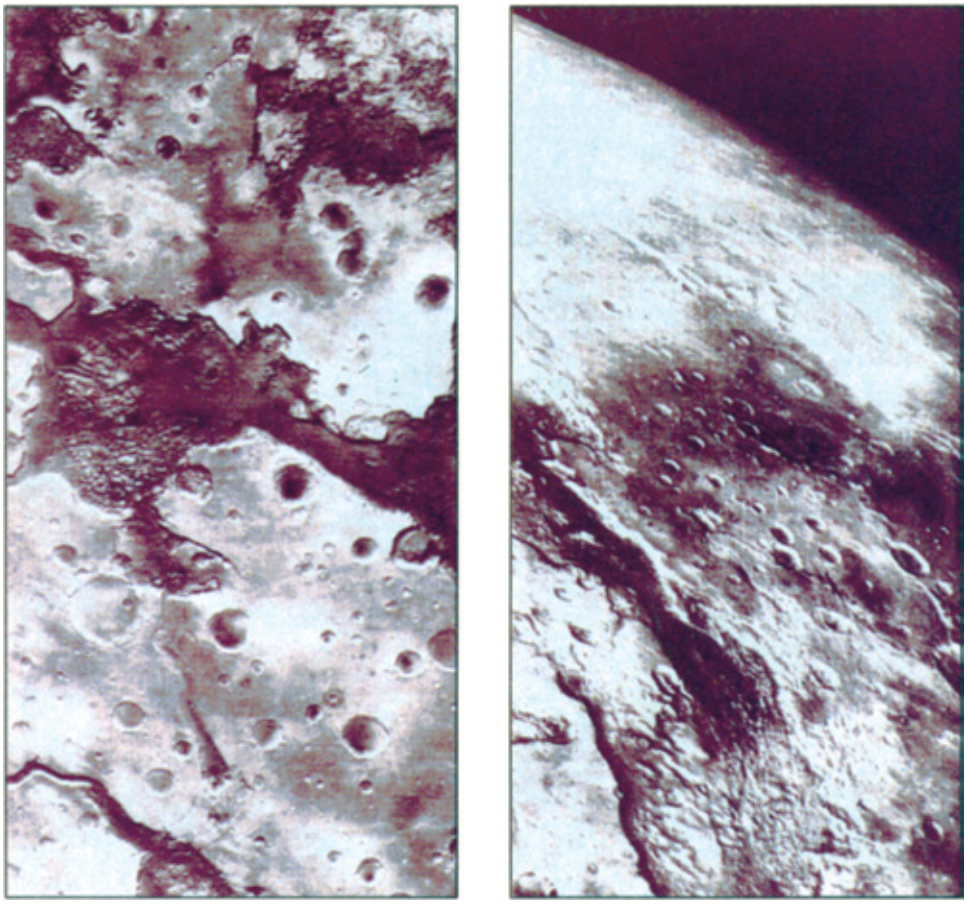
The magnetosphere is largely filled with a relatively cold plasma that comes from the atmosphere of Mars. But Phobos-2 also found islands of hotter plasma, which scientists think come from the solar wind. This suggests that Mars's weak magnetic field is closely interwoven with the interplanetary magnetic field, creating a natural "magnetic" channel for solar plasma to penetrate into the magnetosphere. The close relationship makes it difficult for us to distinguish how much of the measured magnetism comes from the interplanetary material and how much is due to the planet. As a result, we cannot tell with any certainty the strength or direction of Mars's own magnetic field.

The interplay between the planet's magnetism and the solar wind has important consequences for the Martian atmosphere, helping its gas to leak away into space. The lines of magnetic force from Mars connect with those in the solar wind, forming a channel by which ions from the atmosphere can escape. Phobos-2 observed this process in action. Its plasma instruments measured separately the flow of plasma in the solar wind (in the main, hydrogen ions) and of the plasma coming from the planet's atmosphere (mainly ions of carbon dioxide, and of molecular and atomic oxygen). The measurements from the atmosphere revealed the rate at which planetary ions are escaping into space. This flow is between $2 \cdot 10^{25}$ and $5 \cdot 10^{25}$ ions per second. In other words the atmosphere of Mars is losing between 1 and 2 kilograms of its substance every second. This may not seem to be a lot, but when we take into account the thinness of the Martian atmosphere (the pressure on the planet's surface is $1/170^{th}$ of that on the Earth), such losses may have a substantial effect on its evolution.

The estimated loss of gas from the Martian atmosphere is practically equal to losses along the magnetic tail of the Earth's magnetosphere. For the Earth, such a loss is negligibly small; it would take 10 billion years — twice the age of the Solar System — for the Earth's atmosphere to disappear.



Phobos spacecraft carried an array of instruments to make the best use of the nine months in space on the way to Mars, and to collect data on the planet and its moon



Heat images of Mars taken as Phobos swooped close to the planet's surface.
Dark areas are cool, bright ones are hot. Credits: Novosti

But in the case of Mars, this rate of loss means that the planet would lose its atmosphere in a time much shorter than the age of the Solar System. If the planet's gases are continuously replenished by the evaporation of water from ice frozen in the soil, the present rate of loss is equivalent to the disappearance from the planet's surface of a layer of water 1 to 2 metres deep during the history of Mars. So the weakness of its magnetic field may have been responsible for considerable erosion of its atmosphere and possibly to the loss of much of the water with which it formed.

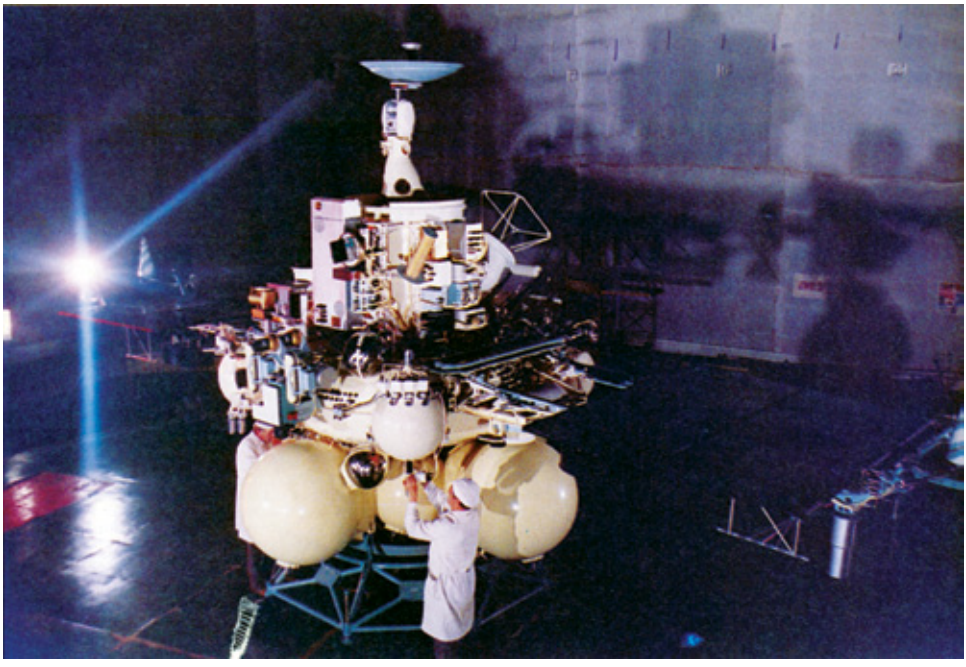
Also unexpected was the discovery of beams of accelerated ions in the magnetosphere, similar to beams of electrons and ions that form the Earth's aurorae when they hit the atmosphere. Unlike the Earth, where these particles form radiation belts or Van Allen belts, around the equator, Mars has no permanent radiation belts. And despite the similarity of the ion beams, the spacecraft did not detect aurorae at Mars.

