PECULIARITIES OF THE SOLAR WIND INTERACTION
WITH THE UPPER ATMOSPHERES OF VENUS AND MARS**

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RESUMEN

Mediciones de plasma y de campos magnéticos en Venus y Marte así como observaciones de radio ocultamiento de satélites por sus atmósferas y ionosferas superiores revelan algunas diferencias y semejanzas en la configuración del flujo del viento solar alrededor de estos planetas.

Ambos planetas tienen campos magnéticos muy débiles comparados con el de la Tierra y sus ionosferas están caracterizadas por un máximo de densidad electrónica similar. Sin embargo, la ionosfera Marciana está más protegida de la acción directa del viento solar que la de Venus y algunas propiedades de la ionosfera superior Marciana se asemejan a las de la ionosfera superior de la Tierra.

Se concluye que la ionosfera de Venus y el campo magnético inducido (el campo magnético del viento solar acumulado alrededor de la ionosfera del planeta) son elementos decisivos para la formación del obstáculo efectivo en Venus. En Marte, el campo magnético intrínseco domina y juega un papel importante en la formación del obstáculo y en la desaceleración del viento solar.

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ABSTRACT

The direct measurements of the plasma and magnetic fields of Venus and Mars as well as satellite radiooccultation observations of their upper atmospheres and ionospheres reveal some similarities and differences in the overall configuration of the solar wind flow as it streams around these planets.

Both planets have very weak magnetic fields as compared with that of the Earth, and their ionospheres are characterized by a similar maximum electron density. However, the Martian ionosphere is protected from the direct action of the solar wind to a greater extent than that at Venus and some properties of the Martian upper ionosphere resemble those of the Earth's upper ionosphere.

It is concluded that the Venus ionosphere and induced magnetic field (the draped solar wind magnetic field) are decisive for the formation of the Venus effective obstacle. As to Mars, its intrinsic magnetic field dominates and plays an important role in forming the obstacle and decelarating the solar wind.

The nature of the obstacles decelerating the solar wind near Mars and Venus has been, in recent years, the subject of extensive and controversial discussion. New experimental data obtained in Venus by the Soviet Venera-9 and -10 satellites, and by the American Pioneer-Venus, and by the Viking spacecrafts in Mars have not resolved the existing controversies despite the substantial increase of useful data. For example, the Venera-9 and -10 magnetic and plasma measurements (Gringauz *et al.*, 1976, Verigin *et al.*, 1978; Breus, 1979; Gringauz *et al.*, 1977; Vaisberg *et al.*, 1976d; Romanov *et al.*, 1978; Dolginov *et al.*, 1977; Eroshenko, 1979) made it possible to understand the nature of the magnetic field measured near Venus as well as the character of the solar wind interaction with the Venus ionosphere; but at the same time these measurements have revealed some similar features with those observed at the solar wind-Mars interaction region and, therefore, have not solved the problem of identifying the nature of the effective obstacle at Mars. Numerous contributions and review papers have been published recently (Ness, 1979; Russell, 1978; Russell, 1979; Breus, 1979) based on the new experimental data and on the ideas developed upon the preliminary results of the Venera-9 -10, and Viking spacecrafts.

In Russell's reviews (1978a, 1979a and b) as well as in the papers of Intriligator (1979), and Cloutier and Daniell (1979) it was suggested that the mechanisms of the solar wind interaction with Venus and Mars should be similar, and that the Martian magnetic moment must be weak enough to be relatively unimportant in the solar wind interaction.

These authors suggested that the observed magnetic field near both planets is the (shocked and compressed) magnetic field of the solar wind draped over the ionospheres of these planets. The electric field of the solar wind generates currents in the ionospheres, and the magnetic field of these currents thus form a magnetic barrier around the day side ionosphere.

It might appear at first sight that there are some reasons for reaching such a conclusion. However, the more detailed analysis of the data characterizing the regions of solar wind interaction with Venus and Mars shows that those regions differ in some substantial features which were either not mentioned or underestimated by the authors who advocate the similarity of mechanisms of solar wind interaction with both planets.

In Russell's earlier papers (1976a, b, 1977, 1978b, c, 1979b), as well as in some other papers dealing with the problem considered, only part of the experimental data obtained by the Mars and Venera-type Soviet spacecraft, was used.

The objectives of the present paper are:

I) to compare the typical features of the regions of solar wind interaction with Venus and with Mars taking into account the data not yet used by Russell;

II) to analyze, with the use of all the available experimental data, the arguments given to support the view that the effective obstacles near Venus and Mars are different;

III) to analyze the pecularities of solar wind interaction with the Venus and Mars atmospheres.

I. Similar features of the regions of solar wind interaction with Mars and Venus

Some measurements made by instruments on board the Soviet artificial satellites in the vicinity of Mars and Venus (Dolginov *et al.,* 1972, 1973; Gringauz *et al.,* 1973, 1974a, b; Vaisberg *et al.,* 1972, 1973, 1974, 1975, 1976a, 1977; Gringauz, 1976) showed that the peculiarities of the magnetic fields deep in the umbra depend on the interplanetary magnetic field and that the behavior of the measured magnetic field in the dayside is not typical of the dipole field. This dependence, observed in five out of ten measurements made with the Mars-satellites (Mars-3 on 21.1.72; Mars-5 on 14.2.74, 15.2.74, 20.2.74 and 24.2.74) led Russell (1978b, c) to state that the Soviet artificial satellites had never entered the Martian magnetosphere formed by its intrinsic magnetic field.

The same data were used by Russell (1978b, c) to get a lower estimate of the magnetic moment of Mars as compared with those of Dolginov and co-workers (1973, 1976).

We examine this question in more detail in Fig. 1 which shows two magnetograms and ion spectra taken on February 13, 1974 (Fig. 1a) and on February 14, 1974 (Fig. 1b) by the Mars-5 spacecraft (Dolginov *et al.*, 1976). Since the period of revolution of the Mars-5 around the planet is almost equal to that of the planet's rotation, the aerocentric coordinates of the satellite, in the same phase of revolution, were practically the same in neighbouring orbits. This implies that if Mars has an intrinsic magnetic field, the magnetic field intensity measured along the satellite orbit should remain the same for the two neighbouring orbits (assuming that the variations of the solar wind flowing around the planet, and of the interplanetary field can be neglected).

In five out of nine orbits of the Mars-5 spacecraft a similar field pattern in region 2-3 (typical of the 13.2.74 session) was observed at aerographic latitudes of about -15° to 20° and independently of the orientation of the interplanetary magnetic field. That is why this region was defined as a magnetospheric region produced by the intrinsic dipole magnetic field of the planet.

The Martian dipole's exact inclination to the ecliptic plane is still an open question. Smirnov and co-workers (1978) returned to the original assumption made by Dolginov and co-workers (1973) about the low (17°) inclination of the Martian dipole and gave examples of the magnetic-field topology observed in three different measurements which resemble the low-latitude cusp in the Mars magnetosphere (but with a -17° inclination).

