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Determining Local Concentrations of Charged Particles in the Ionosphere and Interplanetary Space

Methods used on Soviet Rockets and Earth Satellites and some results obtained

By

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Summary: Electron concentration determinations in the ionosphere by radio wave dispersion measurements using transmissions from rockets are discussed with reference to the results obtained by various workers. Charged particle trap experiments carried on satellite and space probes are also described, and some conclusions are reached regarding the distribution of charged particles in the sunlit part of the Earth's gas envelope.

1. Introduction

Several descriptions of Soviet rocket and satellite experiments aimed at studying local ionospheric concentration have been published during the last three years.[1-9] Therefore this paper will mention only some of the essential features of the experiments and some of results obtained; full and systematic descriptions of methods and experiments which would be impossible in such a report are omitted.

When we speak about measurements of local concentrations of charged particles in the ionosphere, we mean those measurements each of which makes it possible to determine the concentration at a definite altitude, in definite time, and without the use of observations from ionospheric stations or suppositions on the height distribution of charged particle concentration. Since experiments aimed at ionospheric studies by means of radio waves emitted from Earth satellites do not satisfy these conditions they will not be considered in this paper.

2. Electron Concentration Measurement Experiments by Means of Radio Waves Emitted from Rockets

Coherent unmodulated radio waves with frequencies $f_1 = 24$ Mc/s, $f_2 = 48$ Mc/s and $f_3 = 144$ Mc/s are radiated from vertically launched geophysical rockets of the U.S.S.R. Academy of Sciences. To determine the electron concentrations at various altitudes, radio wave dispersion measurements by the phase method are carried out at several points on the Earth (with the use of frequency combinations 48–144 Mc/s and 24–144 Mc/s). Faraday rotations of polarization planes of each radio wave received are also recorded.

Figure 1 shows a geophysical rocket in flight. This rocket reaches a height of about 470 km. The important feature of the rocket is the extreme closeness of

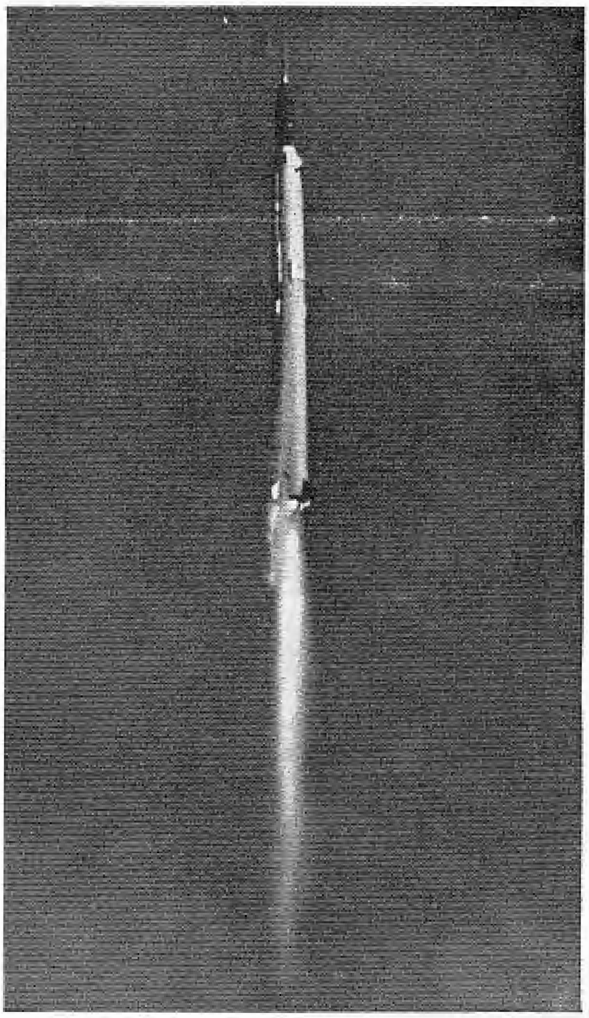

Fig. 1. Geophysical rocket in flight.

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its trajectory to the vertical, which makes it possible to ignore its horizontal velocity while processing experimental results. The second important feature of the rocket is its complete stabilization after power cut-off with respect to three mutually perpendicular earth-bound axes. Thus the only cause of rotation of the plane of polarization of radio waves received on the Earth is the Faraday effect. Therefore, the height distribution of electron concentration can be obtained from observing the rotation of the polarization plane at one frequency.

