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SOME RESULTS OF U.S.S.R. EXPERIMENTS IN THE IONOSPHERE AND INTERPLANETARY SPACE

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ABSTRACT

A review is given of the results of some experiments made in 1961–62 which are a part of the Soviet programme of upper atmospheric and interplanetary space investigations. These include rocket measurements of electron densities and electric fields in the ionosphere, ion density and composition changes in the upper ionosphere determined by the satellite Cosmos 2, and plasma measurements in the magnetosphere and interplanetary space made in the space probe Mars 1.

RÉSUMÉ

L'auteur passe en revue les résultats de quelques expériences réalisées en 1961 et 1962 dans le cadre du programme soviétique de recherches sur la haute atmosphère et l'espace interplanétaire. Ces expériences comprennent des mesures par fusées des densités électroniques et des champs électriques dans l'ionosphère, des variations de la densité ionique et de la composition de la haute ionosphère déterminée par le satellite Cosmos 2, ainsi que des mesures de plasma dans la magnétosphère et l'espace interplanétaire effectuées par la sonde spatiale Mars 1.

1. IONOSPHERIC EXPERIMENTS BY MEANS OF GEOPHYSICAL ROCKETS

1.1. *The Determination of Electron Density*

Experiments involving studies of the ionosphere by means of coherent radio waves in the metre-band emitted from vertically launched geophysical rockets of the U.S.S.R. Academy of Sciences have been conducted since 1954. In 1958 these experiments were for the first time conducted in the outer ionosphere (above the main ionization maximum) up to a height of the order of 470 km [*1*]. The technique and the devices used in these experiments are described in detail in the literature [*2, 3*]. Results of experiments conducted in 1958 were presented to the previous URSI General Assembly in London in 1960 by A. N. Kazantsev [*4*]. These measurements have been continued by the same technique. They were aimed at obtaining data on the variations of the structure of the ionosphere (including the part lying above the main ionization maximum) in a period of decrease of solar activity from its maximum to its minimum. Measurements were made using frequencies of $f_1 = 24$ Mc/s, $f_2 = 2f_1$ and $f_3 = 6f_1$. Rockets were launched up to a height of the order of 500 km. Measurements of radio wave dispersion and the Faraday effect were made on the ground.

Fig. 1 shows the results of electron density measurements conducted at the same geophysical point in a medium latitude zone of the European territory of the U.S.S.R. in the same season (autumn) and approximately at the same time of day in three separate years. Curve 1 refers to a launch time of 15 h. 54 min. on October 31, 1958, curve 2 to 15 h. 00 min. on November 15, 1961, and curve 3 to 11 h. 30 min. on October 18, 1962. Curve 2 was published in [*5*], curve 3 is taken from Rudakov's paper [*6*].

From Fig. 1 it is evident that the decrease of solar activity causes not only a decrease of maximum electron density in the ionosphere (which has been known from measurements of critical frequencies of the F-layer), but also a change in the vertical electron density distribution N_e above the maximum (the decrease of N_e with height becomes more rapid).

Vertical launchings of geophysical rockets of the U.S.S.R. Academy of Sciences were accompanied by simultaneous recordings of height–frequency characteristics of the ionosphere made at an ionosphere station situated near the launching pad. Gringauz and Gdalevich have compared simultaneous measurements of $N_e(h)$ obtained during three rocket flights (by means of radio waves emitted from rockets) and by an ionosphere station [*7*]. Comparison was made in a dual manner. Firstly, $N_e(h)$ profiles were calculated from ground-based ionograms by the Shinn–Kelso method [*8*] and were compared with $N_e(h)$ distributions from rocket data. Secondly, height–frequency characteristics were calculated on the basis of rocket data and compared with the corresponding characteristics obtained at the ionosphere stations. The main conclusions of the comparison are the following. It is