It is evident that it is only possible to say that the dipole forms an angle of more than 20° with the planet's rotation axis and that the polarity of the Martian dipole is opposite to that of the Earth (i.e. in the southern hemisphere the B_x-component is 'sunward', $B_x > 0$).

In the 4 passes of the Mars-5 spacecraft mentioned above, a pattern similar to those of the February 14 measurements was observed. In those cases the B_x-component sometimes had, at the same aerographic latitudes in region 2-3 a direction unusual for the expected dipole field, i.e. $B_x < 0$ (from the Sun in the southern hemisphere); it often changed its orientation (in some parts of region 2-3) to coincide with that of the interplanetary magnetic field (before point 1 and after point 4).

Russell's statement (1978b, c) regarding the fact that the satellites Mars-3 (on

21.1.72) and Mars 5 (on 15.2.74 and 20.2.74) did not enter the intrinsic Martian magnetosphere was based only on magnetic measurement data. Plasma spectra, however, obtained simultaneously with the magnetic field data gave a pattern peculiar to the entry into a magnetosphere similar, for instance, to the Earth's magnetosphere (Bezrukikh *et al.*, 1976).

Plasma characteristics measured when the vehicles entered the magnetosphere of Mars (and, as we will see later, also in the inner regions of the tail of Venus) have such peculiarities. Changes in the properties of the solar wind planet interaction region when the vehicle crossed the characteristic boundaries were seen simultaneously in the plasma and magnetic field data, for example, as a decrease of the magnetic field fluctuations and as a drastic decrease of ion fluxes when the vehicle passed from the transition region into the obstacle (transition from region 1-2 and 3-4 into 2-3).

Figures 2 and 3 give some results of magnetic field and plasma measurements made on Venera-9 and -10 deep in the umbra region behind Venus. Let us take, for example, the December 1, 1975 data of the Venera-10 spacecraft, shown at the left side of figure 2. Different symbols correspond to different directions of the B_x-component in the Z_{SE} Y_{SE}-plane measured when the vehicle emerged from the depths of the tail and entered the transition layer (point 3) and then into the solar wind (point 4) (Dolginov *et al.*, 1977). Everywhere in the southern hemisphere the B_x-component should have been directed 'sunward' $\odot$ ($B_x > 0$) in the dipole field (see the right circle) but as we can see there is a contradiction with the observations. Deep in the tail the B_x-component was 'antisunward' $\oplus$, when it changed sign before entering the transition layer $\ominus$ and, in the solar wind, it either became 'antisunward' $\oplus$ (1.12.75) or preserved that direction (28.10.75) as seen in Fig.3.

As it turned out, most measurements made during different passes of the Venera -9 and -10 gave a pattern similar to the one shown in Figs. 2 and 3 (Dolginov *et al.*, 1977, Eroshenko, 1979; Breus, 1979); that is: the B_x radial component of the magnetic field in region 2-3 of the tail often had a direction different from that expected for the dipole field (Eroshenko, 1979; Breus, 1979), it changed its direction over some parts of the orbits, and its orientation deep in the region of solar wind planet interaction often corresponded to that of the interplanetary magnetic field. The pattern of the changes of the B_x-component direction in those observations is like that in Fig. 1 which is the pattern for the Mars magnetosphere taken on February 14, 1972.

The plasma characteristics measured when the Venera-10 entered the tail of Venus were also similar to those of the Mars magnetosphere boundary crossing.

Fig. 3 shows the drastic decrease of ion fluxes when the vehicle passed from the transition region (3-4) into the obstacle (to the left from region 3-4).

Thus, the similarity of the macrostructure of the magnetic field observed in the tails of Mars, Venus and Earth, as well as similar plasma structures detected there make it difficult to interpret the results and to determine the nature of the effective planetary obstacle (particularly when only the data about the tail are used). The laboratory simulation experiments by Dubinin and co-workers (1978) clearly illustrate this conclusion.

Magnetic Field properties in the near-Venus tail, detected by Venera-9 and Venera-10 were explained —and rather convincingly— by the solar wind magnetic field draping over the obstacle and by the induction effect produced by ionospheric currents; the latter are created by the Lorentz electric field $\bar{E} = \frac{1}{c} (\bar{V}_{SW} \times \bar{B}_{SW})$ (Eroshenko, 1979; Breus, 1979). The data of Pioneer-Venus magnetic measurements obtained by Russell and co-workers over the dayside (1979c) and nightside (1979d) of the planet confirmed, in fact, that conclusion.

The only difference appeared to be the following: Induced currents seldom flow in the depth of the ionosphere and the "magnetic barrier" is formed by currents flowing in the vicinity of the ionosphere's upper boundary (Johnson and Hanson, 1979; Elphic *et al.*, 1979).

Hence it is now evident that Venus does not have any significant dipole moment which plays an important role in the interaction process, and that the magnetic field created by the solar-wind-induced currents at and near the ionopause are determinant of the deflection of the solar wind flow around the planet.

Consequently, the apparent similarity of the results of the magnetic and plasma measurements made during the 4 passes of the Mars-5 spacecraft indicated above and the data obtained in most passes of the Venus' Soviet satellites give grounds to assume a similar origin for the effective obstacles at the two planets.

After the results of the Pioneer-Venus experiment were published, Cloutier and Daniel (1979) proposed (using their previous studies of induced currents in the ionospheres of both planets) identical models of ionosphere barriers to the solar wind near Mars and Venus without taking account of the role of intrinsic magnetic fields of the planets in the interaction with the solar wind. (Intriligator and Smith (1979) have also expressed similar concepts). Mars has, according to the estimates by Cloutier and Daniell (1979), an intrinsic magnetic field which is too weak to decelerate the solar wind ($\sim 25 \, \gamma$ on the surface of the planet) and the effect of that field can be observed only in the planet tail. We will later return to the discus-

sion of these papers after examining the differences in the behavior of the solar wind plasma near both planets.

II. Differences between the solar wind planet interaction regions near Mars and Venus

Despite the above-mentioned similarities of the properties of the effective obstacles at Mars and Venus there are essential differences, both in size and other properties that contradict the conclusion that both obstacles have the same origin.

If, as assumed by Russell (1978b) and Cloutier and Daniel (1979), the effective obstacle of Mars and Venus is the local ionosphere, then it is interesting to examine their properties by comparing the ionospheric properties of the two planets.

It should be expected in this case that the topside ionospheres of both planets must be exposed to the solar wind, and that their properties must differ from situations where the ionosphere is protected by an intrinsic magnetic field as occurs, for example, in the Earth.

Let us use, for comparison, the statistical data of $N_e(h)$ profiles obtained through radio occultation techniques by the same group of soviet experimenters (Ivanov-Kholodny *et al.*, 1978; Vasiliev *et al.*, 1975; Kolosov and Savich, 1973; Ivanov-Kholodny *et al.*, 1973).

The ionopause, or upper boundary of the Venus ionosphere (Breus, 1979; Wolfe *et al.*, 1979), is also the obstacle's dayside boundary.

