INVESTIGATION OF INTERPLANETARY PLASMA AND PLANETARY IONOSPHERES BY MEANS OF CHARGED PARTICLE TRAPS ON SPACE ROCKETS

By

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(With 8 Figures)

According to modern conceptions ionized gas in interplanetary space exists in two forms: in the form of a "stationary gas" consisting of charged particles with thermal velocities and in the form of solar corpuscular streams which represent streams of ionized gas moving from the Sun with velocities of the order of 1000 km/sec.

According to S. CHAPMAN [1], [2] (who considers the stationary ionized gas in the Solar System as a continuation of the solar corona) the concentration of free electrons (and ions) should be of the order of 10^3 cm^{-3} at the temperature 10^5 °K at a distance of one astronomical unit from the Sun. L. BIERMANN [3], [4] assumes that in solar corpuscular streams the concentration of free electrons (or ions) can reach 10^3 and even 10^4 particles per cm^3. Suppositions were also expressed on the existence of a constant stream of charged particles ejected by the Sun, frequently called the "solar wind." E. PARKER estimates that in the solar wind the ion concentration is of the order of hundreds in 1 cm^3 with stream velocity of about 500 km/sec. [5].

Investigation of the problem of the state and concentration of the ionized gas in interplanetary space is important for astrophysics (since it allows us to define more precisely the physical properties of the medium in which planets of the Solar System move) and for geophysics (since solar corpuscular streams cause such significant geophysical effects as aurorae, geomagnetic storms, and ionospheric storms, which exert considerable influence on radio communication between various regions of the Earth).

In addition, this question is also important for astronautics or, to be more precise, for radio navigation in interplanetary space.

In fact, with the increase of instrumental precision of radio navigation means, those components of radionavigation errors which are connected with precise knowledge of the velocity of radio waves propagation, will acquire more importance. At present the speed of light in vacuo, C can be regarded as known to an accuracy of 0.3 km/sec., i.e., to 10^{-6} [6]. If N_e (the concentration of free electrons) in the re-

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gion of the location of a space vehicle is 10^3, then for all radio waves with frequencies not more than 2×10^8 c/s the error of the ground determination of the coordinates and the speed of the space vehicle with radio methods caused by the difference of the radio wave propagation velocity in the ionized gas from the velocity of propagation in vacuo will be greater than the error caused by insufficient knowledge of the constant C. If $N_e \sim 10^4$, then this statement will refer to all radio waves with frequencies less than $\sim 6 \times 10^8$ c/s. The influence of a planetary ionosphere on radio measurements is not taken into account.

Thus from some characteristics of interplanetary plasma described in literature, apprehensions appeared that the influence of the interplanetary ionized gas can limit accuracies of radio navigation measurements in interplanetary space. Certainly, it is possible to exclude the influence of the ionized medium on radio wave propagation velocity using simultaneous measurements by means of radio waves at different frequencies; but this involves an increase in equipment weight and energy consumption on board a space vehicle and, therefore, is undesirable.

On all Soviet space probes beginning with the first artificial planet launched on January 2, 1959, and including the Venus interplanetary automatic station launched on February 12, 1961, three-electrode charged particle traps were installed for studying interplanetary plasma.

Experiments with these traps made possible some conclusions regarding both the possible concentration of interplanetary ionized gas with thermal velocities of particles and the directed streams of solar corpuscles.

Within the framework of the present report it is impossible to give detailed descriptions of all experiments conducted (after each experiment changes were introduced into technique and instrumentation). Information on the technique and apparatus used in these experiments was published in Soviet scientific periodicals [7], [8], [9] and reported in April of this year at the Second International Space Science Symposium in Florence. Nevertheless, it seems useful to expound some data of experiments and the results obtained.