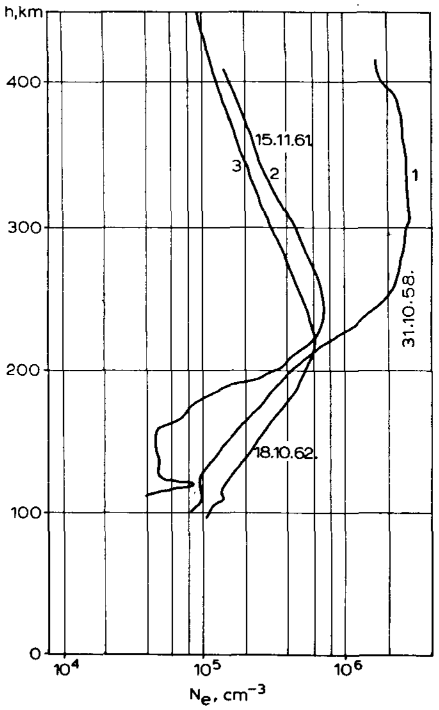

Fig. 1. Results of electron density measurements carried out on geophysical rockets of the Soviet Academy of Sciences.

confirmed that the ionosphere at heights of 100–300 km is a medium with almost monotonic increase of electron density without division into separate layers. Slight deviations of the $N_e(h)$ curve cause, however, on $h'(f)$ records height discontinuities reaching approximately 100 km which in the past led to the conception of a layered ionosphere. Calculations of height distributions of electron density up to the main ionization maximum from ionograms using an integral equation method with Shinn–Kelso coefficients which take into account the effect of the earth's magnetic field give results which are close to rocket ones.

1.2. *Direct Detection of an Electric Field in the Ionosphere*

Measurements of an electric field near the surface of a rocket flying in the ionosphere are of great interest for two reasons. The first is that direct measurements of ionospheric parameters by probes are complicated by the fact that a rocket in the ionosphere has a screening sheath of volume charge around it due to differences in electron and ion velocities and due to emission of electrons from its surface under the influence of different radiations. In interpreting the results of probe measurements it is very helpful to have information on electric fields inside this volume charge.

The second reason for interest in rocket measurements of electric fields is more important. To understand some phenomena in the ionosphere, for instance drift of ionospheric irregularities, it is necessary to know the magnitude of existing electrostatic fields in the ionosphere.

Measurement of these fields extraneous to the rocket, i.e. independent of its appearance in the ionosphere, is strongly complicated by the existence of an electric field produced by the rocket's own charge which was mentioned above.

Since 1957 a series of experiments on geophysical rockets of the U.S.S.R. Academy of Sciences has been conducted to study electric fields near the surface of rockets flying in the ionosphere. These experiments were carried out by means of electrostatic fluxmeters—instruments which are widely and successfully used for terrestrial measurements of electric fields in studies of atmospheric electricity [*9*]. Modifications have been introduced to take into account the specific character of measurements in an ionized gas. To distinguish an electric field produced by the rocket's charge from an outer electric field two instruments are used which are mounted at diametrically opposite points of a cylindrical part of the rocket or in some cases of a spherical container separated from the rocket.

Analysis of results of experiments made in 1957–1958 allowed Gdalevich to determine the value of the electric field produced by charge on the rockets at different sections of their flights, and led him to the conclusion that some part of the differences in the simultaneous indications of two fluxmeters observed in these experiments could be explained only by an outer electric field [*10, 11*].

In 1961–1962 these experiments were continued by Gdalevich, Imyanitov and Shvarts [*12, 13*]. Modifications were introduced into the design of the instruments to minimize the effect of charged particle fluxes getting in the fluxmeter plates and electron emission from these plates (the fluxmeter plates were made grids). Despite these modifications the results turned out to be close to the 1957–1958 results. After analysis of possible errors due to instrumentation, methods of measurement and uncertainty of the sheath of volume charge, the authors [*12, 13*] have come to the conclusion that a difference ΔE of field measured by oppositely mounted fluxmeters of the order of 0.1 V/cm is to be attributed to an outer electric field in the ionosphere. Such a high value of ΔE is due to an increase of the outer electric field strength near the surface of the rocket by a factor of one hundred or more. Phenomena resulting in such an increase in the electric field near the rocket are considered in [*12, 13*]. The experiments have led to the following conclusion: the outer electric field strength in the ionosphere can reach a value of 10^{-3} V/cm. The dimensions of regions in which there are electric fields of this order and the causes of the appearance of such fields should be determined in further investigations. It is interesting to note that at the beginning of 1963 the paper by Megill, Rees, and Droppleman [*14*] was published in which the authors came to the conclusion that there is an electric field in the ionosphere with the strength of 10^{-3} V/cm, from absolutely different considerations, namely, from the intensity of the red lines of atomic oxygen in the spectrum of the twilight sky.