Among the most interesting results on Mars itself are the infrared images of the planet's surface, taken by the Soviet-made Thermoscan instrument. In these images we see the planet in the heat radiation that it produces rather than reflected sunlight. So the brightness in these images indicates the temperature of the surface. The heart

of the Thermoscan is a highly sensitive infrared detector cooled by liquid nitrogen. Never before has an instrument like this been put in a long-distance spacecraft. Nor has a visible image of a planet been built up from its thermal emission, with the sole exception of the Earth — its "thermal portraits" are transmitted regularly from weather satellites.

From a circular orbit 6000 kilometres in radius, the Thermoscan surveyed a considerable region around the equator of Mars in a sweep approximately 1500 kilometres wide and with a resolution of some 2 kilometres. Its thermal images are remarkable for their sharpness and high contrast— superior to the best television pictures of Mars. The differences in temperature that are revealed indicate the physical characteristics of the surface, especially the degree to which the soil is fragmented. Thus, the thermal images simultaneously offer information on the large-scale features of the surface and on its microstructure. The Thermoscan also detected radiation of shorter wavelengths reflected by the planet's surface. A comparison of the brightness at these visible wavelengths with those at the infrared wavelengths will be very important in interpreting the data.

Another Soviet-built instrument registered Mars's emission not just in two, but in 16 parts of the spectrum. Six of them were in the thermal infrared band, and 10 at shorter wavelengths in the near ultraviolet and visible parts of the spectrum. This instrument could not construct images. But thanks to the large number of wavelengths that it observed, it enjoyed a number of advantages. For example, it made measurements at infrared wavelengths absorbed by carbon dioxide, which allowed it to determine the temperature of the Martian stratosphere. Its observations at shorter wavelengths should help us to understand the nature of aerosol particles in the atmosphere of the planet.



Final preparations for a Phobos craft before launch
on the Proton rocket in July 1988. Credits: TASS

Phobos above Mars: how it might have looked. Credits: Julian Baum/SPL

Another instrument, the French mapping infrared spectrometer, measured the planet's spectrum at 128 wavelengths in the near infrared. A series of absorption bands characteristic of various minerals is located in this range. The data should allow researchers to map rocks made up of different minerals over the planet's surface. In particular, they will show the content of water bound in the structure of minerals. Scientists are also going to make maps of pressures and height of the terrain, using information from absorption lines of carbon dioxide, and to evaluate how much water vapour the atmosphere holds.

A FRESH LOOK AT THE SUN

BOTH of the Phobos craft made important astronomical observations and measurements during the long flight from the Earth to Mars. A joint Soviet-Czech instrument on Phobos-1 investigated X-ray emissions from the Sun. In 14 observation sessions (out of a planned 50), the instrument produced 140 high-quality pictures of the Sun and its corona, the upper layers of the solar atmosphere which are heated to a million degrees.

This solar telescope, specially designed for the Phobos mission, yielded unique data on the distribution and dynamics of hot gas at different temperatures in the atmosphere of the Sun. These will enable astronomers to examine various mechanisms that could produce the atmosphere of the quiet Sun, the hotter gas over "active areas" and large holes in the corona where there is a deficit of hot gas. These coronal holes produce high-velocity streams of charged particles that can affect the Earth's ionosphere.

The telescope on Phobos-1 was also the first to measure the polarisation of radiation from the Sun's helium — in a cloud of hot gas ejected by the Sun on 27 August 1988. It is difficult to measure the polarisation of X-rays even in laboratory conditions, but such observations are essential if we are to understand eruptions on the Sun.

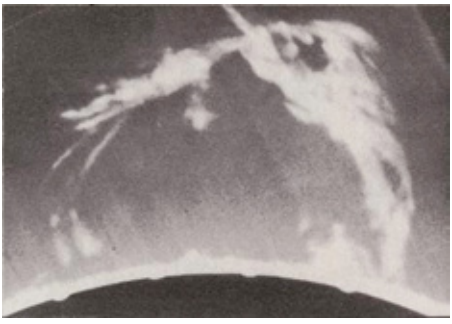
Phobos-2 also studied the Sun and its outflow of charged particles, the solar wind. Its complement of instruments involved Czechoslovakia, Hungary, Ireland, East Germany, France and the European Space Agency, as well as the USSR. They observed an extremely large active region of the Sun from 4 to 18 March 1989, when Phobos-2 was already in orbit around Mars. In this period, the Sun produced a series of major X-ray and gamma-ray flares, with a resulting increase in the force of the solar wind which later caused a magnetic storm on the Earth. Such storms disturb compasses, radar and radio communications, and slow down satellites moving through the atmosphere. In view of the wide coverage provided by the measurements, scientists hope that the data may yield new and important information on how and why solar flares occur.

Both Phobos craft also observed how the Sun vibrates, using an instrument developed by Switzerland, France, the USSR and the European Space Agency. The journey provided several months of data, uninterrupted by periods of night that affect observations of the Sun from the Earth's surface. Solar vibrations should tell us more about the structure and composition of the Sun's interior.

The two craft also observed bursts of gamma rays from beyond the Solar System. Scientists first detected these in the early 1970s. Phobos-1 and Phobos-2 registered more than 100 bursts of gamma rays and observed their rapid changes of intensity in the greatest detail ever achieved.

They found that the bursts can flicker in just a few thousandths of a second, and the spectra of the bursts varies rapidly as well. Some extreme bursts involved changes taking place in less than a thousandth of a second, and spectral lines from gamma rays with energies above 1 megaelectronvolt.

Astronomers are still baffled about the origin of these bursts, and are now trying to match various theories to the new data.



Solar flares burst high above the corona.
Credits: Hale Observatories

Even preliminary analysis of these data shows considerable variations in the mineralogical make-up of the surface. The amount of water bound up in some of the rocks suggests that they are sedimentary, indicating that they formed in bodies of water that no longer exist on Mars. If so, this would provide an important clue to understanding the planet's evolution.

Phobos-2 also studied the vertical structure of the planet's atmosphere, using two linked instruments, one made in France, the other in the USSR. This new method involves measuring the spectrum of solar radiation that passes through the Martian atmosphere when the Sun is seen near the edge of the planet. At this point the sunlight crosses the largest possible amount of atmospheric gas and dust. Successive spectra correspond to different heights above the planet's surface, so an analysis can reveal the distribution of various components in the atmosphere with altitude. The instruments observed at wavelengths corresponding to spectral lines of carbon dioxide, ozone and water vapour, and so for the first time we now have a vertical section of the relative amounts of different atmospheric gases on Mars. Preliminary analysis of the data has shown that at altitudes of 20 to 60 kilometres above Mars, the content of water vapour in the atmosphere is on average close to one ten-thousandth of that of the main component, carbon dioxide. The content of ozone varies considerably with altitude.

One of the major achievements of the mission was the series of television pictures of Phobos. The television system comprised three cameras, a spectrometer, a control system and a video recording system. The light detector in each of the cameras and the spectrometer consisted of a single crystal of silicon, the surface of which contained hundreds of thousands of sensors. These transformed incident light into electric signals in proportion to its brightness.

Many Soviet and foreign scientists helped to develop this system. Soviet specialists were in overall charge and they also devised and built the optics and the light-detecting silicon chips. East German scientists developed a video memory to store more than 1000 pictures for subsequent transmission to Earth, while Bulgarians developed the electronics and microprocessor units, and undertook perhaps the most difficult part of the job — piecing together the system from its separate elements. At various stages, scientists and experts from France, the U.S. and Finland also gave a helping hand.

The controllers initially used the television pictures to help them to navigate. The pictures increased the accuracy of predicting the position of the Martian moon approximately tenfold. As a result, the controllers could correct the probe's orbit and bring it within 200 kilometres of Phobos. The motion of Phobos and its gravitational effect on the spacecraft will provide information on the mass, density and internal structure of the moon.