This is observed as a drastic decrease of the ionospheric electron density and is located, near the subsolar region, at 280 to 300 Km (the approximate thickness of the region being about 50 to 100 Km, Ivanov-Kholodny *et al.*, 1978).

The comparison of $N_e(h)$ profiles in the Mars (upper part of Fig. 4) and Venus ionospheres (lower part of Fig. 4) reveals the following:

a) a sharp upper ionospheric boundary (i.e. the ionopause) is distinctly observ- ed only near Venus. Within the limits of errors of the $N_e(h)$ measurements no distinct boundary near Mars can be discerned (down to the threshold of the ins- truments against the background of electron density fluctuations, $\Delta N \sim 10^2 - 10^3$ cm^{-3} as shown in Fig. 4).*

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* The ionopause was observed in the Martian ionosphere at 280 to 300 Km only once - in one of the two direct measurements of the $N_e(h)$- profiles by the Vikings spacecrafts.

b) the diurnal variations of the electron density profiles at Mars show (Fig. 4a) that with increasing solar zenith angle χ, i.e. as the profile changes from the day-side (solid line in the picture) to the near terminator region (dotted line), the Martian ionosphere became thinner, obviously colder and less extended. The electron density variations in the Mars ionosphere is well described by a simple law typical of the Earth's ionosphere both in the ionization maximum and in the topside iono-sphere (photochemical equilibrium characterizes the region of maximum density, and diffusion equilibrium dominates at some height above the maximum; Ivanov-Kholodny et al., 1973; Chen et al., 1978).

The properties of the Martian dayside ionosphere seem to be consistent with those of the ionosphere of a planet protected by an intrinsic magnetic field from direct exposure to the solar wind. The properties of the plasma and the magnetic field recorded by the 'Mars-2' spacecraft showed changes typical of the entry from the transition layer into a dayside magnetosphere. This boundary was considered by Breus and Verigin (1976) as the boundary of an obstacle, i.e., of the Martian "intrinsic" magnetosphere.

The geometry of the Venus ionosphere is somewhat different. Radio-occultation data show that unlike the Mars ionosphere, the extent of the Venus dayside iono-sphere increases with the solar zenith angle χ . The increase of the ionopause height h_0 up to $\chi \sim 60^0 - 70^0$ (compare the solid-to-dotted curves in Fig. 4), almost corresponds to the $1/\cos^2\chi$ dependence (Ivanov-Kholodny et al., 1978) determined by the pressure balance with the solar wind dynamic pressure $\rho v^2 \cos^2\chi$ (Breus, 1979).

As a whole, the Pioneer-Venus results confirm the growth of h_0 with χ. However, they show a rather high mobility of the ionopause. The topside ionosphere of Venus near the terminator ("ionosheet") cannot be described by purely ionospheric mechanisms, without consideration of the solar wind direct influence upon the ion-osphere (Breus 1979; Cravens et al., 1978, 1979). At the same time Pérez-de-Tejada and Dryer (1976) showed that a viscous-like interaction of the solar wind with the ionosphere leads to the formation of a boundary layer whose thickness grows with the local zenith angle.

Thus, the properties of the Martian and Venusian topside ionospheres are dif-ferent; at Venus an immediate contact of the solar wind plasma with the iono-sphere is evident.

c) The experimental electron density profiles obtained from direct measure-ments made by the Viking spacecraft in the Martian ionosphere were used by Clou-

tier and Daniell (1979) to construct a model in which a "magnetic barrier" created by the magnetic field compressed above the ionopause, exists at h $\approx$ 250 Km.

As mentioned above, Cloutier and Daniell did not take into account any intrinsic magnetic field of the planet in its interaction with the solar wind. At 250 Km, an (induced) magnetic field of about 60 γ is required to balance the solar wind ram pressure $\rho V^2 \cos^2\chi \sim 1.6 \ 10^{-8}$ dyn/cm^2 with the thermal pressure providing $N_e K \ (T_e + T_i) \sim 0.5 \ 10^{-9}$ dyn/cm^2 (Hanson et al., 1977; Rohrbaugh et al., 1979). However a magnetic field of the same order of magnitude at the suggested ionopause height, can also be produced by the intrinsic field of the planet if a magnetic field $\sim$ 30γ (measured in the Mars-2 orbit pericenter at a height of $\sim$ 1000 Km with zenith angle χ = 35 – 45° , Dolginov et al., 1977) is extrapolated to lower heights. In this interpretation the convection in the Cloutier and Daniell's model (1979) can correspond to the plasma convection in the Mars magnetosphere created by the intrinsic magnetic field; and the Martian ionopause can be a boundary similar to the Earth's plasmapause.

It should be emphasized that the $N_e(h)$ profile calculation performed by Cloutier and Daniell (1979) for the Martian ionosphere (and which takes into account convection processes and the formation of a "magnetic barrier") turned out to be less successful in the Venusian ionosphere. The authors have indicated, however, that this could be due to the great mobility of the Venus ionopause, thus admitting the difference between the properties of the upper ionosphere of both planets.

The observation of an ionopause on the $N_e(h)$ profile (as reported by Hanson et al., (1977) from the Viking measurements might have the same nature as the Venusian ionopause only if:

1) Viking-2 entered (at latitudes 34° - 42°) the region of a Martian cusp with not too great an inclination angle between the dipole axis and the ecliptic plane.

2) That particular event coincided with the extreme increase of the solar wind intensity so that due to a strong compression of the "intrinsic magnetosphere" the contact between the solar wind and the ionosphere became better and induction effects manifested themselves distinctly.

As it becomes more clear after the Pioneer-Venus mission, the topside ionosphere of Venus interacts directly with the solar wind. Evidently, the observation of magnetic flux ropes puts forward the existence of short-scale convection in the boundary layer between the solar wind plasma and the plasma in the Venusian ionosphere, i.e. in the ionopause. Such a convection, most likely having an irregul-

ar character, would carry elementary magnetic flux tubes from the solar wind plasma, through the ionopause. At the present time two instabilities have been suggested to provide the convection needed: a) the flute, or interchange mode; b) the shear flow mode, more familiarly known as the Kelvin-Helmholtz instability.

The first one resembles the plasma magnetic confinement instability with a growth rate $\nu \sim \sqrt{g_{eff}k}$, where k is the wave number and g_{eff} the effective gravity. In the case of a curved magnetic field confinement g_{eff} is T_I/M_iR_c , where T_I is the ionospheric plasma temperature near the ionopause, M_i is the ion mass and R_c is the radius of curvature of the ionopause. This expression is valid for instability wavelengths λ significantly greater than the thickness of the ionopause ($\lambda \gg \delta$). The growth rate ν increases as the instability wavelength λ decreases down to $\lambda \approx \delta$ and further down ($\lambda < \delta$) it becomes practically independent of λ. Thus, the maximum growth rate ν_{max} is $\nu_{max} \sim [T_I(M_i \delta Rc)]^{1/2}$. (Michailovsky, 1977).