Lunik III launched on October 3, 1959, carried four three-electrode charged particle traps. The location of these traps is shown in Fig. 1. The design of all traps was the same. It is shown in Fig. 2. Equal negative potentials with respect to the body $\varphi_k = -90$ volts were applied to collectors of all traps, equal potentials $\varphi_{g1} = -200$ volts with respect to the body were applied to inner grids (to suppress the current of photoelectrons emitted by the collector under the influence of solar ultraviolet radiation). However, potentials of outer grids were not equal. In flight during four-minute time intervals sawtooth voltage pulses with a period of 18 seconds were applied several times to outer grids of two traps (one of which was on the lower part of the container and the other on its top). They were interposed on the constant voltage -5 volts with respect to the body. Therefore, these trap outer grid potentials φ_{g2} with respect to the body varied from $+9$ volts to -19 volts. Graphs of φ_{g2} and both trap collector current charges I_k during one of such intervals (at 14^h52^m Moscow time on October 4, 1959, when $R \sim 126{,}000$ km from the Earth) are presented in Fig. 3. For the time interval corresponding to these graphs in total 240 values of voltages on the outer grids of the traps and collector currents were transmitted from the rocket. The dots indicate the absence of measured values.

These graphs clearly show alternate increase and decrease in positive collector currents of both traps (with a period of ~ 150 sec) which reflect the rotation of

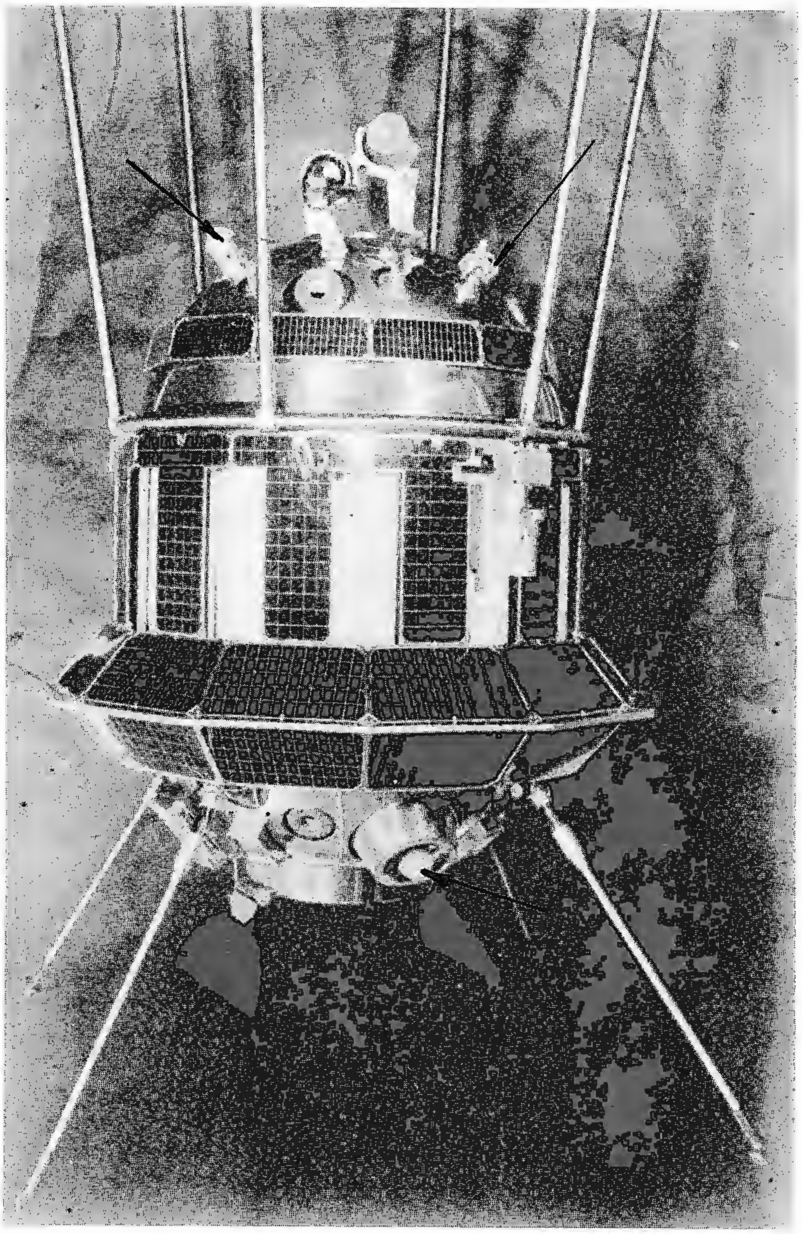

Fig. 1. The location of the three-electrode charged particle traps

the automatic interplanetary station. At the same time it is evident from the graphs that the change of the trap collector currents is in no way connected with the change of potential of their outer grids. Apparently this takes place because positive particles which cause collector currents have such high energies that outer grid potential changes by approximately 30 volts do not exert any influence on them.

