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PLASMA MEASUREMENTS CONDUCTED IN THE VICINITY OF VENUS ON THE SPACECRAFT "VENERA-4"

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SUMMARY

Preliminary results are presented of plasma flux measurements by charged particle traps carried out in the near-planetary flight sector of spacecraft "VENERA-4".

The increase in plasma fluxes detected at distance ∿ 19,000 km, is explained by VENERA-4 crossing the shock wave front formed in the vicinity of the planet.

Considerations are brought out on the low charged particle concentrations measured in the night ionosphere of Venus.

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1. The main task of the experiments described in this article was the study of charged particle concentration in the ionosphere of Venus. Measurements of planetary ionosphere characteristics may be conducted both by radiophysical methods (related to studies of the passage of radio waves through the ionosphere or on their reflection from the ionosphere) and by sounding methods (by means of Langmuir probes or charged particle traps installed on a spacecraft passing through the ionosphere of the planet). Considerations favoring the use of sounding methods for studies of planet ionospheres are discussed in [1]: the experiment described hereunder is a first attempt of realizing such sounding measurements.

Four charged particle traps were installed on spacecraft "VENERA-4", launched on June 12, 1967. The sketches of a plane and hemispherical traps, their couplings and their arrangement on the spacecraft are shown in Fig.1. The designs of the traps were similar to those previously used for studies of the Earth's ionosphere (on satellites of the "ELEKTRON" type in particular [2]).

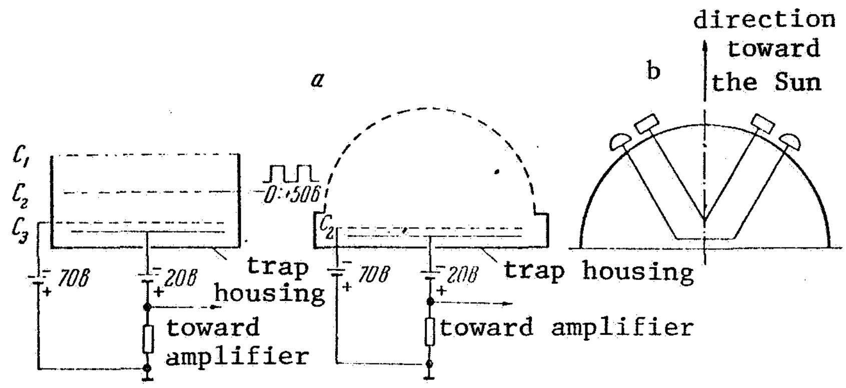

Fig. I

The angle between the axes of two plane traps, as well as of the two hemispherical ones, was 60°; the plane trap collectors were coupled with the input of the common current amplifier. The hemispherical traps were connected in a similar manner. The purpose of such a connection was in the substantial expansion of the angular diagram of the trap, i.e. a reduction of the dependence of the registered current produced by the flux of ionospheric positive ions on the direction of the trap relative to spacecraft's velocity vector. Since the spacecraft's near planet velocity was $\sim 10^6$ cm/sec, it was assumed that, by comparison with the directed velocity of ionospheric ions relative to spacecraft, their thermal velocities could be ignored.

The plane traps were intended for measuring small ion concentrations in the peripheral region of Venus' ionosphere. The collectors of these traps were coupled with an electrometric amplifier on whose input an electrometric tube was set with a grid current $\sim 10^{-14}$ amp. The minimum registered collector current was $1 \cdot 10^{-10}$ amp. This ratio between the aforementioned currents guaranteed a high degree of stability of amplifier's zero reading during the flight. The constant orientation of the space craft toward the Sun made it possible to register in the plane traps the positive ions of the solar wind (during the first stage of near-planetary measurements that began at a distance $\sim$ 40,000km from Venus, ionospheric ions could not be present in the medium surrounding the spacecraft). Measurements of the total collector current of the plane traps in the near-planetary sector were carried out once every 7 sec. To separate the registration of ionospheric ions by plane traps from that of higher energy particles of nonionospheric origin (for instance, solar wind ions), a positive voltage of 50 v relative to spacecraft frame was fed to plane traps once every 14 sec. This voltage would have decelerated the ionospheric ions without hindering the incidence of nonionospheric charged particles on the collector. Variations in the magnitude of collector currents with changes in grid voltage from 0 to 50 v made it possible to evaluate the contribution of nonionospheric ions to the measured current.