The spacecraft obtained some 40 images of Phobos, from distances that ranged between 200 and 400 kilometres. They cover more than 80 per cent of its surface. The pictures taken at the minimum distance show details as small as 40 metres across. The photographs from Phobos-2 complement those from Mariner 9 and the Viking orbiters, both in terms of the surface covered and in spectral zones. Phobos-2, for example, produced more detailed photographs of an area west of the largest crater on Phobos, Stickney. The new photographs will do much to determine the shape of Phobos and improve our maps. For the first time Phobos was also photographed in the near infrared. The television pictures show how the brightness of the surface depends

on the angle at which light strikes it, so providing information on the size and shape of the microscopic particles that make up its surface.

A combination of instruments on Phobos-2 provided, for the first time, a spectrum that stretched all the way from the ultraviolet to the infrared, at wavelengths ranging from 0–32 to 3–2 micrometres. This shows that Phobos is very dark, reflecting only 4 per cent of the light falling on it, and that the reflectivity is almost the same at all wavelengths. These properties are similar to a type of meteorite — the carbonaceous chondrites — that occasionally falls to Earth. But Phobos has less water than a typical carbonaceous chondrite, and the surface varies in composition from place to place. The findings show that the temperature of the surface of Phobos is about 300 K (27 °C).

Scientists around the world still have a great deal of data from Phobos-2 to analyse. As well as its successes in observing Mars and Phobos, the spacecraft has been important as the proving ground for future Soviet missions. "The Phobos spacecraft is a new modification of interplanetary probes and has been developed for more sophisticated tasks of space investigation up till the year 2000," says Vyacheslav Kovtunenko, the general designer at the G. N. Babakin Centre. Previous Soviet probes to the planets, including the Venera craft that went to Venus, had their instruments encased in a cylindrical vessel. The instruments on Phobos were arranged in blocks on the outside of the craft. This more versatile arrangement allowed the craft to carry an additional 540 kilograms of scientific payload.

"It is, therefore, an entirely new type of probe," Kovtunenko continues. "We believe it has lived up to expectations. The only malfunction, apart from an operator's mistake on Phobos-1, was due to the more complex problem of integrating command devices used for scientific and control purposes. Today we are fully aware of the kind of changes that need to be effected in the space probe to make it dependable in future launches."

"COSMOS" ANNIVERSARY*

01 JUNE 2007 12:58

Yuri Zaitsev

For 45 years national satellites of *Cosmos* series have been working in the near-Earth space. However, few are aware that *Cosmos 1* launch was the maiden flight for one more special design bureau in the country — OKB-586 from Dnepropetrovsk, headed by Academician Mikhail Yangel. The satellite was lifted by the rocket launcher, made in the same OKB-586 and later also named *Cosmos*. Before that, Yangel's Bureau was mostly engaged with warfare. The satellite and the launcher were the first but by no means the last «peaceful» offsprings of rocket engineers from Dnepropetrovsk.

Yuri Zaitsev, expert, Space Research Institute, Russian Academy of Sciences, for RIA Novosti

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The satellite was lifted by the rocket launcher, made in the same OKB-586 and later also named *Cosmos*. Before that, Yangel's Bureau was mostly engaged with warfare. The satellite and the launcher were the first but by no means the last «peaceful» offsprings of rocket engineers from Dnepropetrovsk. *Cosmos 1*, small in every sense of the word (it did not even carry any scientific payload), paved the way for lots of national spacecraft named "satellites of *Cosmos* series".

For example, *Cosmos 8* was the first spacecraft dedicated to meteorite studies in the near-Earth space. It was the only spacecraft at that time, which had been launched with the sole purpose to assess the hazard that meteorite may pose for manned spaceligths. These data would be used to choose the right materials to protect the cosmonauts.

The result of *Cosmos 26* and *49* launches was that 75 % of the Earth globe was covered with magnetic survey, made actually simultaneously. *Cosmos 215* was, in fact, the first step on the way to deliver the telescopes with modern measuring equipment beyond the terrestrial atmosphere. Important in the scientific program of the *Cosmos* series were the studies of the Earth's atmosphere, solar radiation, cosmic rays, and even such exotic experiments as the search for the antimatter in the Universe by studying its gamma-ray emission born during annihilation. By solving scientific problems, *Cosmos* spacecraft also helped to find the answers to many technical questions, concerning further exploration of space and flight performance of various systems.

Since the program envisaged many launches, serial production was needed. That's why the engineers soon developed variants of standard spacecraft design, which would have common structure (the frame, service systems, etc.), but different scientific payload. These unified spacecraft became the basic ones for the further studies under national *Cosmos* program and, after they had been improved and transferred to a larger launcher, under international *Intercosmos* program.

Their role in the national defense capabilities should also be mentioned. As early as 1962 the first military experimental spacecraft *Cosmos 6* and others were delivered to space in order to test ground-based radar station for missile defense. Some *Cosmos*

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* Originally published on the web by RIA "Novosti" News Agency (now "Rossiya Segodnya") on http://ria.ru/science/20070601/66487911.html — *ed.*

spacecraft were used as targets to test interceptor spacecraft, or so-called “satellite fighters”. Other *Cosmos* satellites could be rightfully called “two-purpose”, since they were used both for scientific and military purposes (the latter were for the most part scientific as well, but quite specific).

All purely military satellites were also called *Cosmos*, be they for photo- or radio surveillance, navigation, missile warning systems, special communication, etc.

This tradition still lives. In 1962–63 24 *Cosmos* satellites were launched, in the next two years — 79. In 1970 72 launches were performed, 81 — in 1971, 85 — in 1979, 100 — in 1974.

Today Russian scientists as well as Russian military can nothing but dream about such numbers.

The editorial board may not share the author’s opinion.

IKI RAN: YESTERDAY, TODAY, TOMORROW*

Yuri Zaitsev

In July 1963 the President of the Academy of Sciences of the USSR Academician Mstislav Keldysh in a letter addressed to the national governing bodies proposed to organize a Joint Institute for Space Research within the Academy of Sciences. Its main goal would be systematic exploration of outer space with standardized small and then heavy artificial satellites, made in the country. The Institute should develop and build scientific equipment, mount it on serially produced spacecraft, prepare them to launch, and participate in launches [Институт..., 1999].

By that time the Soviet Union had launched the first artificial satellites of the Earth and started to explore the Moon and planets of the Solar System. Many outstanding results were obtained, which determined the leading position of our country in this novel field of science and technology. Main directions of space research were also justified. But those were only the first steps on the path of exploration of the Universe. At that time space research was made by separate institutes of the Academy of Sciences, as well as by engineering and industrial facilities of various ministries and departments. At the dawn of the space era this form of space experiments fully justified itself, because launches were singular and every space experiment was installed aboard, in fact, unique spacecraft. Further research aimed at a more detailed, in-depth study of outer space, systematic accumulation and compilation of data, specialized experiments demanded not just a broader field of research and new scientific and engineering organizations, but their effective cooperation as well.

Mstislav V. Keldysh, president of the Academy of Sciences of the USSR

According to Keldysh, this task could be solved by establishing a scientific and methodological center (or institute), which would significantly streamline the work underway, eliminate overlaps, and make the activities more structured, so that all areas of scientific space knowledge would develop. Finally, such a center would make it possible to get as much new data as possible at the lowest cost [Институт..., 1999]. Most importantly, the Institute would be the customer for all research satellites, thus avoiding that their specifications are imposed by manufacturer rather than scientists ("Here's your spacecraft, you are free to refuse, if you don't like it, but you won't get another").

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IKI Main Building

According to Keldysh, such Joint Institute should have a regular staff of highly experienced scientists with background in space research; and a batch of well-equipped laboratories and production facilities, a data processing center for quick access to information, test facilities for prelaunch tests. The Institute was envisioned as the leading organization for basic science space research.