Results of determining electron concentration height-distribution obtained by the dispersion method and by the Faraday rotation method are in good agreement.

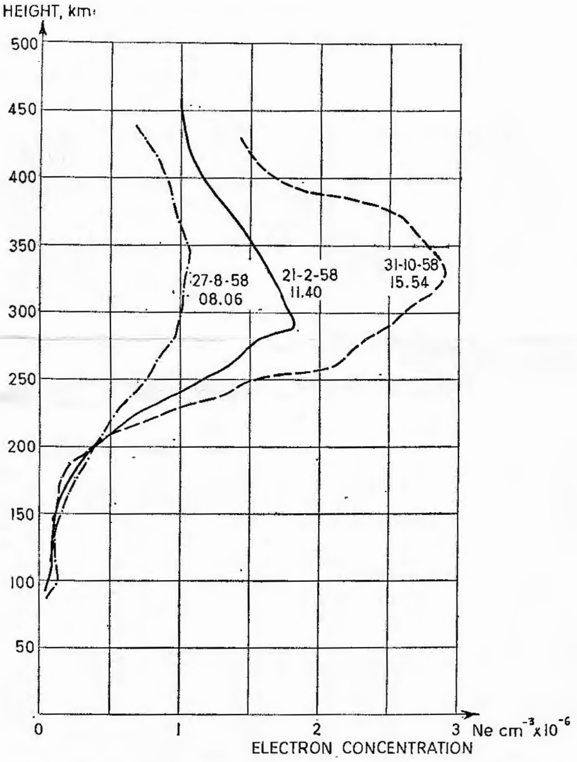

Fig. 2. Variation of electron concentration with height.

The variability of the ionosphere (including its outer part lying above the maximum of ionization of the F-layer) is to some degree characterized by the three electron concentration height distributions shown in Fig. 2. All three distributions were obtained in 1958 by means of rockets of the type shown earlier, above the same point (in middle latitudes of the European part of the U.S.S.R.) with the same instrumentation. The first curve refers to the launching on 21st February (the beginning of the launching at 11.40), the second curve refers to the launching on 27th August (beginning at 08·06), the third one shows the launching on 31st October (beginning at 15.54). From the curves it is seen that values of electron concentration vertical gradients above the F-region maximum over the same point can vary considerably in time.

It is well known that during electron concentration measurements made from vertically launched rockets by the phase dispersion method, time variations of the total electron content in a column under the rocket are starting to exert a growing influence as the rocket approaches the apex of its trajectory.

It is easy to show that the change of the phase difference of two coherent radio waves received on the ground during the time Δt from a rocket flying in the ionosphere and reduced to one frequency can be presented as

$$\Delta\phi = \Delta\phi_{\text{loc.}} + \Delta\phi_{\text{int.}} \qquad \ldots\ldots(1)$$

As the frequencies considered are sufficiently high, then we have

$$\Delta\phi_{\text{loc.}} = K\overline{n_e v_h}\Delta t$$

$$\Delta\phi_{\text{int.}} = K\frac{\partial}{\partial t}N_e\Delta t$$

K is a constant which depends on the instrumentation parameters and frequencies received.

$\overline{n_e}$ is the mean electron concentration in the height range Δh passed through by the rocket in the time Δt.

$\overline{v_h}$ is the rocket's mean vertical speed in this range.

$N_e = \int_0^h n_e \, dh$ is the total electron content in a vertical column from the observer to the beginning of the interval Δh.

The term $\Delta\phi_{\text{loc.}}$ is related to the height increment Δh for the time Δt and depends on electron concentration $\overline{n_e}$ in the interval Δh.

The term $\Delta\phi_{\text{int.}}$ is related to the changes in the N_e value for the time Δt. Such N_e changes take place as a result of the regular diurnal variations of the state of the ionosphere and as a result of motions of non-homogeneous formations in the ionosphere.

With sufficiently large values of the $\overline{n_e v_h}$ product $\Delta\phi_{\text{loc.}} \gg \Delta\phi_{\text{int.}}$ and the second term in (1) can be ignored. It is evident, however, that with very small $\overline{n_e v_h}$ values (which in particular take place near the rocket trajectory apex where v_h passes through zero) the measured value of $\Delta\phi$ depends only on $\Delta\phi_{\text{int.}}$, i.e. the value of $\partial N_e/\partial t$, the rate of change of the total electron content in a vertical column below the rocket.