Plane traps made it possible to measure ion concentrations in the ionosphere from 50 to 5000 cm^{-3}.

The hemispherical charged particle traps were intended for measuring large concentrations of positive ions in the vicinity of the main ionization maximum in the upper atmosphere of Venus. To obtain a detailed altitude distribution of charged particle concentration in the vicinity of the main ionization maximum, collector current measurements for these traps were conducted much more frequently than in the case of plane traps, namely once every 0.8 sec. Ionospheric ion concentrations within the limits of 10^4 to $10^7 cm^{-3}$ could be measured by means of the hemispherical traps.

As already mentioned, plane traps could register fluxes of solar wind positive ions on the route between Earth and Venus. However, the results of this registration will be dealt with separately, this article presenting only the preliminary results of the measurements conducted during the last near-planetary radiocommunication with the spacecraft on October 18, 1967 at distances of less than $\sim$ 40,000 km from Venus. The phenomenon of ion fluxes increase recorded at distances of less than 22,000 km from the planet is considered and discussed in the second section of this article. The final section deals with the conclusions that can be drawn from the data on the ionosphere of Venus obtained by means of the traps.

2. At distances from 40,000 to $\sim$ 19,000 km almost constant currents corresponding to relatively low solar plasma proton fluxes were registered in sensitive plane traps. At the same time, a magnetometer installed on the same spaceship [3] was registering the steady magnitude of the magnetic field (about 16γ). At a press conference on the scientific results obtained by means of "VENERA-4"* which was held a few days after the end of the flight it was noted that the interplanetary plasma and the magnetic field disturbances induced by the planet had been detected. A considerable increase in positive ion fluxes registered by the traps began at distances starting at about 19,400 km from the planet surface. An increase in the measured magnetic field started simultaneously. Subsequently, variations in the magnitudes of positive particle fluxes registered by the traps and in the field measured by the magnetometer occurred with a high degree of syn-

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* In the book: "Two Miracles of Space Technology". Izd-vo "Izvestiya", 1967, p.130.