The complete evaluation of the role of this instability needs of a more detailed analysis including possible stabilizing mechanisms, such as shear flow or the time limit imposed by the convection of the flow around the dayside ionospheric obstacle. These restrictions also impose limits on the generation of the magnetic ropes, namely, if the convection time from the nose region is smaller than the instability growth time $R/V_{sw} < \nu^{-1} \approx (M_i R_c \delta/T_I)^{1/2}$, the plasma is stable (R denotes here the planetary radius). The onset of the flute instability can be predicted only when $R/V_{sw} < \sim (R \delta/V_T^2)^{1/2}$ or $\dfrac{V_T^2}{\sqrt{R/\delta}} < V_{sw}/V_T$ where V_T is the thermal ion velocity.

b) The shear flow (K–H) instability is frequently invoked in relation with magnetospheric boundaries as a momentum transfer mechanism between the solar wind and magnetospheric plasmas. In our case the velocity shear could provide the convection of magnetic flux tubes frozen in the moving plasma. The growth rate of the instability is given by $(\rho_{sw}/\rho_I)^{1/2}V_{sw}/\delta$. The difference of this mode where the energy reservoir is contained in the shear flow, from the flute instability mechanism, is that the magnetic rope convection represents here a secondary effect. In a way this type of convection may be analogous to the magnetic loop convection in the solar chromosphere and the corona. If so, one could expect the formation of magnetic loops inside the Venusian ionosphere (evolution of ropes into loops). Dissipation of their magnetic energy would provide an additional heating mechanism in the ionosphere.

The two modes under discussion differ drastically in their geometry. The flute

mode is most unstable near the stagnation flow region where each convecting elementary tube tends to keep its geometry (Fig. 5). The K -- H mode is expected in the regions of higher velocity shear ($\sim$ $\pm 90^o$ off the stagnation point). In this case the magnetic field is bent in such a way that it provides a stabilizing effect loop--like fashion as shown in Fig. 6, (Syrovatsky stability criteria). The electric currents induced in the ionosphere along magnetic field lines should, however, twist them into a kind of field-free configuration forming the ropes. Thus, the final geometry of the twisted ropes might be fairly insensitive to the original mode of instability.

One could speculate also in terms of some hybrid instability for our complex flow geometry combining the features of both modes. According to the Pioneer-Venus data (Russell *et al.*, 1979c) the configuration of the magnetic field deep in the Venus tail is in agreement with that inferred from the Venera-9 and -10 high-altitude measurements and differs significantly from that observed near Mars. At low altitudes, in the night-side ionosphere, a negligible small value of the field is often observed. As a rule, the intense magnetic field observed in the night-side ionosphere (at the same altitudes) has a different and often opposite direction. Russell and co-workers concluded that the low-altitude fields near Venus appear to be the remnants of some previously induced currents. In contrast, the following phenomena were observed in the Martian wake (Dolginov *et al.*, 1976): 1) the existence of a stable positive B_X-component distribution during 5 orbits of Mars-5 in the 2-3 region (see Fig. 1a; 2) a rather large value of $|B|$ (more than 6 γ) during the other 4 orbits, when the B_X-component changed sign in the 2-3 region (see Fig. 1b); 3) the B_X-component practically never had a stable negative distribution in the 2-3 region. This may signify that the Martian field has a constant component: that is, the Martian intrinsic field is greater than that of Venus. This constant component may be apparently picked out from the measured field. This also means that the induction mechanism is less intense and stable near Mars.

In extreme cases, when the dynamic pressure of the solar wind is high, the Martian magnetopause could approach the surface at rather short distances and in such a case the transition layer might immediately interact with the ionosphere. In such cases intense currents might be induced in the ionosphere and the magnetic field of these currents could be more distinct in the structure of the solar wind-Mars interaction region, changing the dipole field pattern near Mars. This was apparently the case during the Mars-5 pass on 20.2.74 when the B_X-component changed sign in region 2-3. In fact, the solar wind dynamic pressure was maximum that day in comparison to other satellite passes (Dolginov *et al.*, 1976).

Thus, if as mentioned above, the obstacle's upper boundary in the Martian subsolar region (as indicated by the Mars-2 Data, Breus and Verigin, 1976) has an al-

titude of $\sim$ 1000 Km, the size of such an obstacle exceeds three times that of Venus. The Martian obstacle reaches, in fact, an altitude of $\sim$ 2000 Km near the terminator (Vaisberg et al., 1976b, 1977; Dolginov et al., 1977; Gringauz et al., 1977) as compared with $\sim$ 1000 Km at Venus (Verigin et al., 1978).

III The position of the bow shock at Mars and Venus

As it is known, *the Martian bow shock is farther away from the planet than that at Venus. This also reflects an essential difference between the Martian and the Venusian solar wind-planet interaction region.* Russell (1978b, c) and Vaisberg and co-workers (1976a, 1977) believe that the average position of the Martian bow shock is closer to the planet than that predicted from the intrinsic magnetospheric model.

The average bow shock position does not characterize the obstacle's nature since the obstacle must be consistent with all bow shock positions observed (including those located far away from the planet). The fact that Vaisberg et al. (1976a, 1977) and Russell (1978b, c) used the average bow shock position to analyze the obstacle's nature was repeatedly criticized by Gringauz (1976), Gringauz et al. (1977), Dolginov (1978), and Breus (1979). However, even a comparison of the average position of the bow shocks of both planets, as reported by these latter authors, shows that the bow shock at Venus is much nearer to the planet than that at Mars, and even closer than those indicated by the Pioneer-Venus measurements for which the shock front distance from Venus increased by 35%. Fig. 7 shows the average position of the shock front near Mars obtained by Vaisberg and co-workers (1976a). This shock front is closer to the planet than that reported by Gringauz and co-workers and also closer than the shock front position at Venus (this latter one was obtained from the data of 32 bow shock crossings by Venera-9 and Venera-10 as reported by Verigin et al., 1978). The fact that the bow shock near Venus is closer to the planet than the Martian bow shock is consistent with the above mentioned lower size of the obstacle near Venus. The following additional considerations can be made regarding the implications of the different position of the bow shocks of both planets:

a) In studies of the nature of the ionospheric obstacle of both Venus and Mars, Rassbach and co-workers (1974), and later Russell (1977) assumed that due to the higher conductivity of the Martian ionosphere the obstacle may have larger size than that at Venus. Comparison between the atmospheric and ionospheric properties of the two planets is not in favour of such a conclusion.

Table 1 gives the characteristics of the planetary ionospheres and neutral atmospheres, the magnetic field values according to Russell (1978c) and Dolginov et al.

(1969, 1977) as well as the Larmor frequencies ω_e and ω_i, which can be used to estimate the conductivity and collision frequencies ν_{en} and ν_{in} of electrons and ions. To calculate ν_{en} and ν_{in}, we use the most recent atmospheric models based, in part, in the Viking experimental data. According to these models the atmospheres of both planets, in the region of the main ionization maximum, completely consist of CO_2, and the ionospheres of O_2^+ (Chen et $al.$, 1978; Cravens et $al.$, 1979).