Values of $\partial N_e/\partial t$ were measured near upper points of the trajectories of the rockets launched on 21st February and 27th August 1958. They were determined as $\frac{1}{K}\left(\frac{\Delta\phi}{\Delta t}\right)$ with $v_h \simeq 0$ (which corresponded to

$h \simeq 470$ km in one case, and to 450 km in the other) and $\Delta t = 0{\cdot}3$ seconds. In both cases values $\partial N_e/\partial t$ were close to 5×10^9 cm^{-2} s^{-1}.

One should bear in mind that these measurements refer to the period of maximum solar activity and that lower $\partial N_e/\partial t$ values are possible for vertical columns at the same height.

From the above results of measurements it is evident that in general it is impossible to determine local electron concentration in interplanetary space near the space vehicle by means of terrestrial observations of radio waves emitted from the rocket, since the influence on radio waves of processes occurring in the Earth's ionosphere will be greater than the effect made by the change of the optical length of path of radio waves which is due to the interplanetary ionized gas near the rocket. In fact, if one takes the electron concentration in interplanetary gas as equal to $n_e \simeq 10^2$ cm^{-3} (actually n_e we think may be much lower) and if the rocket velocity $v_r \sim 10$ km/s, then, nevertheless, $n_e . \ v_r \simeq 10^8$cm^{-2}s^{-1} and $\partial N_e/\partial t$ exceeds this value more than by one order of magnitude.

It is of interest, however, to consider the possibility of determining the total electron concentration N_{eR} by radio methods on the path from the Earth to the space vehicle.

Knowing N_{eR} and the distance to the rocket it is possible to determine $\overline{n_e}$—the mean electron concentration in interplanetary space, if one is confident that N_{eR} considerably exceeds N_{eE}, which is the total electron content of the part of the path of the radio waves in the Earth's ionosphere. Evaluation of this possibility was made in 1959 by Kelso[10] who considered the case of $\overline{n_e}$ determination by measuring the difference of group paths of two pulses of radio waves with different frequencies, simultaneously emitted from a space vehicle. Taking $\overline{n_e} \simeq 10^2$ per cubic centimetre the author concluded that $N_{eR} \gg N_{eE}$ with $f_1 = 100$ Mc/s and $f_2 = 400$ Mc/s at a distance of 10^8 km and that the difference between the group paths of radio waves with the above frequencies is about 40 km. This can be recorded with confidence.

The drawback of the above computation is that it assumes an excessively high value of electron concentration in interplanetary space n_e (~ 100 cm^{-3}). At the same time, the method of measurement under discussion (i.e. reception of the signals on the Earth as two pulses and determination of delay of one in respect to the other) requires a wide-band receiver. It is difficult with such a system to ensure reception of the signals transmitted with powers acceptable for rocket-borne transmitters over the necessary distances of the order of 100 million km.

The experimental variation considered by Soviet radiophysicists E. E. Mityakova, N. A. Mityakov and V. O. Rappoport from the Gorky University[11] is more to be recommended. They proposed to conduct the experiment in the following way. Radio waves are transmitted from a space vehicle at three frequencies f_1, f_2 and f_3, in-phase and sinusoidally amplitude modulated with a frequency Ω. Frequencies f_1 and f_2 are close to each other in magnitude, but frequency f_3 essentially differs from them. By observing the rotation of planes of polarization of the radio waves with frequencies f_1 and f_2 the total electron content in the Earth's ionosphere N_{eE} should be determined as it was made in Evans' well known experiments at the Jodrell Bank Observatory when signals reflected from the Moon were used.[12] Measurements of the phase shift of the modulation envelopes of radio waves with frequencies f_1 and f_3 (or f_2 and f_3) will make it possible to determine the difference between the group paths of these waves and consequently the N_{eR} value.

The mean electron concentration in interplanetary space can be obtained as $(N_{eR}–N_{eE})/R$, where R is the distance from a space vehicle to the Earth.

The possibility of taking into account and excluding the total electron content in the Earth's ionosphere as well as the possibility of using receivers with much narrower bands (at the expense of sinusoidal modulation) are considerable advantages of this variant of the experiment. Its sensitivity to electron concentration is much higher than in Kelso's version.