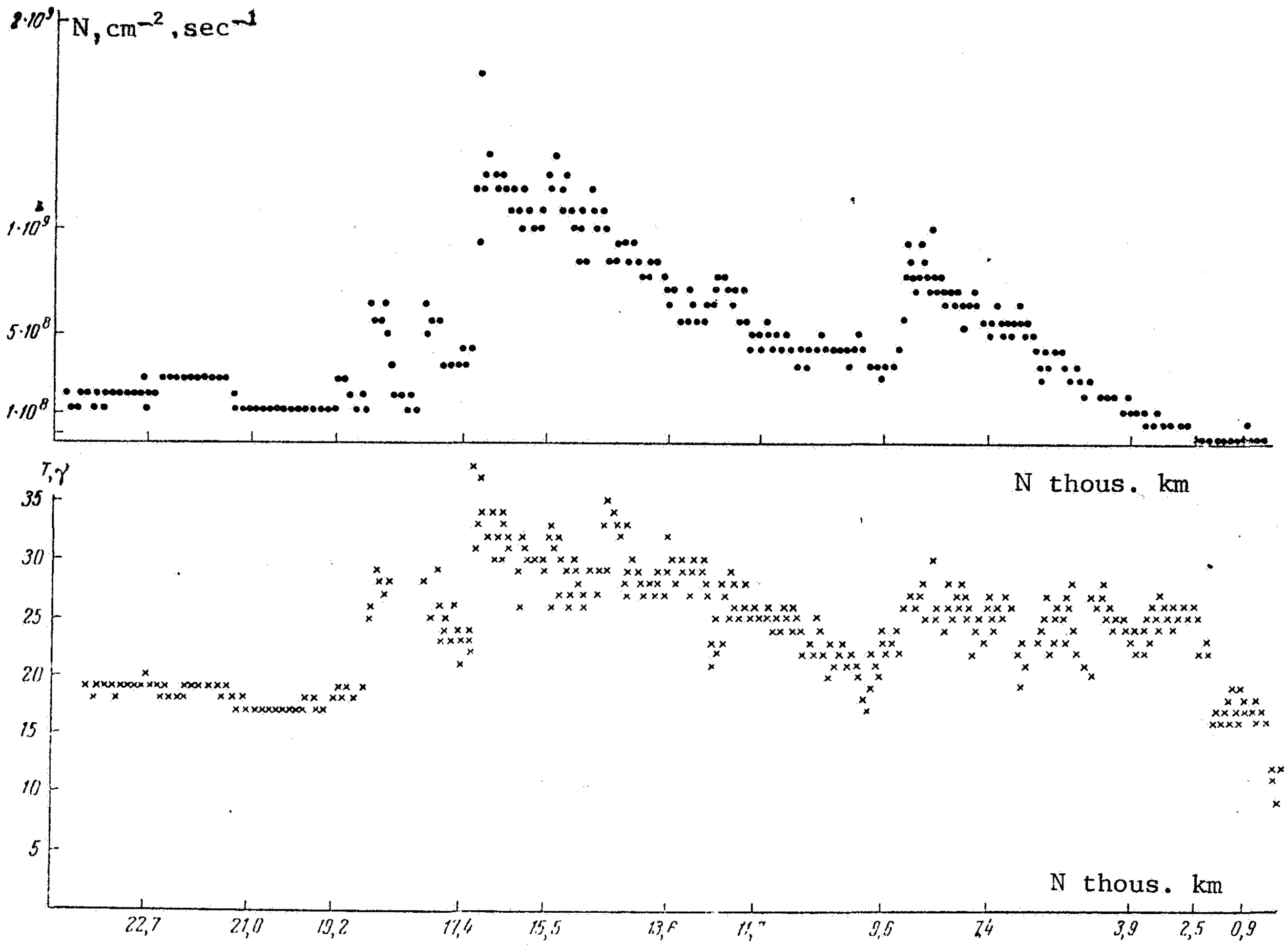

Fig. 2

chronism (Fig.2).

This pattern of a rapid increase in charged particle fluxes and in the magnetic field reminds one of an analogous picture occurring during the approach toward the Earth of a spacecraft moving from interplanetary space (a satellite with apogee of the order of hundreds of thousand km), when the spacecraft intersects the collisionless shock wave front produced by the interaction between solar wind and the geomagnetic field. However, near Earth the closest approach of this shock wave front takes place in the Earth-Sun direction and is approximately $14R_E$, i.e. about 80,000 km from the Earth's surface [4,5].

In the case of Venus, lacking a proper magnetic field, it can be assumed that the shock wave is formed when solar plasma