2. IONOSPHERIC STRUCTURE REVEALED BY SATELLITE COSMOS 2

During ionospheric measurements made in the U.S.S.R. in the period of the IGY by means of geophysical rockets and satellites [*1, 2, 15, 16*] some previously unknown properties of the outer ionosphere (lying above the main ionization maximum) have been established. These included the facts that the decrease of charged particle concentration in the region of the outer ionosphere, close to the main ionization maximum, took place much more slowly than the increase with height below the main maximum; and that up to an altitude of about 1000 km the outer ionosphere consisted predominantly of ions of atomic oxygen (O^+). In 1959–1960 similar results were obtained in American experiments on rockets and satellites [*17, 18, 19*]. In particular, from the results of measurements made by means of ion traps on the satellite Explorer VIII launched in November 1960 Bourdeau, Whipple and others [*19*] came to the conclusion that up to heights of 800 km there were predominantly O^+ ions, and at high altitudes there was a region which contained a considerable quantity of helium ions (He^+).

Experiments aimed at studies of the ionosphere were conducted on satellite Cosmos 2, launched on April 6, 1962 in an orbit with perigee $\approx$ 212 km and apogee $\approx$ 1546 km, and inclination 49° to the equator. Among the instruments mounted on this satellite were spherical and plane ion traps and also Langmuir probes.

Experiments with ion traps were the continuation of experiments successfully started on Sputnik III in May 1958 [*15*]. Spherical ion traps, as on Sputnik III, were installed far from the satellite's surface. Voltages on their outer grids were varied according to a bipolar sawtooth pulse law, but in contrast to the 1958 design of spherical traps third electrodes were introduced —inner grids having constant negative potential with respect to the collectors for suppression of photoemission and secondary electron emission from the collectors of the traps. On the surface of satellite Cosmos 2 there were also eight plane three-electrode ion traps, each in one of the eight octants into which space can be divided so that the angles between the normals to the outer grids for any adjacent traps were $\lesssim 90°$. The outer grids of these traps had the potential of the satellite body. The inner grids had a constant negative potential. A device for memorizing information has made it possible for a number of satellite rotations to memorize the value of collector currents and voltages on the outer grids of the ion traps along the entire orbit and to transmit this information to earth during flight near receiving points over the U.S.S.R. territory. At the time of preparing this report (May 1963) processing of primary data obtained in experiments on satellite Cosmos 2 is not completed, so that only some of the results obtained are described below.

Fig. 2 shows graphs of the distribution of positive ion concentration N_i along the satellite's orbit during six revolutions of the satellite plotted as a function of height above the earth, obtained from data from a plane trap system. The graphs are reproduced from an article by Gringauz, Gorozhankin, Shutte and Gdalevich [*20*]. See also [*21*]. From Fig. 2 it is evident that the decrease of ion concentration N_i with increase of height above the main maximum at all rotations of the satellite is considerably more rapid than the data of 1958 have shown (a summary graph is given in [*22*]). In particular, it is much more rapid than was indicated by ion traps on Sputnik III. The decrease of N_i becomes slower only at a height of 600 km.

In a paper [*23*] in 1957 mass-spectrometry applications of ion traps were indicated. An analysis of the volt–ampere characteristics of spherical ion traps on satellite Cosmos 2 has shown that at altitudes of even 550 km there was a considerable number of helium ions and at a height of about 580 km the He^+ ion concentration is approximately equal to the O^+ ion concentration. This result considerably differs from the results of experiments on Sputnik III. Although in experiments with the mass-spectrometer on