Keldysh's proposal was approved and the Institute was established, albeit with far less authority than had been planned initially. Government Resolution No. 392-147 from May 15, 1965, was signed by the Head of the Government A. N. Kosygin. In the same day it was preliminary approved by the Resolution of the Presidium of the USSR Communist Party Central Committee No. P202/16. The Ministerial Council gave the Academy, the Ministry of General Machine Building, and Ministry of Defense two months to outline the Provision of the Space Research Institute of the Academy of Sciences, which should be approved by the Commission on Military and Industrial Issues. The Provision envisaged that the Institute is to be built immediately.

<...> 5. To allow the Academy of Sciences of the USSR to build in 1965—1967, by way of exception, in Moscow laboratory buildings for Space Research Institute, with the total work area of main assignement up to 30 thousand sq. meters.

Moscow City Executive Committee is to allocate land area to the Academy of Sciences of the USSR for the construction of aforementioned buildings.

The construction works for the Space Research Institute buildings are to be entrusted to Glavspezstroi by State industrial committee on assembling and special building works of the USSR.

6. To allow the Academy of Sciences, by way of exception, to include the construction works of the laboratory and production buildings of Space Research Institute in the plan of capital works for 1965—1966 without properly approved construction documentation.

<...> The State Bank of the USSR is to finance the building of the aforementioned objects, up to the moment when the construction documentation is approved, on the basis of projects and financial estimates, made according to working drawings.

At the same time, the Space Research Institute (or IKI, short for "Institut Kosmicheskih Issledovany" in Russian) was not granted the customer's rights for scientific spacecraft. Ministry of General Machine Building Industry, then the producer and the customer of space technology at the same time, was uncompromising in this question. Perhaps, this was one of the reasons for today's weakening of Russia's positions in space research.

Neither was the Institute named "Joint" as had been initially proposed by M. Keldysh's, although it was formed from many divisions and departments of the institutes of Academy of Science and other bodies (including S. Korolev's OKB-1), that had dealt with space research.

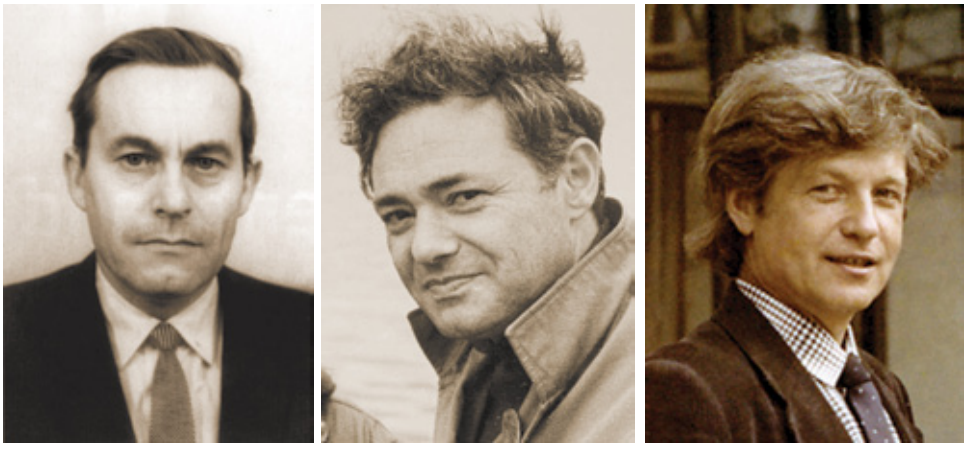
The Institute was in charge for experimental activities in the following fields of space physics: astrophysics; physics of planets and small bodies of the Solar System, solar physics and solar-terrestrial interactions, space plasma research and nonlinear geophysics. It also was commissioned with development of space research programs; development and testing of technologies for the projects included in the national space program [Зеленый, Зайцев, 2005].

Mstislav Keldysh did not only establish IKI, but was, in fact, the driving force of its forming, especially in the first and most difficult years. Symbolically, the Institute's building is located on the square bearing Keldysh's name. There was a project of a statue of this famous academician, however it has not yet been built.

THE STRUCTURE OF THE INSTITUTE

Over the years IKI was headed by Academician G. I. Petrov (1965–1973), Academician R. Z. Sagdeev (1973–1988), Academician A. A. Galeev (1988–2001); in 2002 academician L. M. Zelenyi was elected its director.

The structure of Institute changed throughout its history as did the scope of tasks it was engaged in, and the changes were sometimes truly radical.



The pioneers of the Institute:
G. A. Skuridin (left), Yu. I. Galperin, O. L. Vaisberg (right)

Georgy I. Petrov (1913–1987) — the first director of the Institute. Doctor, corresponding member of the Academy of Sciences in 1953, and full member in 1958. Physicist with specialization in mechanics, whose name is closely connected to many outstanding achievements of national rocket technology in the second part of the XX century.

An extraordinary scientist, Georgy I. Petrov posessed both wide and deep insight of the physical phenomena, which allowed him to grasp their essence and to build an adequate mathematical model to describe them. A theoretician as much as an experimenter, he was among the first to justify the potential of high-speed computers for mechanics and made a large contribution to aeromechanics of high speeds and thermal insulation of spacecraft, entering the atmosphere with supersonic velocities close to orbital velocity

One of the first scientific departments in the Institute was the Department of Geophysics and Space Plasma Physics. It was formed from a group of theoreticians headed by G. A. Skuridin (previously at the Department of Applied Mathematics of the Steklov Mathematical Institute of the USSR Academy of Sciences) and Laboratory of Aurorae (Institute of Atmospheric Physics, also from the Academy) headed by Yu. I. Galperin. Within the Department there was space plasma working group headed by O. L. Vaisberg.

Cosmic Rays department was established almost in the same time, and its field of interest was quite close to that of the Department of Geophysics. Another department, which studied space plasma and space gas dynamics, was headed by Academician G. I. Petrov. It included theoretical (V. B. Leonas) and experimental (V. B. Baranov) laboratories. Later they were joined by a group headed by I. M. Podgorny (from the Kurchatov Institute for Atomic Energy), who formed a separate laboratory.

Roald Z. Sagdeev — IKI director in 1973–1988. PhD, Professor, corresponding member of the Academy of Sciences in 1964, and full member in 1968. He worked at Kurchatov Institute and Institute of Nuclear Physics (Siberian Branch of the RAS), where he became one of the founders of the modern plasma physics. After 1988 R. Z. Sagdeev headed analytic research department of the Institute.

He authors numerous works on plasma (shock waves, transfer processes, instabilities) and space physics. Among the most renown is his theory of collisionless shock waves, which is one of the keystones of modern space physics, thermonuclear fusion, and many other fields. He was awarded with Lenin prize (1984) for development of neoclassical theory of transfer processes in thoroidal plasma. R. Z. Sagdeev founded a school in physics, which counts tens of PhD's and is acknowledged worldwide

Albert A. Galeev — IKI director in 1988–2001. PhD, Professor, corresponding member of the Academy of Sciences in 1987, and full member in 1992. Specialized in plasma physics. He graduated from Novosibirsk State University; while studying, he also worked at Institute of Nuclear Physics (Siberian Branch of the RAS). In 1973 he started working at IKI, where he headed Space Plasma Department.

His bright talent and energy were the keys to his unique results in space physics. He elaborated a theory of explosive reconnection of force lines in the tail of the magnetosphere, the theory of weak wave interactions in plasma, and, together with Sagdeev, neoclassical theory of transfer in tokamaks. He suggested a theory, explaining solar wind acceleration from coronal holes by Alfven waves

They were engaged in laboratory modeling of solar wind interaction with the Earth's magnetic field and atmospheres of planets [Георгий Иванович Петров..., 2012].

In 1971 a large group of scientists, led by K. I. Gringauz (from the Radio Technical Institute of the Academy), formed an independent department for experimental studies of solar plasma.