However, it is likely that the determination of the mean electron concentration of interplanetary ionized gas by means of radio waves emitted from space vehicles can become very difficult, even in the case of the most sensitive variants of such an experiment. These apprehensions are based on the fact that experiments with traps of charged particles on board space probes give reason to believe that the concentration of stationary ionized gas in interplanetary space is very low.

Let us return to the lower part of the ionosphere.

Figure 3 shows height distribution of electron concentration obtained by the phase dispersion method during the vertical launching of the U.S.S.R. Academy of Sciences' geophysical rocket which began at 06.43 on 15th July 1960 in the middle zone of the European part of the U.S.S.R. (local time).[13] The maximum electron concentration at a height $h = 105$ km is of particular interest. Earlier we repeatedly observed small maxima at these altitudes. They were also observed in the American experiments conducted by Seddon and Jackson.[14]

The same geophysical rocket launched on 15th June, 1961, carried the radio-frequency ion mass spectrometer of the Bennett type installed in the capsule which was separated from the rocket to make measurements in an ionospheric region not contaminated by the rocket.

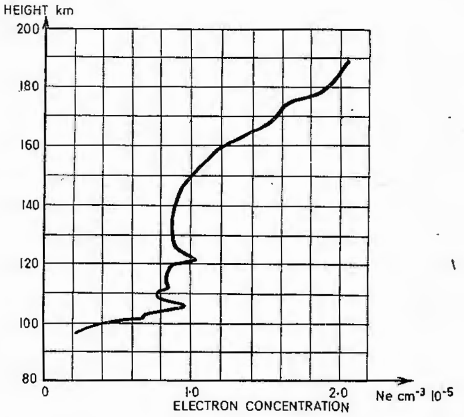

Fig. 3. Variation of electron concentration with height.

The analysis of measurements by the ion mass spectrometer performed by V. G. Istomin makes it possible to give an interesting explanation of the above-mentioned electron concentration maximum.[15] In the region of this maximum there were revealed peaks in positive ion mass spectra corresponding to mass numbers 24 and 26. Magnesium isotopes correspond to these mass numbers.

Besides there were revealed peaks at the same altitudes with mass number 40 which corresponds to calcium ions (Ca^+). The magnesium ion concentration was estimated as n^+ Mg $= 1\times 36\times 10^4$cm^{-3}. This estimation was made by the use of maximum values of the relative intensity of magnesium ion peaks with respect to the total intensity of all ion components recorded by the mass spectrometer. The values of electron concentrations at these altitudes determined by the dispersion radio-interferometer were also used. Calcium ion concentration was estimated as n^+Ca $\simeq 540$ cm^{-3}.

Measurements were made during the activity of the daytime meteoric streams of Arietides and Perseides. Comparison of values of the height of the layer, in which Ca^+ and Mg^+ ions are revealed, with data on the height of the layer of CaII line of twilight airglow as well as comparison of concentrations of these ions with relative distribution of magnesium and calcium in stone meteorites, have led Istomin to the conclusion that the Mg^+ and Ca^+ ions which were recorded are the product of the interaction of the atmospheric molecules with swiftly flying Mg and Ca atoms evaporated from meteors. If this supposition is true, then the rather frequently observed small electron concentration maximum in the region of the height $h \sim 105$ km has a meteoric origin.

It should be pointed out that though these mass-spectrometric observations were made in morning hours, they indirectly confirm considerations in favour of the meteor origin of the nocturnal E-layer expressed by Nicolet in 1955.[16]

3. Experiments made with Charged Particle Traps on Soviet Satellites and Space Probes

Langmuir probe shielding by means of a grid to which an electrical potential is supplied was successfully used for the first time by R. L. F. Boyd in a plasma of a gas discharge and was described by him in 1950.[17] Such a "shielded" probe moving in a plasma with a speed exceeding thermal ion velocities acquires a number of new properties.[2]

In 1958 we used such spherical shielded probes called ion traps on board *Sputnik III* to study the concentration of positive ions in the ionosphere. Later all Soviet space probes, including the Venus probe launched on 12th February, 1961, carried charged particle traps in which a third electrode—an inner grid—was introduced to suppress photo-emission from collector. This photo-emission is caused by solar ultraviolet emission and limits the instrument sensitivity to the charged particle streams getting into traps from the surrounding medium. Figure 4 shows the placing of charged particle traps on a capsule with