In addition to CO_2, the Venus atmosphere contains atomic oxygen. For example, at $h \approx 160$ Km n [O] ~ 50 % n $[CO_2]$ (Cravens et $al.$, 1978; Niemann et $al.$, 1979); the concentrations of O in the Venus atmosphere (not considered in the present study) can only increase the estimate of the conductivity of the Venus atmosphere.

The two last columns of Table 1 give the estimates of the Pedersen σ_1 and Hall σ_2 ionospheric conductivities in the main maximum of ionization for various estimates of planetary magnetic fields. In order to compare these estimates we will restrict ourselves to the values of the σ_1 conductivities in the maximum. This is justified by the fact that the properties of the upper atmospheres of both planets are sufficiently similar (see Figs. 4a and b).

According to the Pioneer-Venus data the magnetic field within the Venus ionosphere must be lower than $B_0 = 10\gamma$ (as measured by Venera-4 at a height of ~ 200 Km, Dolginov et $al.$,1969). Using lower B_0 values as well as taking into account other atmospheric components (in addition to CO_2) will increase the estimated conductivities of the Venus ionosphere.

Table 1 shows that according to the magnetic field values for both planets (as observed by Dolginov and co-workers) the conductivity of the Venus ionosphere exceeds by an order of magnitude that of Mars. For $B_0 = 5\gamma$ near Mars (Russell, 1978c) the conductivities are about the same. It should be also mentioned that the solar wind electric field $\bar{E} = -\frac{1}{c}[\bar{V}_{sw} \times \bar{B}_{sw}]$ which induces $\bar{J} = \sigma \bar{E}$ electric currents in the Venus ionosphere, exceeds that present in the Mars ionosphere because $\bar{B}_{sw}$ decreases by about a factor of 2 to 3 with the increase of the heliocentric distance from Venus to Mars.

Thus, the idea that the more intense induced magnetic field near Mars (due to a higher conductivity of the Martian upper ionosphere) increases the size of the obstacle more than 3 times that of Venus is unconvincing.

The considerations given above on the bow shock position and the obstacle-sizes near Venus and Mars confirm the point of view regarding the "intrinsic" magnetosphere of Mars.

Table 1

*Planet	h_{max} km	h_{iono-} *pause km	N_e max cm^{-3}	*Te °K	$n[CO_2]$ cm^{-3}	Tn, °K	B_0, γ	ω_i sec^{-1}	ω_e sec^{-1}	ν_{en} sec^{-1}	ν_{in} sec^{-1}	σ_1 Mo/m	σ_2 Mo/m
Mars	135 (Vasiliev et al., 1975)		$1.7.10^5$ (Vasiliev et al., 1975)	300°	8.10^9 (Chen et al., 1978)	180° (McElroy et al., 1976)	a)60 (Dolginov et al., 1969)	0.15	$8.8.10^3$	23	4.6	0.02	0.55
							b) 5 (Pussell, 1978a)	0.015	$8.8.10^2$	23	4.6	0.02	5.5
Venus	140 (Ivanov-Kholodny) et al., 1978)	300-500	5.10^5	400°	4.10^{10} (Cravens et al., 1978)	285° ±10° (Von Zahn et al., 1979)	10 (Dolginov et al., 1977)	0.03	$1.76.10^3$	132	23	0.6	8

b. Different variations in the position of the Mars and Venus bow shock are essential for finding out the nature of their corresponding obstacles (Gringauz, 1976). Fig. 7 distinctly shows a more stable position of the bow shock at Venus and very large amplitude variations of the bow shock position near Mars. According to the data of Vaisberg and Bogdanov (1975) the change in the position of the subsolar point of the bow shock near Mars was up to one planetary radius.

Large amplitude variations in the position of the bow shock (up to magneto-spheric sizes) are known to be observed in planets with intrinsic magnetic fields, such as the Earth and Jupiter. Vaisberg *et al.* (1977) and Smirnov and co-workers (1978) assumed that the amplitude of such variations could be related to a change of orientation of a greatly inclined Martian magnetic dipole as the planet rotates. However, they could not reveal this fact.

According to the $N_e(h)$ profile observations from the Soviet Mars satellites and the Mariner Mars vehicles, considerable variations of the Martian ionospheric extension and of its upper boundary height were not detected. Along with this, the Venus ionopause altitude varied from 280 - 300 Km to more than 1000 Km with a relatively stable bow shock position (Pioneer-Venus data). Thus, the remote cross-ings of the Mars bow shock and the large amplitude of its variations cannot be ex-plained in the framework of the concept of a purely Martian ionospheric obstacle.

c. Russell (1978c) has also mentioned that on the dayside of Mars, the maximum field value measured on Feb.21.72 by the Mars 3 spacecraft was located at a posi-tion which did not correspond to the minimum distance from the satellite to the planet, i.e., it did not coincide with the orbit pericenter. In his opinion, this could not have occurred in the dipole field of an "intrinsic" Martian magnetosphere and, in fact, opposes the "intrinsic" magnetosphere model. It should be emphasized, however, that in the presence of a dipole magnetic field, the resulting magneto-spheric shape should have dayside cusps whose position and size depend on the di-pole inclination and the distance from the magnetopause to the planet. It is pos-sible that the orbit pericenter occurred in the dayside cusp region (magnetic field depression zone) and hence did not coincide with the maximum in the magnetic field.

The pericenter of the Mars-3 orbit during that particular pass occurred at the aerographic latitude 40° on the planet dayside (Dolginov, 1978). The effect noted by Russell could be associated with a Martian magnetospheric dayside cusp.

d. Finally, Russell has also used Vaisberg *et al.*'s communications (1978b, 1978c) regarding the detection of heavy ion fluxes at the obstacle's boundary layer and in

the transition region behind the bow shock front as element of support of the non-magnetospheric nature of the Martian obstacle. Additional analysis of the experimental data of Vaisberg *et al.* made by Bezrukikh *et al.* (1978) showed that the pecularities of such data can be explained without requiring of the presence of heavy ions in the plasma measurements.

It should be mentioned however that there could still be a real possibility of effective charge-exchange processes between the solar wind flow and the upper atmosphere of both planets. Because of the direct contact of the solar wind ions with the planetary atmospheres and ionospheres in the dayside cusp regions, heavy ions in the solar wind/planet interaction region probably do exist irrespective of the character of the obstacle. This effect is obviously also present in the cusp regions of the Earth's magnetosphere.

CONCLUSION

It has been mentioned that in addition to considerable similarities, there are essential differences between the regions of solar wind/planet interaction near Venus and Mars. Among them are, in particular, smaller size of the Venus obstacle compared with that at Mars; a closer bow shock location at Venus, different dependences of the properties of the dayside ionosphere on the solar zenith angle, and differences in the magnetic field behaviour in the wakes of both planets.
due to the solar wind intensity and the interplanetary magnetic field.