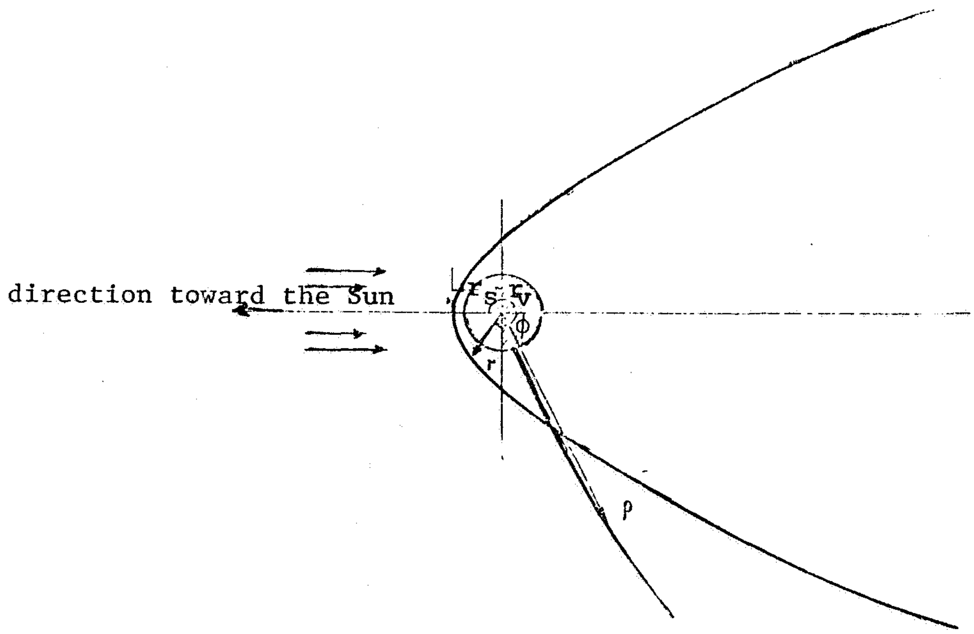

Fig. 3

fluxes (where the magnetic field is frozen-in) flow past the planet, the latter constituting a solid obstacle on their route. The formation of a collisionless shock wave is possible in this case since the Larmor radius of solar wind protons is substantially smaller than the linear dimensions of the planet.

In this case, the position of the shock wave front can be approximately estimated if in determining the Mach number we substitute the Alfvén velocity in an undistrubed solar plasma flux we substitute the Alfvén velocity for the speed of sound by taking advantage of the law of gas dynamics. Then the Mach number is

$$M = \frac{V}{\sqrt{\gamma \frac{p}{\rho}}} \simeq \frac{V}{\sqrt{\gamma \frac{H^2}{8\pi\rho}}},$$

where γ = 2 for the ionized gas, V is the velocity of the unperturbed flux, H the magnetic field intensity, and ρ is the density in the plasma flux (all these parameters characterize the solar wind unperturbed by the planet), and the expressions

$$\frac{r}{r_s} = \frac{1 + \sec\beta}{1 + \sec\beta\cos\varphi}, \quad \sin\beta = \frac{1}{M},$$

$$r_s = 1{,}24\, r_B \sec\beta$$

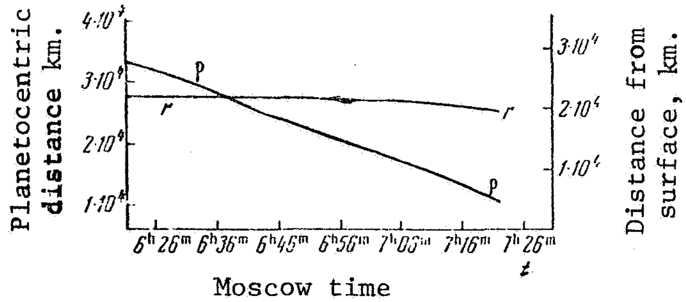

Fig. 4

will determine the position of the shock wave front (see, for instance [5]). (The denotation used by us are shown in Fig.3). The figure shows in scale the results of such a calculation for $M = 5 \pm 4$, which corresponds to the volocity $V = 350 \pm 100$ km/sec [6] and the intensity of the magnetic-field $H = 7 \pm 3\gamma$ most characteristic for the solar wind [7]. The shortest distance between the shock wave front and the planet (in the direction Sun-Venus) is $\sim$ 2000 km.

With data on spacecraft trajectory on hand it becomes possible to determine the angle between the radii-vectors directed from the center of the planet toward the Sun and the current point of the trajectory (see Fig.3 related to the plane passing through the "VENERA-4" trajectory). The distances $\underline{r}$ to the shock wave front were calculated on the basis of formulas (1) for the angles ϕ corresponding to the near-planetary portion of the trajectory and to Mach numbers $M = 5 \pm 4$ and were compared with the distances ρ to the spacecraft (Fig. 4). They were found to be equal at distances $\sim$ 21,000±2000 km from the planet surface. As already mentioned, the increase in positive ion fluxes and in the magnetic field began at a distance $\sim$ 19,400 km.