Shortly afterwards the Department of Geophysics was transformed into Space Plasma Physics Department headed by L. L. Vanyan (previously at the Institute of Physics of the Earth of the Academy of Sciences).

As a result of yet another reorganization in 1972 a new plasma department was organized, 'outside' the regular structure. A newcomer to the Institute R. Z. Sagdeev volunteered to head it. After he had been appointed the Director of IKI, he invited one of his students A. A. Galeev to head the plasma department, transformed into Plasma Physics Department in 1973.

Lev M. Zelenyi — IKI director since 2002. PhD, Professor. In 1972 he graduated from the Moscow Institute of Physics and Technology (Department of Aerophysics and Space Research) and began working at IKI, starting as an engineer. Corresponding member of the Academy of Sciences in 2003, and full member in 2008. Vice president of the Russian Academy of Sciences since 2013, the chairman of the Space Council of the RAS.

Main area of research — space plasma physics. Well-known expert in the theory of collisionless plasma, magnetic fields reconnection, charged particle dynamics, magnetosphere physics. Principal Investigator of one of the most successful international space missions *Interball*. Today — Principal Investigator (Russian part) of *ExoMars* international project and national lunar program. Awarded with the Prize of the President of the Russian Federation

Space Gas Dynamics Department. In the center by the table —
the head of the department, Academician G. I. Petrov

“Space Research of the Earth as an Ecological System” Department, 1991

Besides A. A. Galeev's theoretical laboratory, this new department consisted of Yu. I. Galperin's Laboratory of Aurorae (later renamed to Laboratory for Magnetosphere Processes), laboratory for Circumplanetary Plasma based on K. I. Gringauz's Department for experimental solar plasma studies, I. M. Podgorny's modeling laboratory, and O. L. Vaisberg's Space Plasma and N. F. Pisarenko's Solar Cosmic Rays Groups, which later were transformed into labs.

Later plasma studies in the institute continued to "improve", according to the new Institute director R. Z. Sagdeev. A. A. Galeev headed a new theoretical department and G. A. Skuridin — the Department of Solar-Terrestrial relations. After A. A. Galeev was elected the director of IKI, L. M. Zelenyi became the head of the Space Plasma Physics Department.

Study of planets and small bodies of the Solar System has always been one of the main areas of Institute's research. However, initially these activities were distributed among multiple departments. Not long before his retirement from the office of director G. I. Petrov decided to reorganize the planetary realm, combining several research laboratories into a single Department of Moon and Planets, under his personal leadership. However, it did not find understanding of the new director R. Z. Sagdeev. A number of laboratories engaged in lunar and planetary studies were soon closed, and the Department of Moon and Planets (after being renamed to Comparative Planetology Laboratory) was transferred to Institute of Geochemistry and Analytical Chemistry of the Academy of Sciences. Soon both manned and unmanned moon programs start being scrapped across the USSR. By the early eighties this subject was virtually eliminated in IKI and was revived only recently.

The integrated Planetary Research Department was formed in IKI in 1974. It was headed by V. I. Moroz and included four laboratories: spectroscopy (V. I. Moroz), infrared photometry and radiometry (L. V. Ksanfomaliti), mass spectrometry (V. G. Istomin), physical and chemical planetary exploration (L. M. Mukhin).

The department was initially limited in its subject by physics studies of atmospheres and surfaces of planetary bodies. It was assumed that geologists and television survey experts would be gathered in separate divisions. One of them was, in particular, the Department of Optical and Physical Measurements. The team of scientists and engineers from the Moscow Institute of Geophysics, Aerial Photography, and Mapping, led by B. N. Rodionov, joined IKI in 1967 and made the backbone of this department. By the time of their transition the team have been researching satellite imagery and video processing for already 10 years. One of the department's first results in IKI was topographical analysis of the lunar surface by the images transmitted by *Lunokhod 1* and *2*. For the most part the department was focused on orbital observations of the Earth, on one hand refining photographic techniques and remote sensing methods, on the other — selecting tasks that could be solved by satellite imagery. After a series of administrative reforms and other changes, including changes of the name, the department has retained its optical and physical specialization.

In 1967 a scientific division for radio instruments was established in IKI from the Radio Laboratory of the Lenin Moscow State Pedagogical Institute. As the microwave receivers developed by the group were getting more sophisticated, they started to be used to study the land and the ocean from space. In 1974 the group was reorganized in a separate Department for Applied Space Physics led by V. S. Etkin. The first task of the department was to study processes in a deep ocean by their effects on its surface. But by the early 1990s due to cut in funding of the ocean research, the department's

activities drifted towards environmental studies. Therefore V. S. Etkin suggested another name for his department, which sounded "Space Research of the Earth as an Ecological System".

The laboratory of space physics that once had been the part of the department (headed by V. S. Etkin) became a department of its own. The newly established entity named Applied Space Research Department (later Space Physics) was initially headed by S. S. Moiseev, and after his death by N. S. Erokhin.

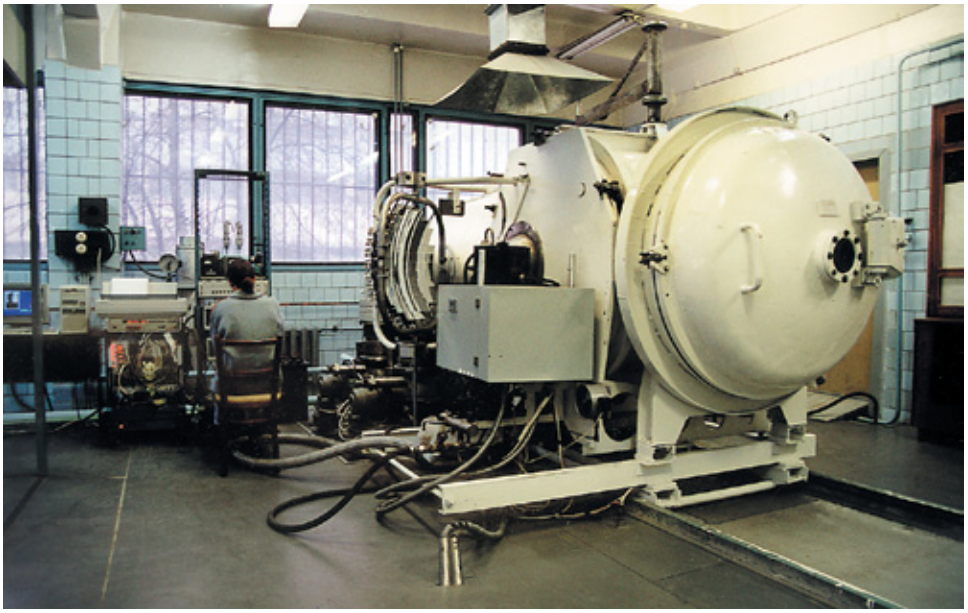
The Department of Astrophysics (head I. S. Shklovsky) based at the Department of radio astronomy of the MSU Shternberg State Astronomical Institute has undergone a major reformation *on par* with the Moon and Planetary Department. Its scientists, before they joined IKI, had already had sufficient experience in space astronomy. Each year the department's scope of work was widening. Shklovsky sought to focus on the "big" of astronomy, i.e. studies of the Galaxy, its star population, and extragalactic objects and cosmology. However, in 1985 he passed.

By that time the Institute had already for more than 10 years had the department of Theoretical Astrophysics led by Academician Ya. B. Zeldovich. It focused at theoretical research in cosmology, study of hot gas in galactic clusters and spectrums of accreting disks around black holes and neutron stars. After the objectives of these two departments were separated and Zeldovich's department was reinforced with an X-ray lab and several specialists from Shklovsky's former department, the department of theoretical astrophysics was transformed into Department of High Energy Astrophysics headed by R. A. Sunyaev. The Department of Astrophysics headed by its new Director N. S. Kardashev joined the P. N. Lebedev Physics Institute of the Academy of Sciences in 1990–91 [Зайцев, 2005].