Analysis of all of the experimental data makes it possible to conclude that the Venus ionosphere and induced magnetic field (the draped solar wind magnetic field) are decisive for the formation of the bow shock and for the behaviour of the solar wind as it streams around the planet. In Mars, on the other hand, it is the intrinsic field of this planet what dominates and determines the formation of the obstacle deflecting the solar wind.
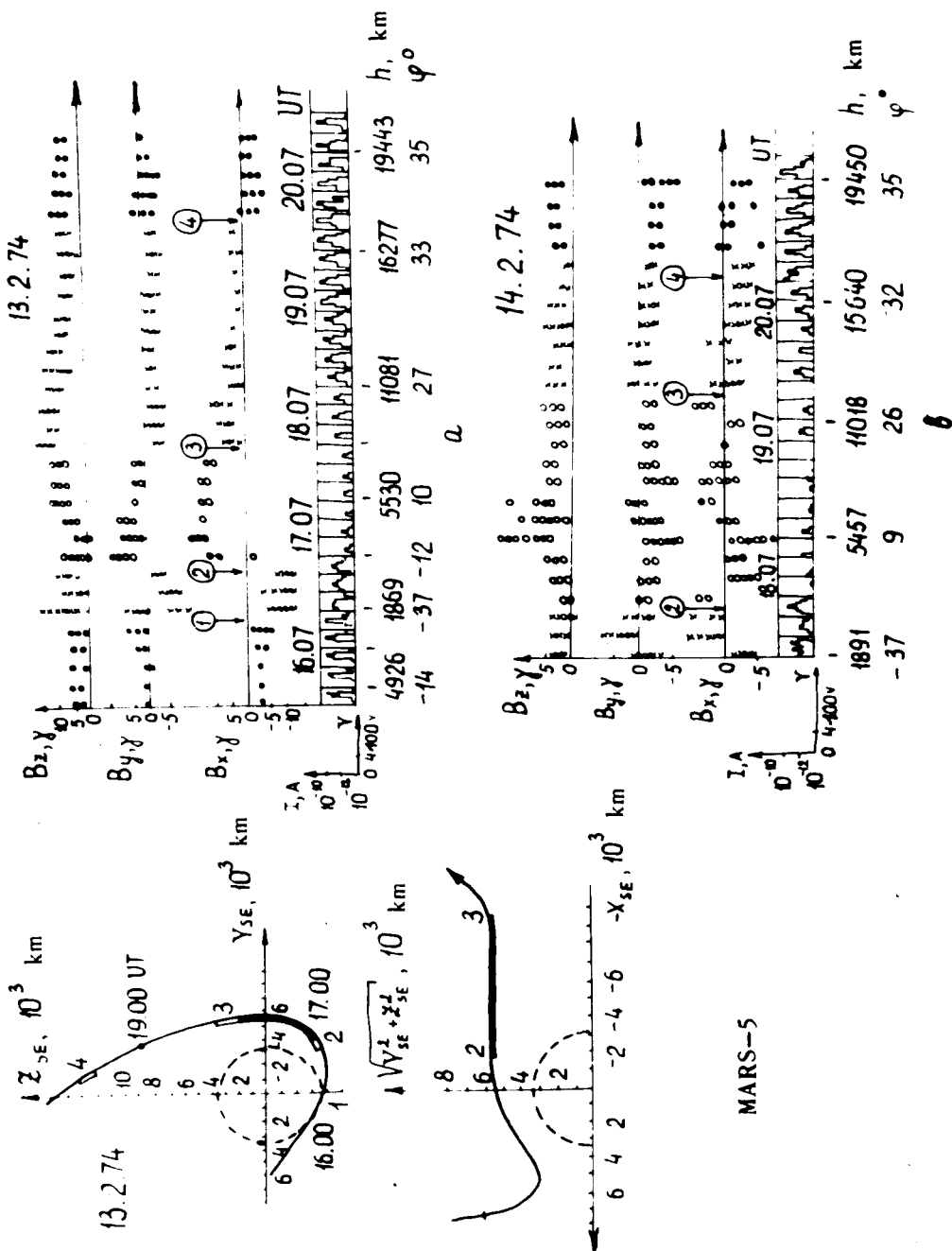
ACKNOWLEDGEMENTS

Fig. 1   The data of the magnetograms (B_x, B_y, B_z) and ion spectra in the energy range of
0 - 4.1 kev obtained on Mars-5 on 13.2.74 and 14.2.74. On the left, the vehicle orbit
in the system of coordinates X_{SE}, $\sqrt{Y_{SE} + Z_{SE}}$ is shown. On the magnetograms
various marks show the data referring to the satellite location in the solar wind (sec-
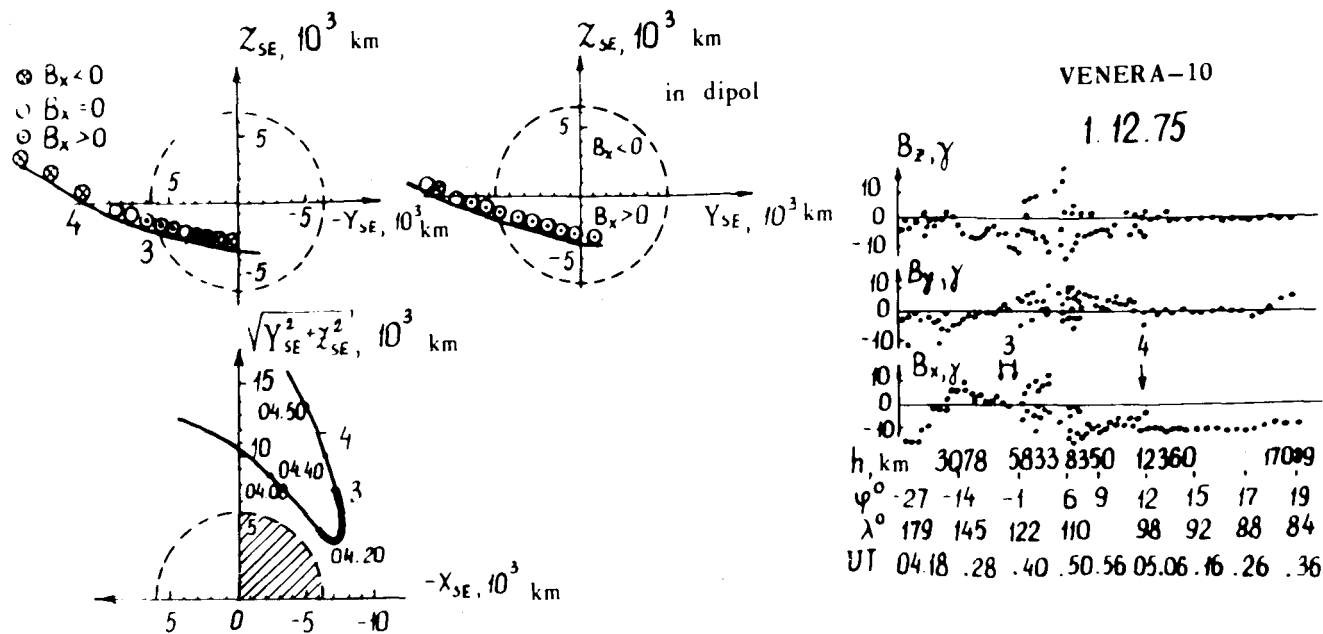tions prior to 1 and after 4) in the transition layer (1 - 2 and 3 - 4) and in the Martian