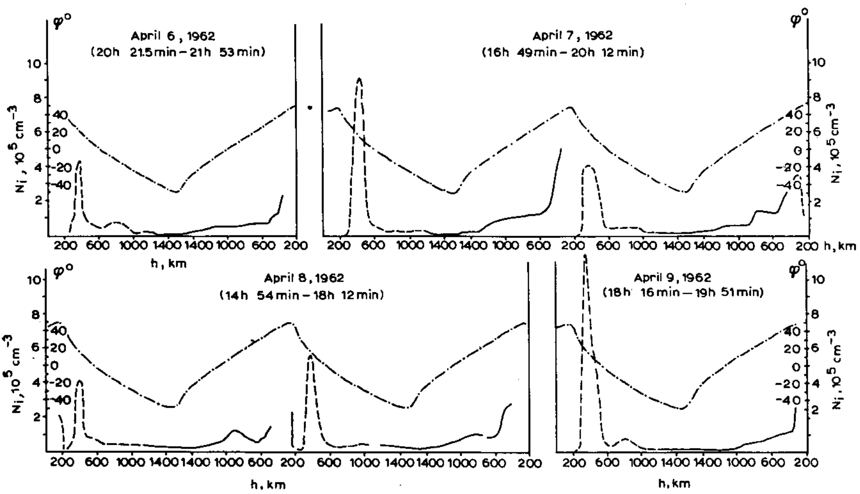

Fig. 2. Altitude distributions of positive ion densities based on data obtained from ion traps on the satellite "Cosmos 2";
– – – – sunlit sections of the orbit;
——— unilluminated sections of the orbit;
—·—·— geographical latitudes (φ°).

Sputnik III there was no possibility of recording He^+ ions, a combined analysis of the results of the mass-spectrometer with results of simultaneous measurements carried out by means of spherical ion traps [*15*] makes it possible to state that during measurements on Sputnik III at heights of 600–800 km no considerable quantities of He^+ ions were recorded.

Thus experiments on satellite Cosmos 2 have shown that since 1958 changes have taken place in the structure of the outer ionosphere in the form of the above-mentioned change in the height distribution of ion concentration above the main ionization maximum and the change of the ion composition at heights above 550–600 km.

These changes seem to be associated with the decrease of solar activity in the period 1958–1962. In this connection the transition region between the ionosphere regions where ions O^+ and He^+ prevail was lowered, which in its turn caused the corresponding variations of the height distribution of N_i.

Such variations of the structure of the ionosphere satisfactorily agree with theoretical calculations of Harris and Priester [*24*] based on height variations of the mean molecular weight of neutral particles in the upper atmosphere and their connection with solar activity variations.

It should be noted that electron density height variations which confirm the above mentioned conclusion about the ionosphere structure variations can be seen on the graphs obtained by means of geophysical rockets in 1958 and 1961–62 given in Fig. 1.

3. PLASMA MEASUREMENTS IN THE MARS 1 SPACE PROBE

In the space probe Mars 1, launched on November 1, 1962 in the direction of the planet Mars, as well as on previous Soviet space probes, charged particle traps were mounted to study plasma. These traps included three-electrode traps similar to those which were used on the first Soviet Luniks [*25, 22*] and on the Soviet Venus-probe launched in February 1961, as well as a multi-electrode trap for studies of the energy spectrum of the solar plasma fluxes.

The processing of the primary data obtained from the Mars 1 probe is not complete. In the present paper only a small part of these data was used.

Fig. 3, reproduced from a paper by Gringauz, Bezrukikh, Musatov, Rybchinsky and Sheronova [*28*], shows graphs of two three-electrode trap collector currents measured on November 7, 1962, on a section of the Mars 1 trajectory near the earth, at heights from about 5000 km to about 20,000 km (the upper scale along the abscissa axis indicates geocentric distances). On the lower part of Fig. 3 the corresponding geomagnetic latitudes λ_m of the lines of force of an ideal geomagnetic dipole crossed by the probe are given.

The potential of the outer grid of the trap 1, to which curve I corresponds, is equal to the space probe body potential. The potential of the outer grid of trap 2, to which curve II corresponds, with respect to the body is equal to $+50$ volts. Potentials of the inner grids aimed at suppression of photoemission and secondary emission from the trap collectors are identical and equal to -80 volts with respect to the body. Voltages were not applied to the collectors of the traps.

At such potentials of the trap electrodes positive ions with thermal energies could penetrate to the trap 1 collector, and only ions with energies $\gtrsim$ 50 eV could get to the trap 2 collector. Besides, electrons with energies $\gtrsim$ 80 eV could penetrate into both traps and reach the collectors.