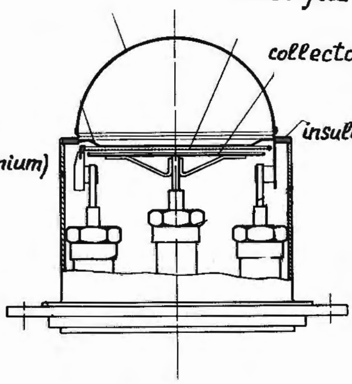

Fig. 2. A diagram of a trap

If there were a sufficient concentration of low energy charged particles with thermal velocities in the surrounding medium, the collector current caused by them would undoubtably be modulated by sawtooth voltage with the range of about 30 volts applied to the outer grids of the traps. Therefore the absence of such modulation can be used to estimate Ni. Such estimation was made in [11] and it shows that Ni does not exceed a few particles cm^{-3}.

The indicated very low concentration of stationary interplanetary ionized gas has turned out to be unexpected and contradictory to the earlier conceptions mentioned at the beginning of the report, on the basis of which the electron concentration at a distance of one astronomical unit from the Sun was usually estimated as 5×10^2 to 10^3 cm^{-3}. At the same time it should be mentioned that quite recently papers have appeared from which it also follows that the concentration of the interplanetary ionized gas is extremely low (BLACKWELL's paper on the zodiacal light in the second half of 1960 [12] and POPE's paper on observations of whistling atmospherics of "noses" type [13] in 1961).

From the experiments by means of charged particle traps on Lunik III it follows that free electrons of the stationary interplanetary gas cannot exert considerable influence on accuracies of radio navigation measurements in interplanetary space since their concentration is too low. Thus solar corpuscular streams present the only form of interplanetary plasma which is of interest from this point of view.

The trap collector currents shown in graphs of Fig. 3 can be explained only by an encounter between the probe and a stream of positively charged particles with energies considerably exceeding 20 ev. Changes of these currents are accounted for by charges of the probe orientation with respect to the direction of the stream of particles. Let us note that kinetic energy of the proton motion with respect to the rocket amounts only to ~6 ev when the rocket velocity with respect to the medium is ~30 km/sec (equal to the Earth's orbital velocity). The electron component of the stream does not influence the collector current since the energy of electrons of solar corpuscular streams is not enough to overcome the retarding electric field created by the trap inner grid. Currents shown in Fig. 3 correspond to a corpuscular stream $N \sim 4 \times 10^8$ cm^{-2} sec^{-1}.