Therefore, these approximate estimates provide a basis to consider that this increase is actually connected with the shock wave found near the planet.

Considerations on the possibility of shock wave during supersonic solar wind flow past the Moon are presented in [8]. These considerations can be applied to solar wind flow past Venus.

If the planet is a nonconducting unmagnetized sphere, solar wind particles must be absorbed by its surface (or neutralized on it), and a shock wave cannot be formed, whereas, if the planet has an ideal conductivity, a shock wave will be forming.

Analogously to the Earth, it may be assumed that Venus has a high conductive core surrounded by a nonconductive or weakly conductive mantle. The frozen-in magnetic field of the solar wind does not penetrate into the conductive core and crowding of magnetic lines of force appears on its surface on the side of the incident flow.

If the thickness of planet's mantle is lesser than that of the region above the upper limit of the core, where the main mass of solar wind particles cannot penetrate on account of their reflection by a perturbed magnetic field, these particles will not be absorbed by the planet surface, and a shock wave sets in.

If a method similar to the one applied in [8] is used to evaluate the overall thickness of the nonconductive mantle surrounding the conductive core of Venus required for the formation of a shock wave for solar wind parameters indicated at the beginning of this section, it will prove to be equal to 0.05 of the venusian radius. In other words, the thickness of the mantle should not exceed $\sim$ 300 km. As is well known, for the Earth the thickness of the mantle surrounding the core is $\sim$ 3000 km [9]. The various hypotheses describing the properties and the structure of the Earth's core [10-12] agree on the representations that it must be endowed with metal properties and, consequently, with a high electric and thermal conductivity. It must also have a higher temperature than that of the adjacent layer of the mantle.

If one assumes that the core of Venus has similar properties, while its mantle is at least 10 times thinner than that of the Earth, as it results from the aforementioned evaluation, the described mechanism can be explained by the formation of a shock wave, while the hot core closely located to the surface may be the reason of the temperature at planet surface being considerably higher than that of the Earth's surface (as follows from the measurements on spaceship "VENERA-4" [13]).

3. As already mentioned, this experiment made it possible to estimate the concentration of charged particles in the Venus' ionosphere above the dark part of planet's surface.

In earlier publications, considerations were expressed on the basis of which it was concluded that electron concentration N_e in the Venus' ionosphere exceeds considerably the N_e of the Earth's ionosphere. Estimates were made, according to which N_e attains $\sim 10^9 cm^{-3}$ in the venusian ionosphere, which is 1000 times more than in the Earth's ionosphere [1]-17]. However, all along the flight the hemispherical traps with sensitivity $n_c = 10^4 cm^{-3}$ failed to register any current. Analysis of the differences of plane trap collector currents registered in the vicinity of the planet and corresponding to the presence of a retarding potential on grid C_2 (Fig.1) and its absence, shows that positive ion concentrations at altitudes of hundreds of km above the planet's surface do not exceed $\sim 10^3 cm^{-3}$. in any case. Therefore, it is substantially lower than the charged particle concentration at corresponding altitude in the night ionosphere of the Earth.

The entire spacecraft trajectory passed above the dark part of Venus' surface; the craft landed in the vicinity of that part of the terminator which separates night from morning. This circumstance may to a considerable degree explain the unexpectedly low values of charged particle concentrations.

It is natural to compare data on the upper atmosphere of Venus with the available data on the upper atmosphere and the ionosphere of the Earth.

On the basis of the experimental results by "VENERA-4", V.G. Kurt and V.I. Moroz came to the conclusion that in the dark upper atmosphere of Venus the scale height is 13 km [18].