One of the significant results of experiments with charged particle traps made in 1959 on the first Soviet Luniks was the conclusion that the earth's ionized gas envelope containing charged particles with thermal velocities ex-

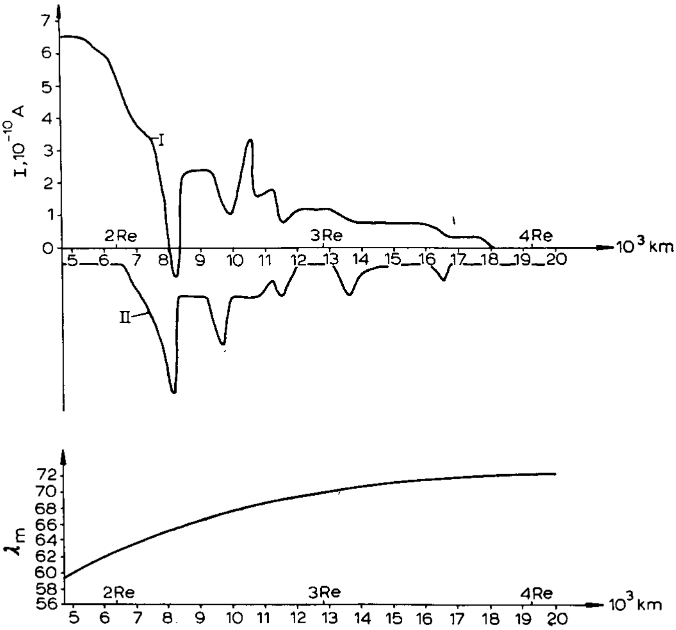

Fig. 3. Altitude variations of collector currents (I) of the charge particle traps on the space probe "Mars 1" and corresponding geomagnetic latitudes (λ_m) of the lines of force of an ideal geomagnetic dipole crossed by the probe.

tends to heights of the order of 20,000 km [25, 22]. This result has been confirmed by the measurements of collector currents of the above mentioned two traps on the Mars 1 probe shown in Fig. 3. In the trap with zero potential on the outer grid, positive collector currents up to a height of about 18,000 km were recorded, while in the second trap with a retarding (for positive ions) potential on the outer grid, currents were negative in the height interval shown in the figure. It should be noted that changes in the orientation of the traps with respect to the sun at the considered section of the trajectory were very small. Variations of the collector current of probe 1 [1] may be explained if we suppose that this current consists of two components. The first component is a current produced by positive ions with thermal velocities which form part of the earth's ionized gas envelope. (This current can only be registered in a trap with zero potential on the outer grid.) The second current component in this trap is produced by electron fluxes with energies $\gtrsim$ 80 eV. (As was indicated above, such fluxes can penetrate into both traps.)

Comparison of curves I and II in Fig. 3 confirms such an interpretation.

since curve II corresponds to the current produced by electron fluxes which belong to the outermost charged particle belt surrounding the earth. This belt, discovered in experiments with charged particle traps on the first Soviet Luniks in 1959, is situated near the boundary of the earth's magnetosphere, beyond the two radiation belts and contains electrons of relatively low energies which cannot be recorded by cosmic ray counters. The current fluctuations in trap 1 correspond to fluctuations of the electron flux density in the outermost belt. In contrast to the 1959 experiments the outermost belt was detected at relatively small distances from the earth in the Mars 1 probe. This is explained by the fact that the Mars 1 probe trajectory passed high geomagnetic latitudes (see the lower part of Fig. 3). Due to this peculiarity, observations were made for the first time from the Mars 1 probe in the region of the intersection of the earth's ionized gas envelope and the charged particle outermost belt.

Finally, it may be noted that measurements of currents in charged particle traps on Luniks in 1959, on the Venus probe launched in February 1961 [*25, 26, 22*], and on the Mars 1 space probe during 1962 and 1963 allow us to draw some conclusions about the solar plasma fluxes which are of interest from the point of view of radio wave propagation in interplanetary space. Up to 1960 in the literature estimates of charged particle densities in interplanetary plasma (S. Chapman [*29*], L. Bierman and R. Lüst [*30*], and E. Parker [*31*]) gave grounds for apprehension that for all radio waves with frequencies less than 2×10^8 cycles per second (and at $N_e = 10^4$ cm^{-3}, even for all radio waves with frequencies less than 6×10^8 cycles per second), changes of phase and group propagation velocities (and, therefore, the corresponding radio-navigational errors) can exceed errors due to inexact knowledge of the speed of light in vacuum, i.e. 10^{-6}.

The experiments with charged particle traps have demonstrated that previous estimates of charged particle densities in interplanetary plasma, and in the solar plasma streams, were too high, and that even in the solar plasma streams with high geoactivity, i.e. in those which produce considerable geomagnetic perturbations, the charged particle density is lower than 10^2 cm^{-3}.

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