Several separate laboratories were established during the early years of IKI. Among them are the laboratory (later department) of astrophysics and applied millimeter, submillimeter and infrared technologies; special laboratories for the Earth remote sensing; laboratory for spectrometry of cosmic gamma radiation; laboratory for active diagnostics; laboratory for very long baseline radio interferometry.

Data from the first high-altitude rockets, artificial Earth satellites, lunar and interplanetary probes were processed at the Department of Applied Mathematics (namely in the Information and Calculation Bureau). In 1966 almost all Bureau staff joined IKI and formed the Department of the Automated Telemetry Processing. In 1988 it was merged with the Department of Ballistics. From that point on IKI had a fully-fledged department for telemetry processing, whose main task was full information support of space experiments.

Ya. B. Zeldovich and I. S. Shklovsky



Vacuum chamber with the Sun radiation simulator

Design and construction of scientific complexes onboard interplanetary spacecraft, tracking platforms, onboard systems, control logic, data acquisition and transmission, etc. was assigned to the Department of Software-controlled Systems (head B. N. Novikov).

Control Testing Facility and Flight Testing Facility (KIS and LIS respectively, according to Russian abbreviation) were created to test the instruments before they were mounted on spacecraft, and to study their performance within onboard systems and under the space conditions. V. M. Ratner, former IKI deputy director, was the supervisor for the design specification of these two testing facilities, approved in 1972 by M. V. Keldysh. Their building was finished in 1976, and the facilities were headed by A. L. Rodin. To a large extent it was his efforts, which brought into life modern testing equipment to run every main type of tests. The facilities are equipped for mechanical (vibration, shock, linear overload), thermal vacuum, and climatic tests as well as tests for electrical compatibility and insulation. During fine-tuning at these facilities the instruments are gradually adjusted according to their specs.

IKI test facilities are certified as the test center for the Academy of Sciences and are part of a Federal System of Certification of Space Equipment, which is entitled to test scientific space instruments according to certificate testing.

In 1967 IKI was reinforced with the Design Bureau (OKB IKI), an engineering organization with a pilot production facility, in Frunze (now Bishkek, the capital of Kyrgyzstan). After the collapse of the Soviet Union this OKB became a foreign organization and now is a contractor of IKI.

A terminal station with automated scientific data processing and transmission system was built at Deep Space Communication Center in Yevpatoria (Crimea). A pilot production facility for scientific instruments was established in Tarusa (Kaluga region) — Special Design Bureau for Space Instruments Development (SKB KP IKI).

It was founded under the order of the Academy's Presidium from 30 June 1978 to build test production line for instrument building for space research. In recent years it works on as the instrument-making department of IKI [Добриян, 2011].

The current Institute structure includes 15 main departments, 16 service departments, and 2 construction departments. The research departments are Space Geophysics (Prof. N. S. Yerokhin); High Energy Astrophysics (Dr. M. N. Pavlinsky); Planetary Physics (Dr. O. I. Korablev); Space Plasma Physics (Dr. A. Petrukovich); Studying Earth from Space (Prof. Dr. E. A. Sharkov); Earth Remote Sensing Technologies (Dr. E. A. Lupyan); Optical and Physical Research (Dr. R. V. Bessonov); Space Dynamics and Mathematical Information Processing (Dr. R. R. Nazirov); Nuclear Planetology (Prof. Dr. I. G. Mitrofanov); Theoretical and Observational Astronomy and Radiointerferometry (Dr. S. G. Moiseenko); Onboard and Special Instruments R&D (I. V. Chulkov). Integrated Departments for Patenting and Innovation Management (G. S. Ustinova); Computer Networks and High-performance Clusters (A. Alexandrov); Ground Control and Operation Complexes (V. Nazarov), and Educational Outreach Centre (Dr. A. M. Sadovsky) are also considered as main departments.

In 1986 IKI was awarded with the Order of Lenin for significant contribution to national science and technology development. R. Z. Sagdeev, the director of the Institute, was awarded the Title of Hero of the Socialist Labour. Orders and medals were also awarded to many Institute staff members.

ACHIEVEMENTS AND PROSPECTS

Not all IKI activities deal with space experiments, but this type of projects is where efforts of hundreds of people come together to embody the essence of space science.

The Institute specialists were directly involved in preparation and performing space experiments, collecting and processing data from spacecraft, launched under national space program as well as within international collaborative projects. In recent years they were also very active in international projects as co-investigators. Total, they participated in more than 100 space launches.

In some projects scientists and specialists of the Institute developed and tested onboard scientific equipment, and then did research with their help (*Mars Global Surveyor*, *Venus Express*, *Mars Odyssey*), in others they received and processed data from spacecraft, analyzed and interpreted it (*Integral*).

Without doubt, one of the most prominent and successful was VEGA international project — Comet Halley flyby made by two spacecraft *Vega 1* and *Vega 2* built in Lavochkin Design Bureau. For the first time ever *in situ* measurements of the comet were made, which yielded data on its composition and interactions with magnetic field and solar wind. The interplanetary stations were Soviet, but scientific payload was designed in built and 9 countries. The project comprised comet flyby and studies of Venus (hence the name of the project VEGA, which is short for "VEnus and HAlley's" (since "Halley" is pronounced as "Galley" in Russian). The latter included experiments aboard descent probes and in the atmosphere, on drifting balloons.

Space Research Institute is the principal research institute for space science in Russia. Together with other science and industrial institutions it makes proposals for the Federal Space Program, which is formed by the Space Council of Russian

Academy of Sciences and its dedicated committees in cooperation with the Federal Space Agency (Roscosmos)*.

IKI implements the Federal Space Program. In a number of projects adopted by this Program it coordinates scientific equipment development and joint work of all collaborators, including international partners. In other projects, both Russian and foreign, IKI enters research programs and supplies part of scientific equipment, processes information, provides ballistic and navigational support.

In 2003 Education Outreach Center was established to cooperate with various educational institutions, to work with young scientists and students, to participate in exhibitions and science festivals, and to promote space science and cosmonautics. It organizes tours at IKI's exhibition, where original instruments and spacecraft mock-ups are shown.

Current research and development works correspond to a wide range of astrophysical and cosmological problems, such as the origin, structure, and evolution of the universe, the nature of dark matter and dark energy, exploration of the Moon and the planets, the Sun and solar-terrestrial interactions, development of technologies for extra-atmospheric astronomy and space research, coordinate and time support of fundamental research and everyday activities.

Still an important issue is temporal and spatial distribution of neutron fluxes and spectra in the near-Earth space. From February 2007 joint measurements were run as a part of the program "Science on the ISS" implemented on the Russian segment of the International Space Station, which used BTN-M1 instrument aboard the ISS and HEND instrument aboard NASA's *Mars Odyssey* Martian spacecraft, both developed in IKI. Combining these data the scientists evaluated neutron component of background radiation in all parts of interplanetary cruise trajectory "Earth-Mars-Earth", received synchronous data of neutron fluxes in Earth and Mars orbit, and collected data on GRBs, which are used to determine their coordinates on the celestial sphere. The work is still in progress.

Other important areas of basic research are scientific approach to methods and technologies of study of the Earth's surface, subsurface and atmosphere, ionosphere and magnetosphere, hydrosphere and cryosphere; computer simulation and geoinformatics: geoinformation technologies and geospatial data infrastructure; evolution of the Earth and climate under the influence of natural and anthropogenic factors; scientific principles of environmental management and sustainable development; territorial organization of economy and society.

Finally, yet another area of today's basic research in IKI is theoretical mechanics; navigation systems; celestial dynamics, vehicle and control dynamics; mechanics of living systems [Зеленый, Зайцев, 2014].