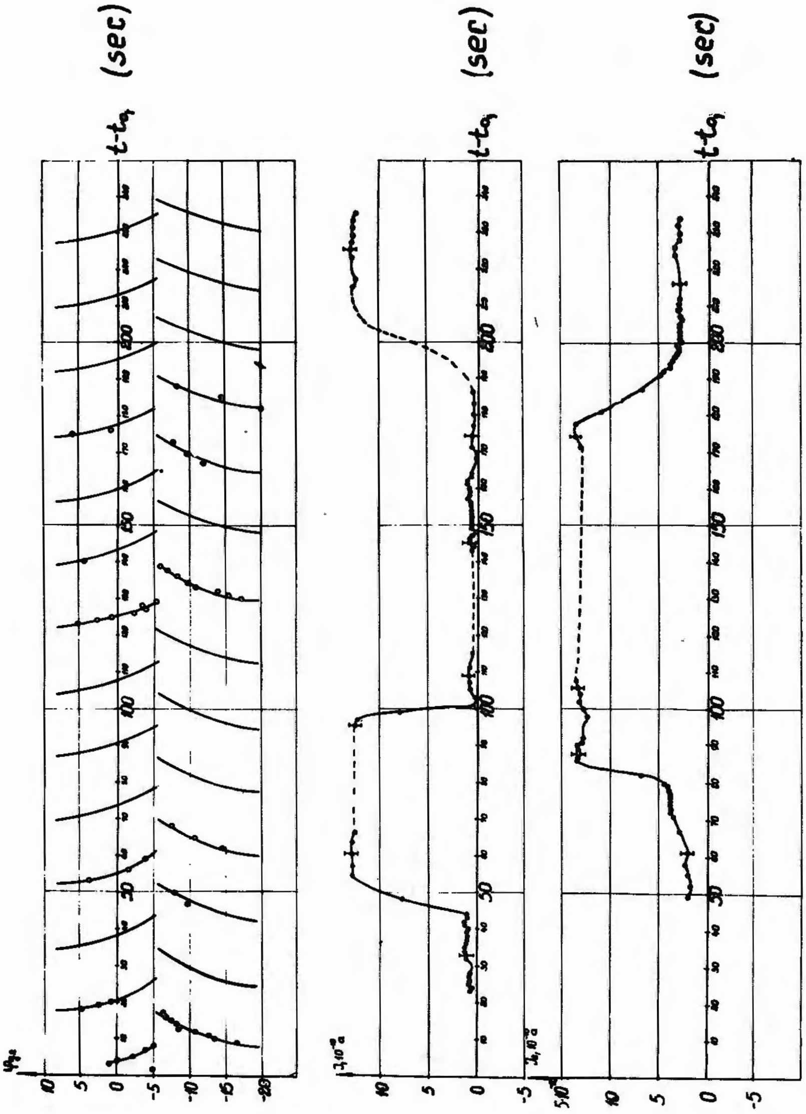

Fig. 3. Graphs of φ_{g2} and both trap collector current charges I_k

For the first time the ion component of solar corpuscular streams beyond the Earth's magnetic field was recorded on September 13, 1959, by means of three-electrode traps during Lunik II flight [7]. During Lunik III flight in the first half of October 1959 at distances of the order of hundreds of thousands of kilometers from the Earth solar corpuscular streams were repeatedly recorded by means of charged particle traps. As a rule, a good correlation was observed between registration of corpuscular streams and the increase of K-indexes of geomagnetic disturbances at the Earth [11].

Up to the present time the most intense corpuscular stream was recorded by means of charged particle traps during the flight of the Venus probe launched in

February 1961. The location of traps at the Venus rocket interplanetary automatic station is shown in Fig. 4. The outer grid potentials were $\varphi_{g2} = 0$ volts for the first trap and $\varphi_{g2} = +50$ volts for the second trap. During contacts by radiotelemetry the traps were oriented to the Sun with great precision. In connection with this the recorded collector currents for the first time were unmodulated due to rotation of the container. During the radio contact started on February 17 this year at 14^h35^m Moscow time the Soviet Venus probe was at a distance of about 1,890,000 km from the Earth. During a 20-minute radio contact with the Venus probe, currents were recorded in traps which correspond to a flux of positive corpuscles equal to $\sim 10^9$ cm^{-2} sec^{-1}.

The commencement of a magnetic storm with an amplitude of disturbance of about 100γ was recorded at the Earth at 12^h Moscow time. The corpuscular stream velocity was determined from the time of delay of the magnetic storm commencement with respect to the passage of a flocculus over the central meridian of the solar