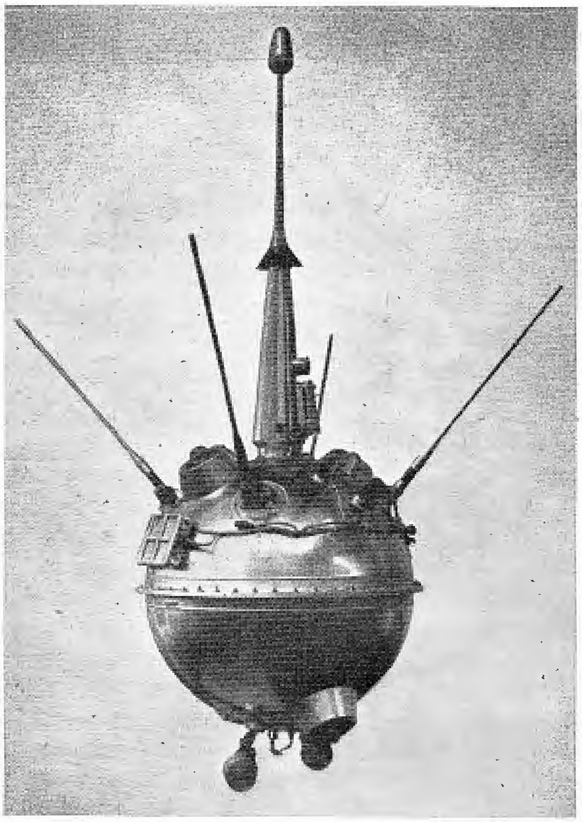

Fig. 4. *Lunik II.*

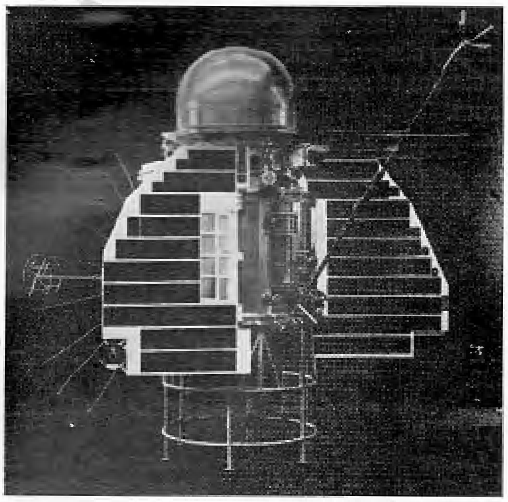

Fig. 5. Venus probe automatic interplanetary station.

Lunik II scientific instrumentation. Figure 5 shows the placing of traps on the Venus probe automatic interplanetary station.

Lack of time prevents the description of the peculiarities of the technique of measurements by means of charged particle traps on *Sputnik III* and each of space probes. There is also no opportunity of discussing theoretical considerations on the basis of which recorded currents in the trap collector circuits were recalculated into charged particle concentrations. These data were published in Soviet scientific periodicals[6, 7, 8] and were reported in April this year at the Second International Space Science Symposium in Florence.[18]

Only some conclusions made on the basis of the results of charged particle trap experiments and referring to the Earth's ionized gas envelope and the ionized gas in interplanetary space will be discussed.

More than 10 000 ion volt-ampere characteristics ("retardation curves") corresponding to the altitude ranges up to 1000 km were obtained by *Sputnik III* in the period from 15th May to 2nd June, 1958. It was established that at the altitudes of *Sputnik III* flight, the electron concentration is equal to the ion concentration. A number of positive ion concentration measurements were made along the trajectories of *Luniks I, II* and *III* launched in 1959.

A combination of the results of these measurements together with the results of electron concentration measurements made in 1958 by means of vertically launched rockets (which were cited at the beginning of the paper) makes it possible to compose a tentative charged particle distribution in the sunlit part of the Earth's gas envelope in a period close to maximum solar activity (1958–1959). Such distribution is shown in Fig. 6. Dotted lines indicate the region in which there are no data. Measurements of ion mass spectra have revealed that at altitudes up to 1000 km the ionosphere mainly consists of O^+ ions. The height variation of the charged particle concentration makes one believe that at altitudes from 1000 km to 2000 km a transition takes place from the oxygen ionosphere to the hydrogen one which mainly consists of hydrogen ions—protons—with concentration of the order of 10^3 cm^{-3}. At altitudes of more than $\sim$ 15 000 km the negative vertical gradients of the charged particle concentration increase and at altitudes about 20 000 km the concentration reaches the value of $\sim$ 100 particles per cm^3. It continues to decrease with the increase of height.