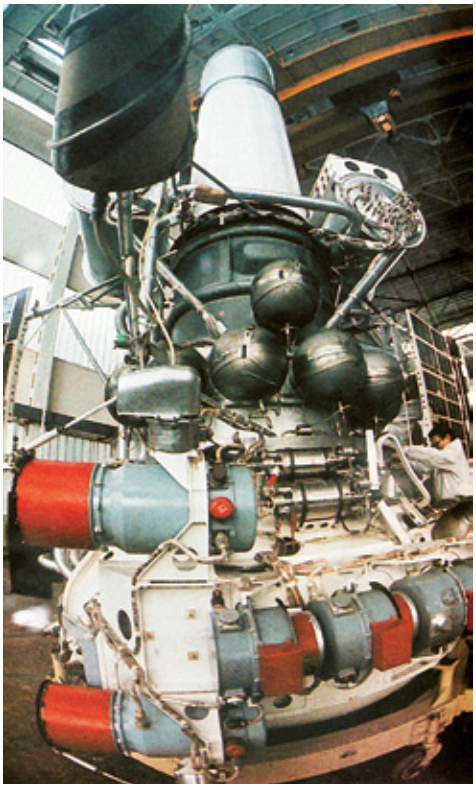
Projects like *Prognoz*, *Interball*, *Plasma-F* did not only contribute to Sun activity and solar-terrestrial relations studies, but brought science even closer to meeting the everyday needs. We now have the opportunity to compare and forecast changes in biological and technological processes on the Earth following the Sun activity.

However, many problems are yet to be solved. How the solar wind is formed, what heats the solar corona to two million degrees, while its surface temperature is many times lower. With the launch of the *Interhelioprobe* spacecraft scientists hope to get clues for the answers.

* Now State Corporation ROSCOSMOS — *ed.*

Institute staff and their American colleagues during
Mars Global Surveyor descent module assembly

IKI Press Center of VEGA project, the first images
of Comet Halley has just appeared on the screens



Astron space observatory

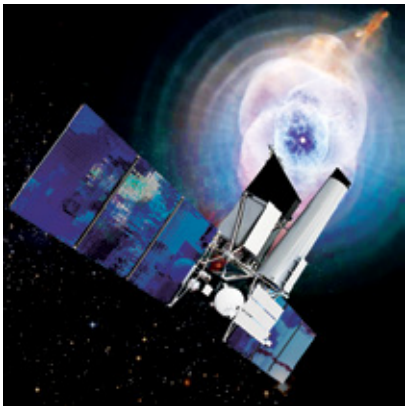
The spacecraft will study our star from the minimal safe distance — less than 40 solar radii, so the Russian project will fill the gap in the solar studies. While the Sun is currently under surveillance of a half a dozen spacecraft operated by various nations, they all work closer to the Earth than to Sun, and most of them on near-Earth orbit. *Interhelioprobe* orbit will be slightly inclined to the solar ecliptic so it would "see" solar polar regions, which are hard to observe from the Earth and near-Earth orbits.

Another important point is that there are no collective plasma flows, which can be called "the wind" near the surface of the Sun. The wind can only be registered at a distance of several solar radiuses from the Sun. It is of particular interest to observe from this very region the processes accelerating the solar wind. It is also unclear why the flux of neutrinos reaching Earth is two times weaker than predicted by theory. There is a recent suggestion that hypothetical dark matter particles in the solar interior capture some of the neutrinos.

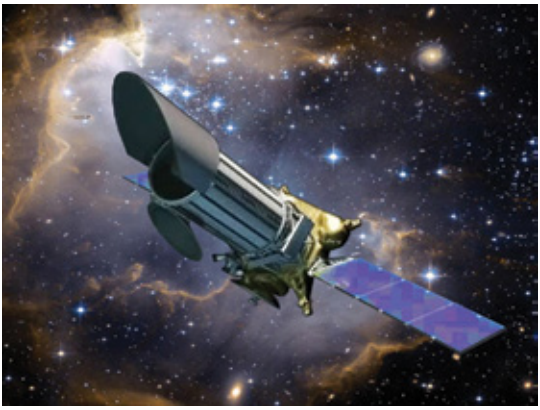
Four *Resonance* satellites to be launched in 2017–2018* to study the outer zone of the Earth's radiation belt where, in particular, geostationary satellites operate. The project will study the so-called relativistic electrons — the main component of the radiation belts, which are the main hazardous factor to communication satellites in geostationary orbits. *Resonance* orbiters will study with high temporal resolution the processes of electron acceleration after interaction with electromagnetic waves.

The first national special satellite for astrophysics — *Astron* space observatory — was launched in 1983. It worked successfully for 7 years and was that time the longest working spacecraft. Even more advanced X-ray observatory *Granat*, launched in 1989, operated for almost 10 years. Further development of Russian astrophysics is connected with *Navigator* bus for satellites developed by Lavochkin Design Bureau. It is a one-fits-all bus for many types of spacecraft. Depending on the given task, it can operate at low circular, elliptical, high elliptical and geostationary orbits and libration points. In particular, *Spektr-R* (*RadioAstron*) space observatory was based on this bus. Another observatory under development, which is *Spektr-RG*, to be launched to the libration point L_2 is also based on *Navigator*. It is a joint project of Russia and Germany.

* According to the new Federal Space Program, the launch is scheduled for 2021 and later. — *ed*.



Spektr-RG space observatory



Spektr-UV space observatory

The observatory is based on two grazing incidence X-ray telescopes: eROSITA (Germany) and ART-XC (Russia), overlapping together the 0.2–30 keV energy region. It will provide an X-ray survey of the entire sky with a sensitivity of almost hundred times the sensitivity of existing sky surveys, and will extend them into hard X-ray.

Future of ultraviolet astronomy for the next decade is linked to the launch of the space observatory *Spektr-UV* (*World Space Observatory — UltraViolet*, or WSO/UV), also built by Lavochkin Association based on the *Navigator* bus and designed for spectroscopy of weak UV-sources.

The universe is poorly studied in the ultraviolet range and in the coming decade the UV-band studies will only gain importance. The areas selected for the research and the Observatory specifications will for at least the next 10–15 years maintain high scientific importance of the project and ensure that the tasks are executed at the highest technical level [Зеленый, 2008].

As seen now, the global goal of the world space flights in this century is to explore the Solar System, to take human civilization to a higher level of development, while ensuring its security and survival in conditions of potential natural and man-made disasters of both terrestrial and cosmic origin.

As of today only two celestial bodies are the nominates for potential area of interest for human exploration. They are the Moon and Mars. Speaking of continuous exploration, in particular establishment of a lunar base with visiting crews or even permanent human habitation, the first step should be to explore the Moon carefully, define its most interesting regions, and point the directions of exploration. Those preliminary tasks need a series of automated stations. Such a series is scheduled for 2018–2020*. Along with studying the Moon some key technological aspects are also to be addressed during the implementation: landing, soil sampling, driving a vehicle on the surface of another planet, finally, automatic delivery of soil samples to the Earth.

To emphasize the continuity of Russian and Soviet lunar programs, the names of the new missions will continue the numbering started by the Soviet *Lunas*. The first of the series, *Luna 25* will land in the polar region. Then the orbiter *Luna 26* will be launched, and a year later — the second lander *Luna 27* a drilling unit.

* In 2019–2022, as of August 2016. — *ed*.

Luna 26 orbiter (left) and *Luna 28* automatic station (right)

The second step of the program is to bring lunar soil from the polar region (*Luna 28*) and deliver the rover *Luna 29* (scheduled for 2020s).

The spacecraft lifetime are estimated to be about a year. The landers will do research near the lunar poles. The orbiter will mainly work to study the Moon and near-moon space at a low circumlunar orbit of 200 km, after that it will be put into a higher orbit (500–700 km), and proceed with experiments to study cosmic rays.

It should be noted that the schedule for this program is not a reiteration of Soviet undertakings. The scheduled lunar missions [Зеленый, 2011] are aimed primarily at the polar regions of the Moon, which barely resemble the equatorial regions explored in 1969–1970.