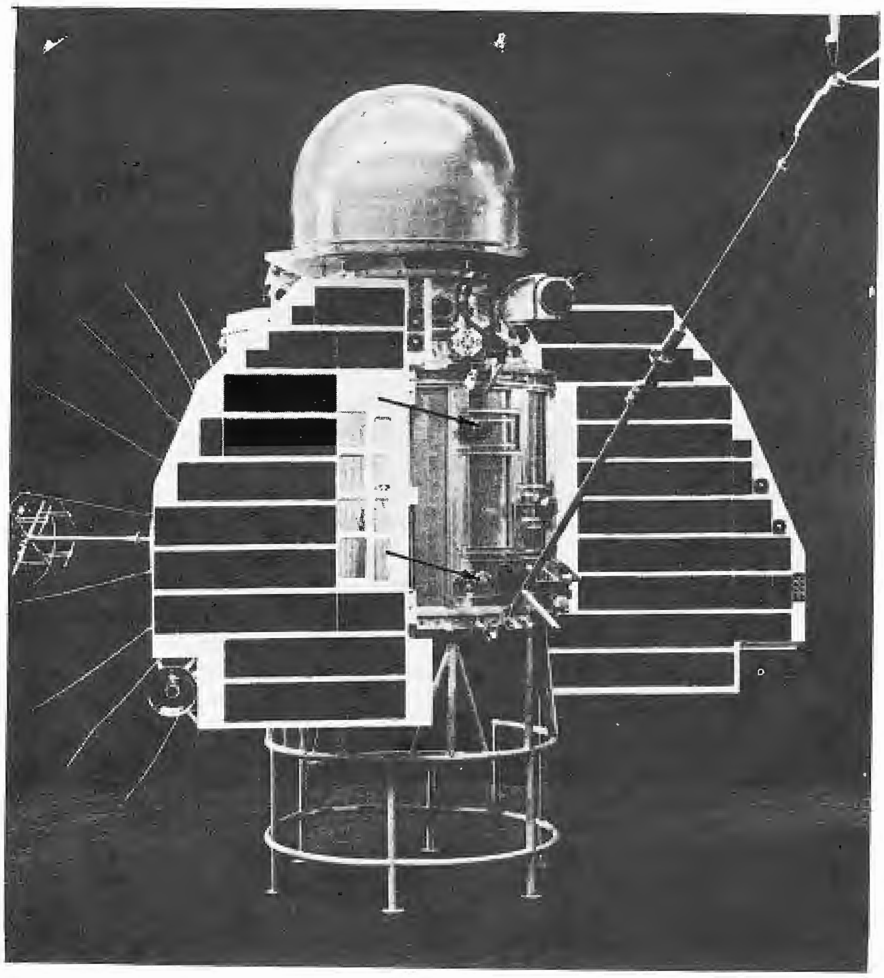

Fig. 4. The trap location at the Venus rocket interplanetary automatic station

disk. It turned out to equal ~ 400 km/sec. This means that the proton concentration in the stream was approximately 25 cm^{-3}.

Thus, the few trap experiments yet carried out in interplanetary space have shown that the concentrations of charged particles in solar corpuscular streams can be considerably greater than in stationary plasma.

It should be pointed out that only direct observations of corpuscular streams beyond the Earth's magnetic field can give information necessary for establishing quantitative ratios between the density of the solar corpuscular stream and the intensity of geomagnetic disturbances caused by it. Later the systematic recording of solar corpuscular streams in interplanetary space by means of traps will make it possible to determine the maximum concentration of charged particles in corpuscular streams and to estimate finally their possible influence on radio navigation errors.

At the present time we have prepared instruments with multielectrode traps which will allow us to determine not only the density of the stream of charged particles, but their energy spectrum too.

Let us turn to the problem of investigating ionospheres of planets. From the point of view of astronautics it is still more important than the problem of interplanetary plasma since near planets one can expect the existence of considerable concentrations of charged particles which strongly influence the velocities of radio wave propagation, accuracies of radio measurements and perhaps even the possibility of radio communication in some wave bands. Strictly speaking, the degree of accuracy of the results of terrestrial radio location of some planet cannot be determined so long as there are no data on the distribution of electron concentration in the planet's ionosphere.

If chemical composition and density of the atmosphere of all planets were the same, it would be possible to estimate the maximum electron concentration of each planet's ionosphere assuming that the only source of ionization is ultraviolet solar radiation. In this case the electron concentration in the Venusian ionosphere would be approximately twice that of the terrestrial ionosphere (in accordance with its distance from the Sun), near Mars it would be approximately one half that near the Earth and so on. In reality, however, it is impossible to resort to such estimates, since the atmosphere of each planet differs from those of other planets in chemical composition and structure. Magnetic fields of various planets seem to differ greatly too, and, as is known, a magnetic field considerably influences the picture of charged particle distribution around the planet. The character of the Venusian ionosphere is not clear. According to the opinion of the Soviet astronomer N. A. KOZYREV based on the study of the spectrum of the Venusian ashen glow, the electron concentration in the Venusian ionosphere is considerably greater than in the Earth's ionosphere [14], [15].