In the graph of Fig. 6 the dates on which the experimental dots were obtained are indicated.

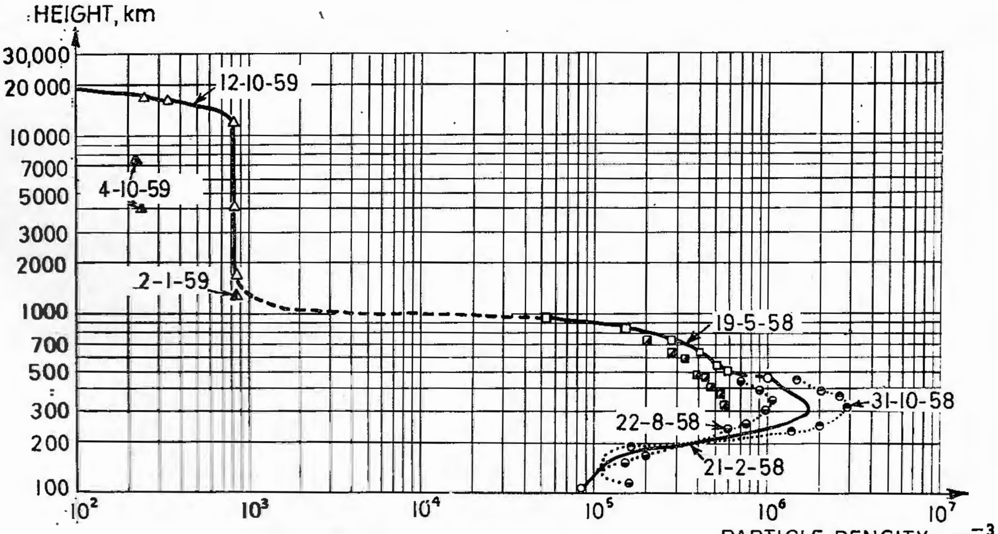

Fig. 6. Variation of the density of charged particles with height.

Data obtained with *Lunik III* (launched on 3rd October, 1959) at distances greater than 200 000 km from the Earth show that the concentration of charged particles with low (thermal) energies of the presumably existent stationary interplanetary gas is very low (apparently not more than 1·5 particles per cm^3).

On 13th September, 1959, during *Lunik II* flight solar corpuscular streams (streams of ionized gas ejected by the Sun) were for the first time recorded in interplanetary space beyond the Earth's magnetic field by means of charged particle traps.

Currents created by the positive ions of the corpuscular streams were repeatedly observed in traps during *Lunik III* flight. There was a good correlation between the presence of such currents and *K*-indexes which characterize geomagnetic disturbances.

The maximum solar corpuscular stream observed up to present time with charged particle traps was recorded on 17th February during the radio contact with the automatic interplanetary station of the Soviet Venus probe at a distance of $\sim$ 1 900 000 km from the Earth.

The density of this stream was $\sim 10^9$ cm^{-2}s^{-1}. A magnetic storm was observed at this time on the Earth. The stream velocity determined from the time of delay of the commencement of the magnetic storm in respect with a flocculus passing through the central meridian of the solar disc amounted to $\sim$ 400 km/s. This means that electron concentration in the stream was approximately 25 cm^{-3}.

One can believe that experiments aimed at measuring the mean electron concentration in interplanetary space by means of radio signals transmitted from space vehicles will make it possible to measure the mean electron concentration in sufficiently intense corpuscular streams.

The minimum stream of charged particles from the surrounding medium which can be recorded in three-electrode traps is limited by the value of the current of the photo-electrons incident from the inner grid to the collector while the trap is lit by the Sun. This limiting value of the recorded stream can be considerably lowered if the charged particles getting into the trap from the outside are modulated with a certain frequency (so that the photo-electron current remains unmodulated) and records are made at the modulation frequency.

At present instrumentation has been prepared to measure by charged particle traps, not only the density of the stream of solar corpuscles, but also their energy spectrum.

There are no doubts that charged particle traps will be one of the effective means of exploration of the Earth's ionosphere, the ionized gas in interplanetary space and ionospheres of other planets.

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