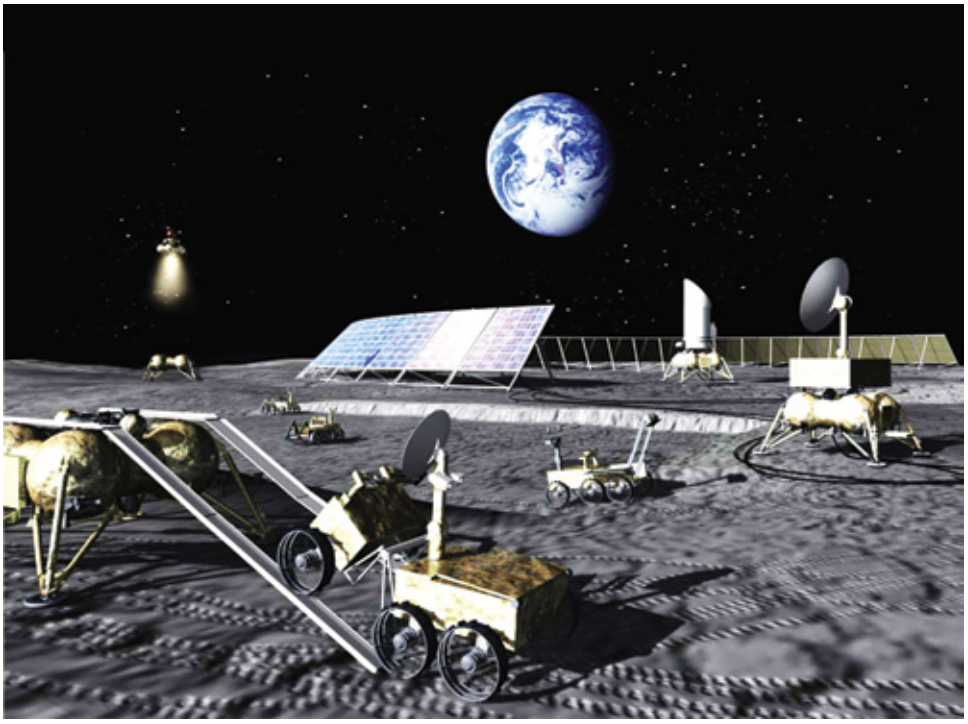
Technologies employed during the lunar missions will also be used in future Martian projects. Russian Mars program primarily includes full participation in the European *ExoMars* project with not only joint experiments, but also joint infrastructure: ground communication and deep space mission control center. In the course of the project Russian *Proton* launchers will loft two missions in 2016 and 2018*.

Then ESA's Mars rover will land on the planet using Lavochkin Association descent module. The rover will do geological studies and search for life in the subsurface layer of soil near the landing site.

Then in 2022 the Martian moon Phobos is planned to be revisited**. This task was previously assigned to the failed *Phobos Sample Return* project. The very name of the new project *Boomerang* represents this return. Delivery of soil samples from Phobos is an interesting scientific problem, which is not yet scheduled in the space programs of other nations. Moreover sampling soil from Phobos and bringing it back to the Earth is an exercise of technology for delivering soil from Mars. Such a mission is planned for 2020s.

* The first mission was successfully launched on 14 March 2016, the second stage was rescheduled for 2020. — *ed*.

** In 2024, as of August 2016. — *ed*.



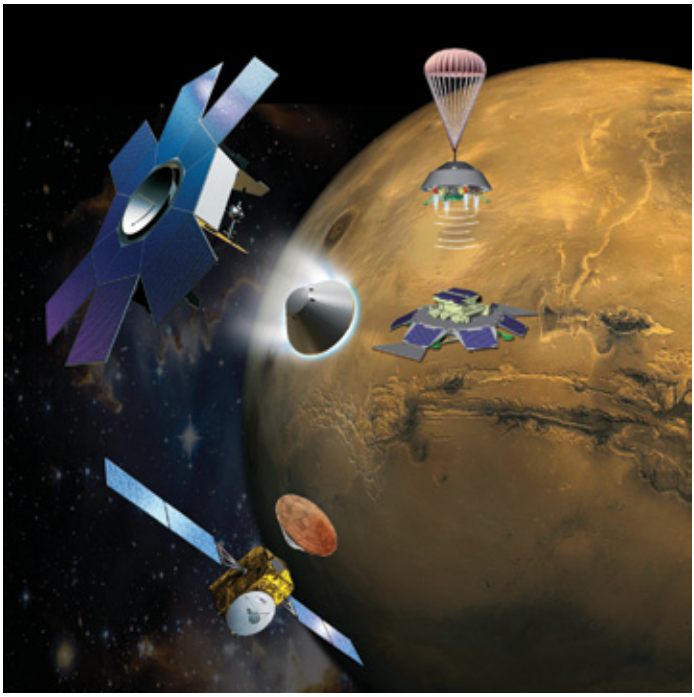
Future lunar science base

As for Mars, it still remains the subject of scientific studies rather than exploration: the planet is too far away to discuss its real benefits to mankind today. Even the possibility of a single human flight is questionable, first of all with regard to radiation safety of the crew during the mission.

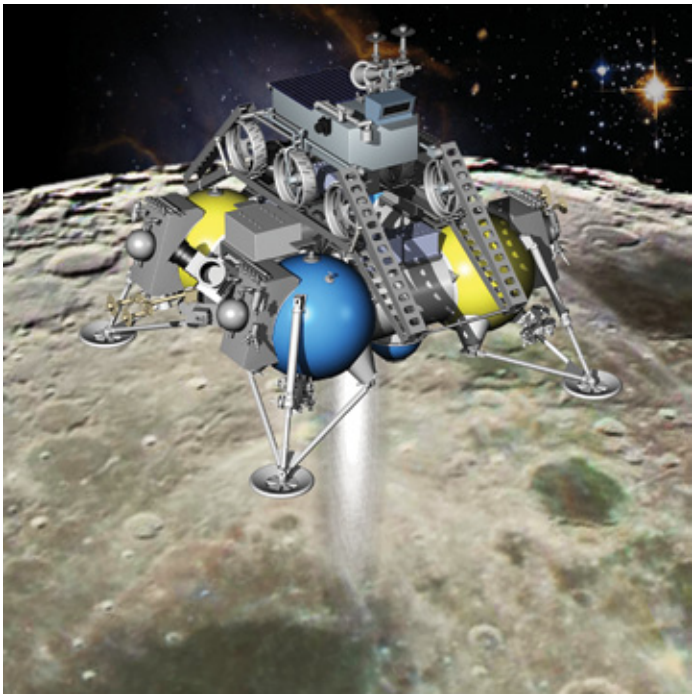
The Moon is a different case. It has a practical interest besides its scientific potential. In particular it may be used as a site for astronomical observatories with no hindering atmosphere and ionosphere, as is the case on the Earth and near-Earth orbits. And, of course, the Moon as our satellite may become a source of fossils, especially rare metals, since they are limited on Earth. The Moon is likely to become the first stage of preparation for the manned expedition to Mars, should we overcome the difficulties of interplanetary flight.

Exploration of the outer reaches of our Solar System is of great interest, if we wish to understand its origin and evolution. After 2020 Russia plans to launch to Jupiter, or rather to its moon Ganymede, the first mission, which will land on the moon's surface.

The trip to Jupiter will take about eight years and will use combined ballistic scheme consisting of four gravity assists from Earth and Venus at the mission's heliocentric stage and will complete with a whole cascade of such maneuvers around Jupiter's moons. Landing on Ganymede is a separate difficult undertaking. Both in scientific terms and its technical complexity such a mission may become a flagman project for Russian cosmonautics.



ExoMars-2016 spacecraft



Lunokhod is delivered to the lunar surface by *Luna 29*

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