It should be noted, however that KOZYREV's result is not yet confirmed by other observations [16].

The existence of Jupiter's radio outbursts in decameter and decimeter wavelength bands can be explained by the existence of a dense ionosphere [17] and a very intense magnetic field [18]. It is clear from the above that the exploration of planetary ionospheres should take one of the first places in the complex of scientific problems which should be solved before landing people on other planets since reliable radio communication between a planet and the Earth is one of the most important conditions of safety of such an expedition.

While preparing experiments aimed at studying ionospheres of the planets of the Solar System it is quite natural to regard their structures as similar to some degree to the structure of the Earth's ionosphere and to consider methods of investigation similar to those used at the Earth.

Figure 5 presents a tentative curve of charged particle altitude distribution in the Earth's ionized gas envelope. This curve is composed from the data of experiments conducted at daytime in 1958–1959 by means of Soviet geophysical rockets, Sputnik III and Soviet space probes and it characterizes a period close to the maximum of solar activity. The portion of the curve referring to altitudes 470–1,000 km is composed according to data of spherical ion traps mounted on Sputnik III. The portion of the curve referring to altitudes 1,400–20,000 km is built on the basis of

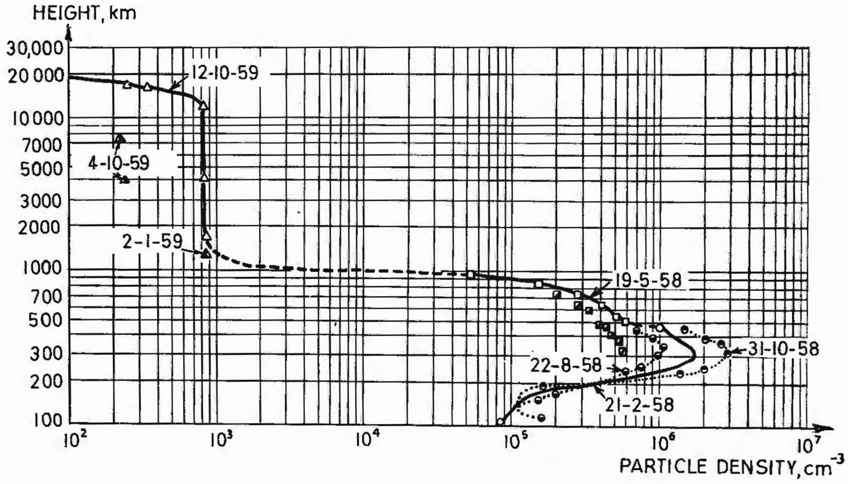

Fig. 5. Variation of the density of charged particles with height

the data of space probe experiments with three-electrode charged particle traps. In the graph the dates on which the experimental dots were obtained are indicated. Dashed lines denote the absence of measurements. Mass-spectrometric measurements on Sputnik III have shown that the ionosphere consists in the main of the ions of atomic oxygen [19] to an altitude of 1,000 km. As is shown in [9] and [10], the altitude variations of the concentration of charged particles presented in Fig. 5 to altitudes of 15,000 km are explainable but the increase of negative vertical gradients of charged particle concentration with height, which begins from an altitude of about 15,000 km, still requires theoretical explanation.