Fig. 2   Magnetograms obtained by Venera-10 on 1.12.75.
On the left the vehicle orbit is shown. Various marks ('to the Sun' $\circ B_x > 0$, $\oplus$ - 'from the Sun' $B_x < 0$ and $\circ B_x = 0$) correspond to various directions of the magnetic field B_x component. On the magnetograms the arrows with numbers show the same regions as in Fig. 1.
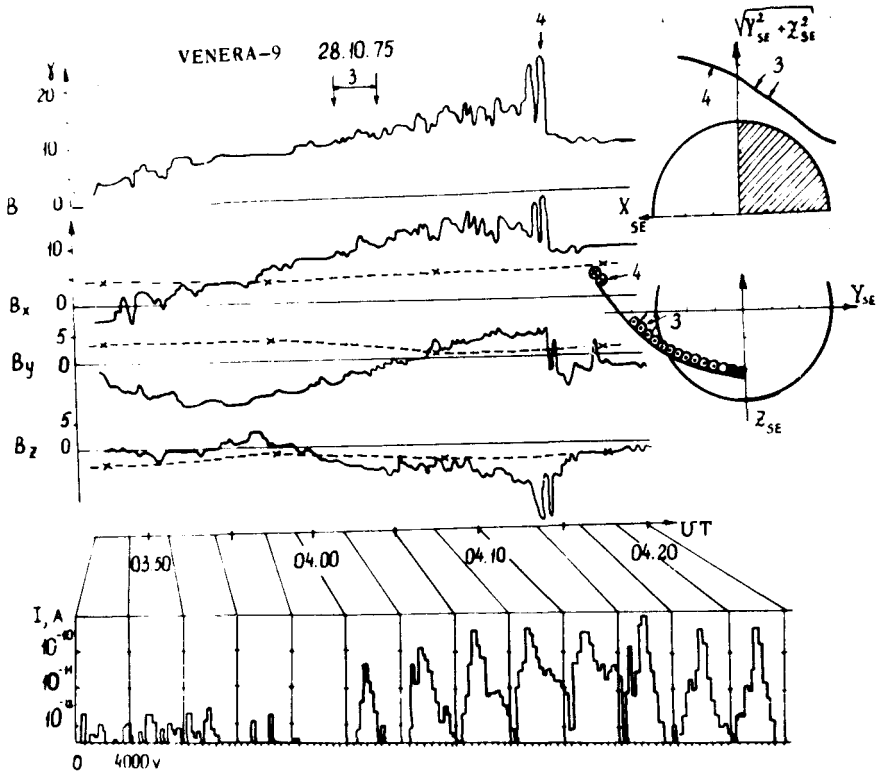
Fig. 3   Magnetogram ($|B|$, B_x, B_y, B_z) and ion spectra obtained by Venera-9 on October 28, 1975. The orbit in the coordinates X_{SE}, $\sqrt{Y_{SE} + Z_{SE}}$ is shown in the right. The arrows and figures show the same regions that in Figs. 1, 2.
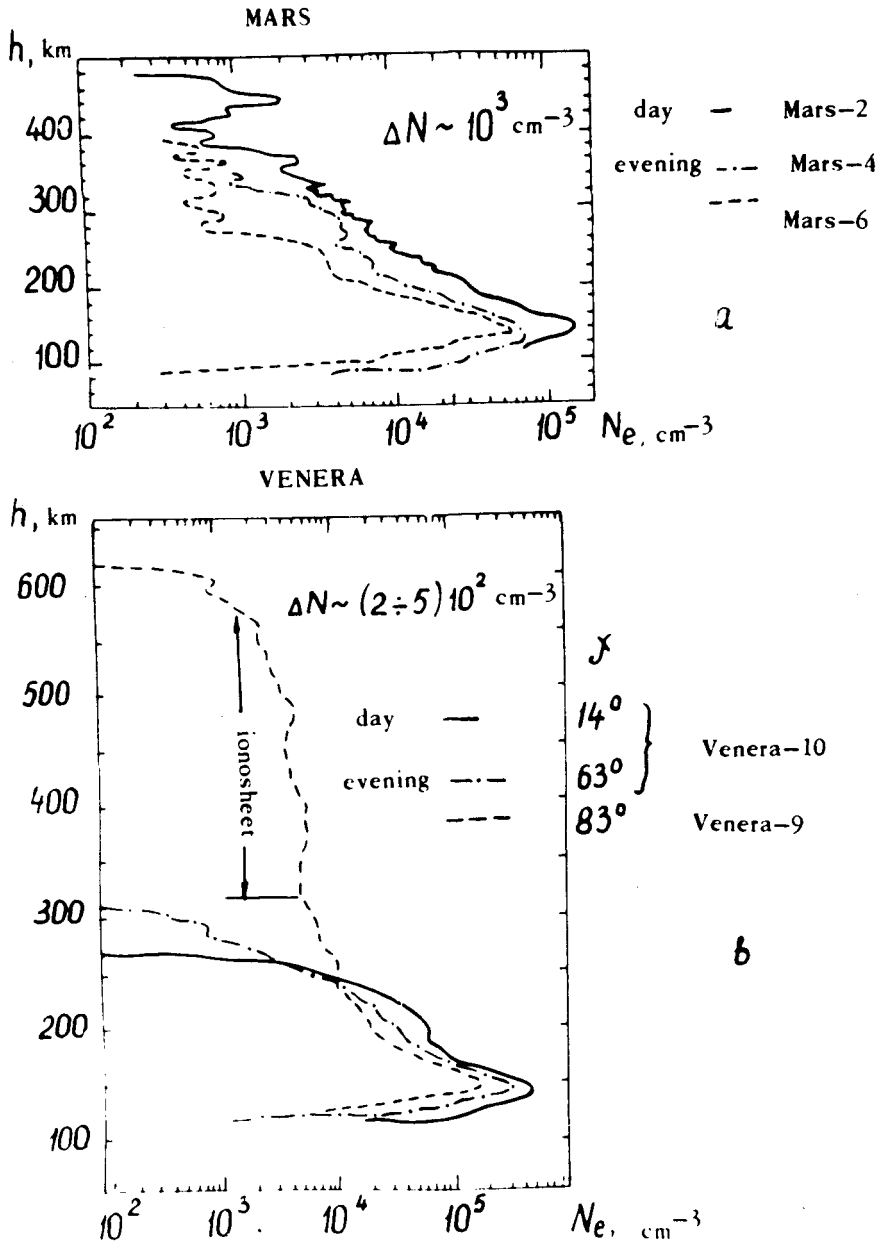
MARS