At the same altitudes, the scale height in the upper atmosphere of the Earth is 3-4 times higher. It means that the upper atmosphere of Venus is less extended than the terrestrial and that, consequently, the initial material for the ionosphere formation on Venus is scarcer than on Earth.

It is well known that in the Earth's ionosphere the ions are formed mainly at altitudes < 400 km. They reach higher altitudes moving along the magnetic tubes of force [19].

In the region where one kind of ions is predominant and where temperature equilbrium exists between neutral and charged particles, the scale height of the ionized component must be equal to the doubled scale height of the corresponding neutral component [20].

Applied to venusian conditions, the scale height of charged particles in the night ionosphere at altitudes of 100-400 km whould be $\sim$ 30 km (while on Earth it is $\sim$ 80 -100 km). Hence, it follows that the night ionosphere of Venus must also be less extended and dense than the terrestrial ionosphere, and all the more so, since because of absence of a magnetic field, Venus lacks such an effective transport and trapping mechanism as the diffusion of charged particle along the lines of force of planet's magnetic field. This last circumstance must affect the extension of the ionosphere also on the diurnal side of the planet.

Moreover, considering that on Venus the night lasts approximately 110 periods of 24 hours [14], the lack of an additional source, continuously sustaining the night ionization means that in the dense upper night atmosphere of the planet all the ions have to recombine. Such source could be the turbulent solar wind fluxes behind the shock wave front, partly hitting the atmosphere of Venus. However, at the present time, data for quantitative estimates of the effect of this source of ionization on the night atmosphere of Venus are still lacking (the magnitudes of fluxes and energy of ionizing particles are unknown). Nevertheless, because of the low density of the venusian neutral atmosphere the effect at high altitudes of this additional ionization source is negligibly small. Even in the sunlit space above the night side of the planet, the concentration of charged particles must be extremely low despite the action of such an ionization source as the Sun's shortwave radiation. As already stated, owing to the absence of a magnetic field on Venus, the ionization influx from below must be extremely low.

There is a certain possibility for the appearance of particles in this region on account of their influx from the diurnal side at the expense of horizontal diffusion, whereas at altitudes where collisions are absent, they could appear on account of the penetration into the night side of ballistic particle trajectories originating on the diurnal side. Evidently, this effect must be more clearly expressed on the night side in the vicinity of the evening and not of the morning boundary of the shadow. On the other hand, "VENERA -4" descended in the vicinity of the morning boundary of the dark part of the planet's surface.

Therefore, the small currents registered by charged particle traps during the described experiment are not in contradiction with all the earlier expressed considerations on the low charged particle concentrations in the night ionosphere of Venus.

At the present time it is still very difficult to forecast the characteristics of Venus' daytime ionosphere inasmuch as they are strongly dependent on the density, temperature and composition of the neutral daytime upper atmosphere. If, in particular, CO_2 molecules are contained in it as a consequence of the diffusion processes, the atmosphere on the daytime side may prove to be sufficiently cold and unextended, which would accordingly affect also the diurnal ionosphere.

If the temperature of the diurnal atmosphere is found to be high, the assumption according to which the ionosphere of Venus, as compared to that of the Earth's, has higher values of electron concentration may prove to be justified.

In this case, during solar wind flow past the planet, the shock wave could be formed by means of the above-described mechanism with the difference that the role of the conductive layer would be played by the diurnal ionosphere and not by the core located within the planet. The formation of a shock wave under these conditions would be possible provided the time of shock wave front formation is shorter than the time of interplanetary magnetic field penetration into the ionosphere.

ANNOTATION DURING PROOFREADING. After sending the article for publication, the authors became acquainted with the results of plasma and magnetic field experiments conducted in the vicinity of Venus on "MARINER-5" on November 19, 1967 (Science, 158, 1665, 1667). From these results it follows, in particular, that there exists in the vicinity of the planet a shock wave in the solar wind and a fairly intense diurnal ionosphere. The authors will publish a comparison of the results of plasma measurement conducted on "VENERA-4" and "MARINER-5" at a later date.

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