It is reasonable to note that by means of the same three-electrode traps aboard the first Soviet space probes which made it possible to obtain the upper part of the graph given in Fig. 5 the existence of fluxes of electrons was revealed with energies more than 200 ev with the flux of the order of 10^8 cm^{-2} sec^{-1} at distances of 55,000–75,000 km from the Earth's surface (in the equatorial plane), i.e., beyond the radiation belts [7]. This gave grounds for supposing the existence of an outermost belt of charged particles surrounding the Earth, with boundaries passing along the lines of force of the geomagnetic field consisting of particles with energies lower than in radiation belts [8] (Fig. 6). Comparison of the data on the current

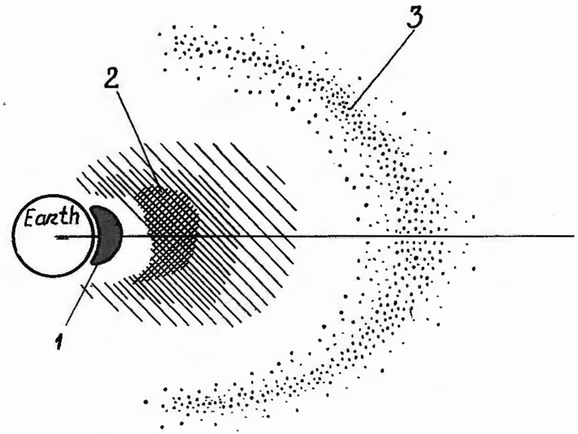

Fig. 6. A diagram of the Earth's radiation belts. (1) An inner belt of high-energy protons. (2) A middle belt of low-energy protons and electrons. (3) A belt of electrons whose energies are very low

ring calculated by American scientists (SONETT and others) from the results of Pioneer V magnetic field measurements [20] with the data of three-electrode traps experiments on Soviet space probes published earlier [7] has shown that the current ring calculated in [20] and electron fluxes revealed in our experiments are located in the same region of space and that both experiments mutually confirm and complement each other [22]. The concentration of free electrons in the outermost belt of charged particles around the Earth is apparently too low to affect considerably the propagation of radio waves. However, it seems to us that there are no grounds to affirm the same *a priori* for other planets.

It seems to us that important data on ionospheres of planets which characterize the total electron content in a vertical column of a planet's ionosphere can be obtained by means of simultaneous radio location of the planet from the Earth at various frequencies. However, this method does not allow us to acquire data on the altitude distribution of the charged particle concentration and on the electron maximum concentration in the planetary ionosphere, which are of decisive importance for radio communication with the Earth of astronauts who have landed on the planet.

Since there is no doubt that the landing of people on planets will be preceded by interplanetary flights of rockets with automatic equipment, apparatus should be devised for exploring the altitude distribution of charged particle concentration near the planet by means of such reconnaissance rockets.

As an example of the apparatus of this kind an impulse ionospheric station can serve which will be carried by a rocket to the planet under investigation at sufficiently close distance. The results of its measurements should be transmitted to Earth by radiotelemetry. This method involves considerable difficulty: the station should have a very wide band of wavelengths (as critical frequencies of the ionosphere under investigation are unknown), and this means that the receiving-transmitting equipment would have considerable weight.

What will be the weight of the station aimed at studying the outer part of the Earth's ionosphere from a comparatively low height, one can judge from the Canadian project of the "Topside sounder" satellite whose weight will be more than 100 kg [21]. The sending in the near future of a heavier ionospheric station to the planet under investigation with characteristics necessary for the exploration of an ionosphere of unknown properties considerably limits the possibility of simultaneous performance of other scientific investigations.

At the same time, the installation aboard an automatized planetary research rocket of apparatus for exploring the planetary ionosphere by a probe-method (for instance, of the type of Sputnik III with spherical ion traps, three-electrode traps used on space probes or some of their modifications) will make it possible to carry out measurements during the passage of the rocket through a planet's ionosphere having an extensive range of concentration of charged particles with a comparatively small apparatus weight. Limitations will be imposed only by the possibility of the passage of radio waves of the telemetry system through the ionosphere under investigation. Such measurements can be easily combined with the complex of other physical investigations. Therefore, charged particle traps can be considered as a means of paramount importance for exploring ionospheres of the Solar System planets by means of rockets.