h, km

400

300

200

100

$\Delta N \sim 10^3$ cm^{-3}

day —   Mars–2

evening —·— Mars–4

- - -   Mars–6

a

10^2 10^3 10^4 10^5 N_e, cm^{-3}

VENERA

h, km

600

500

400

300

200

100

$\Delta N \sim (2 \div 5) 10^2$ cm^{-3}

ionosheet

χ

day   — 14^0 } Venera–10

evening —·— 63^0 }

- - - 83^0 Venera–9

b

10^2 10^3 10^4 10^5 N_e, cm^{-3}

Fig. 4   Electron density distributions in the Mars (a) and Venus (b) ionospheres obtained by the Soviet artificial satellites at various times of the day by the radio-occultation method
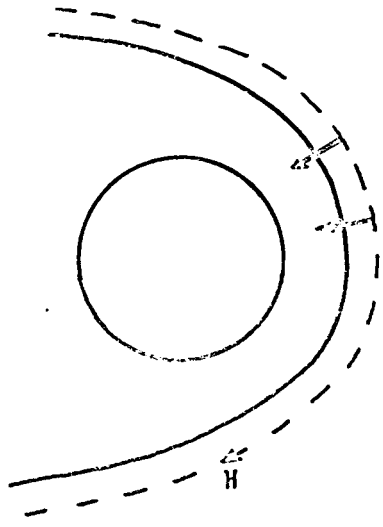
Mars: 1 - day side (Mars-2), 2 - night side (Mars-4 and Mars-6).

$\Delta N_e \sim 10^3$ is the uncertainty in the values of electron density.

Venus: 1 - day side, $\chi = 14^0$; 2 - night side, $\chi = 63^0$ (Venera-10); $\chi = 83^0$ (Venera-9).

Ionopause
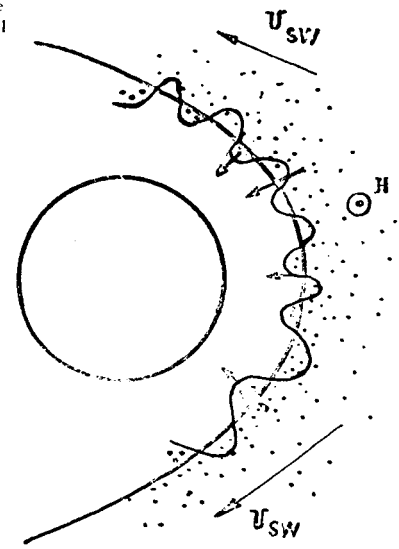
View from above
in the equatorial
cross-section

U_{SW}

Direction of convection
of tubes with the mag-
netic field in case of
'Flute instability'

U_{SW}

H

H

U_{SW}

Formation of the Flute instability

T. K. Breus

Fig. 5 ˙ Schematic representation of the motion of magnetic tubes of force on the development
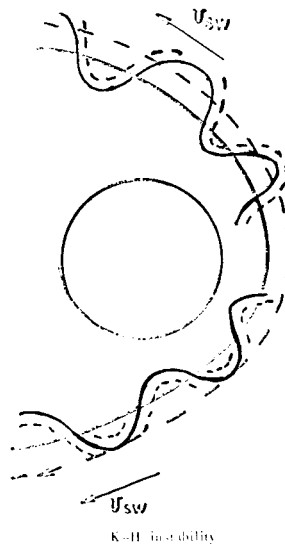of the Flute instability.

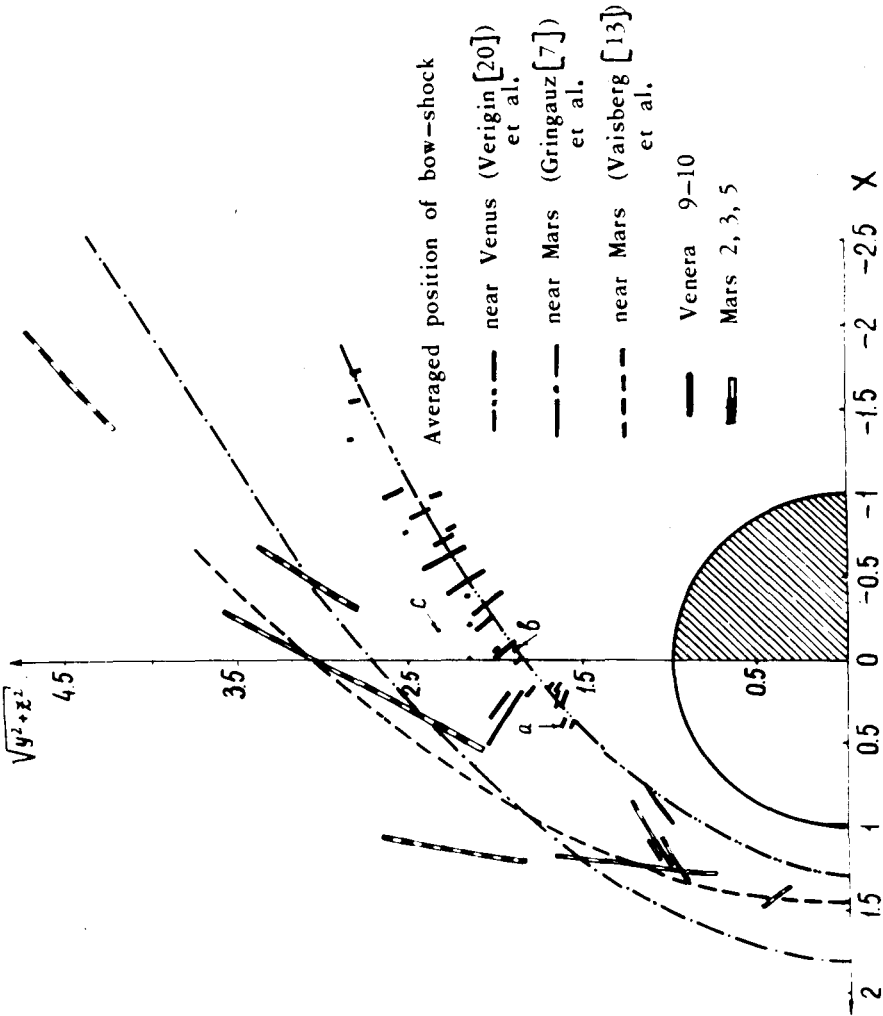Fig. 6   Schematic representation of Kelvin-Helmholtz instability.

Fig. 7   Mean position of the shock wave near Venus and Mars. Shock wave front crossings obtained during the experiment with wide-angular detectors by Venera-9, 10 near Venus and by Mars-2, 3, 5; a - Venus (Verigin *et al.*), b - Mars (Gringauz), c - Mars (Vaisberg *et al.*).

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