In conclusion another important possibility of using charged particle traps in astronautics should be pointed out. On entering the atmosphere of a planet, correct orientation of the interplanetary vehicle with respect to its velocity vector becomes very essential, if the vehicle has no strictly spherical form. Since the ion current

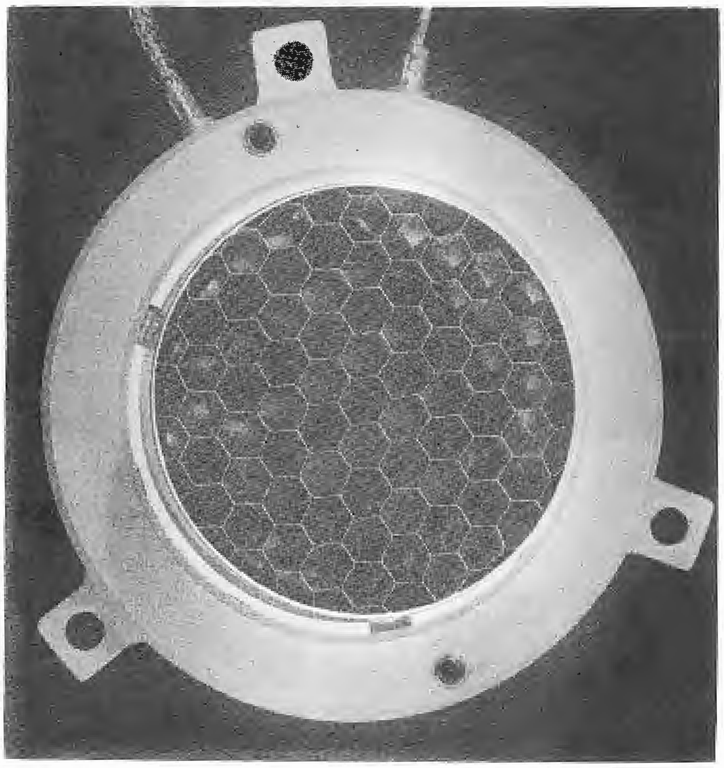

Fig. 7. A possible design of a trap sensitive to the direction of motion.

in nonspherical traps strongly depends on their orientation with respect to the incident ion stream, then from the moment of entering the ionosphere the traps can be used as orientation sensors with respect to the spacecraft velocity vector. One of the possible designs of the traps sensitive to the direction of the motion, in which the outer grid is in the form of elongated hexahedral honeycombs, is shown in photographs (Fig. 7 and 8).

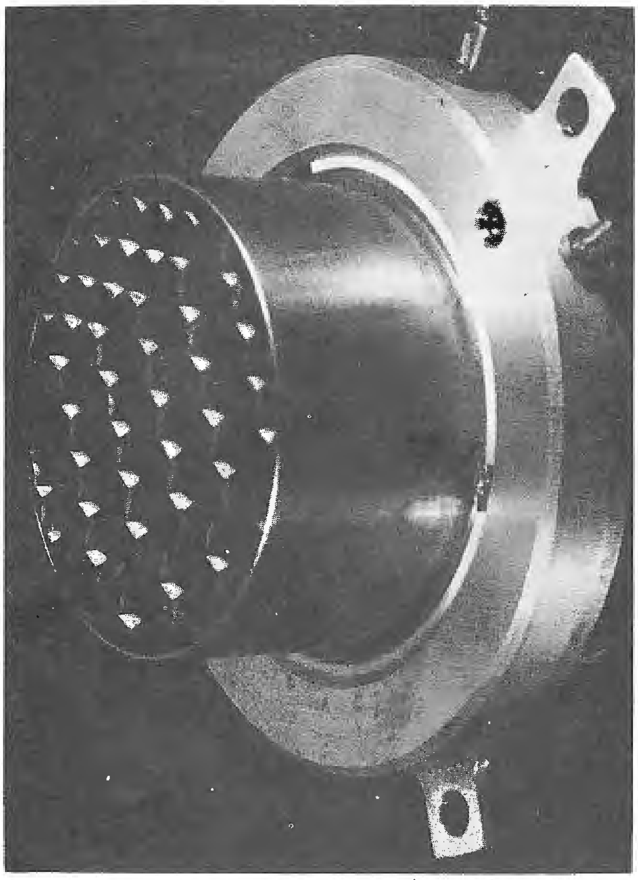

Fig. 8. A possible design of a trap sensitive to the direction of motion

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