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THE DEPENDENCE OF THE MARTIAN MAGNETOPAUSE AND BOW SHOCK ON SOLAR WIND RAM PRESSURE ACCORDING TO PHOBOS 2/TAUS ION SPECTROMETER MEASUREMENTS

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ABSTRACT

The location of the Martian magnetopause and the bow shock is studied based on 3D solar wind proton spectra measured by the TAUS spectrometer on board Phobos 2 in its 56 circular orbits. The clear and strong dependence of the areomagnetopause position on solar wind ram pressure was revealed, while the position of the bow shock was practically independent of this parameter. In the power law expression telling the dependence of the Martian magnetotail thickness the power index turned to be $k \sim 5.9 \pm 0.5$. The close coincidence of this index with $k = 6$ for a dipole geomagnetic field, as well as the large areomagnetotail thickness compared with the planetary diameter, suggests that an intrinsic dipole magnetic field can be an important factor in the solar wind interaction with Mars. On the other hand, the relatively stable position of the subsolar point of the Martian magnetopause and unambiguous induction effects observed by the Phobos 2/MAGMA magnetic experiment in the areomagnetotail indicate the essential role of an induced magnetic field, too. The weak dependence of the terminator bow shock position on the solar wind ram pressure can be related to the relatively stable position of the subsolar magnetopause.

М.И. Веригин, К.И. Грингауз, Г.А. Котова, А.П. Ремизов, Н.М. Шютте, Х. Розенбауэр, С. Ливи, А. Рихтер, В. Ридлер, К. Швингеншу, К. Сегё, И. Апати, М. Татрайаи: Зависимость магнитопаузы и ударной волны Марса от давления солнечного ветра на основе измерений, проведенных спектрометром ТАУС КА "Фобос-2". KFKI-1991-22/C

АННОТАЦИЯ

Исследовалось положение магнитопаузы и ударной волны Марса на основе 3-размерных спектров солнечного ветра, полученных спектрометром ТАУС на 56 круговых орбитах КА "Фобос-2". Установлено, что положение магнитопаузы Марса сильно зависит от динамического давления солнечного ветра, однако, ударная волна сравнительно независима от этого параметра. Зависимость толщины магинтного хвоста Марса от давления солнечного ветра показывает аналогию со случаем Земли, имеющей дипольное магнитное поле, поэтому предполагается, что в взаимодействии солнечного ветра с Марсом большую роль играет внутреннее магнитное поле этой планеты. Однако, слабая зависимость пространственного расположения терминатора ударной волны от солнечного ветра может быть связана со сравнительной стабильностью дневной магнитопаузы, и это означает, что индуцированное магнитное поле тоже является значительным фактором в этом взаимодействии.

Verigin M.I., Gringauz K.I., Kotova G.A., Remizov A.P., Shutte N.M., Rosenbauer H., Livi S., Richter A., Riedler W., Schwingenschuh K., Szegő K., Apáthy I., Tátrallyay M.: A Mars magnetopauzájának és fejhullámának függése a napszél nyomásától a Phobos 2 TAUS spektrométerének mérései alapján. KFKI-1991-22/C

KIVONAT

A Mars magnetopauzájának és fejhullámának helyzetét vizsgáltuk a Phobos 2 szonda 56 körpályáján a TAUS spektrométer által mért 3 dimenziós napszél proton spektrumok alapján. Megállapítottuk, hogy míg a Mars magnetopauzájának helyzete erősen függ a napszél dinamikus nyomásától, a fejhullám viszonylag független ettől a paramétertől. A Mars mágneses csóvája vastagságának napszélnyomástól való függése nagyon hasonló a dipóltérrel rendelkező Föld esetéhez, ezért feltételezzük, hogy a napszél Marssal való kölcsönhatásában is fontos szerepet játszhat a bolygó belső tere. A fejhullám terminátor síkbeli helyzetének a napszéltől való igen gyenge függése viszont kapcsolatos lehet a nappali magnetopauza viszonylagos stabilitásával, ami azt jelenti, hogy az indukált mágneses tér is jelentős szerepet játszik a kölcsönhatásban.

INTRODUCTION

To study the variations in the position of planetary plasma boundaries – the magnetopause and the bow shock – connected with the solar wind ram pressure variations is one of the useful diagnostic tools when investigating the origin of planetary obstacles in the solar wind flow.

Theoretical and observational studies proved that the terrestrial magnetopause and the bow shock are simultaneously being compressed and expanding as influenced by the solar wind ram pressure variations and that the geocentric distance to these boudaries varies in close relation with the solar wind ram pressure ϱv^2 variations: $r \sim (\varrho v^2)^{-1/k}$ where the power index is $k = 6$ for a dipole geomagnetic field [e.g., Spreiter et al., 1966; Binsack and Vasiliunas, 1968; Bezrukikh et al., 1976; Sibeck et al., 1991, etc.].

In the case of Venus, the dependence of the bow shock position on ϱv^2 is weak [e.g. Tatrallyay et al., 1983]; the ram pressure dependence of the location of the magnetopause in the induced magnetotail has not been analyzed.

Though, the early missions of the sixties (Mariner 4) and seventies (Mars 2, 3 & 5) revealed the existence of both the bow shock and the magnetopause in the vicinity of Mars [e.g., Smith, 1969; Gringauz, 1976], no quantitative study has been performed on the dependence of their location on solar wind ram pressure. The compression of the Martian magnetosphere with the increase of ϱv^2 was demonstrated qualitatively by the Faraday cup data on board Mars 5 [Gringauz et al., 1976a,b]. The attempt by Slavin et al. [1983] to clarify the dependence of the Martian bow shock position on solar wind ram pressure cannot be considered as a quantitative study either, since it was based on a limited number of plasma data of the Mars 3 & 5 orbiters which were not cross-calibrated.

Only the Phobos 2 mission provided good statistics in order to study the variations of the location of the areomagnetopause and that of the bow shock. Recently, several authors have analyzed the dependence of the Martian bow shock terminator position on different parameters: the phase of the rotation of the planet (areographic longitude), the density of the upper planetary atmosphere (F10.7 index), the solar wind ram pressure, and the angle between the shock normal and the upstream magnetic field [Schwingenschuh et al., 1990a and b; Russell et al., 1990; Zhang et al., 1991a and b; Slavin et al., 1991]. However, the variations of the location of the areomagnetopause have not been investigated, though the motion of this boundary is more directly determined by the nature of the obstacle in the solar wind flow.

In the present brief paper, the results of the first quantitative studies of the variability of the Martian magnetopause will be presented. The location of the Martian magnetopause will be studied as a function of solar wind ram pressure and it will be compared with that of the Martian bow shock.

INSTRUMENTATION AND OBSERVATIONAL DATA

The TAUS spectrometer on board Phobos 2 was designed to measure 3D spectra of protons, 3D spectra of alphas, and 2D spectra of heavy ions separately. The instrument had a field of view of $\sim 40^\circ \times 40^\circ$ centered on the nominal aberrated solar wind direction ($\sim 5^\circ$ deviation from the solar direction in the ecliptic plane) and divided into 8×8 channels for angular resolution. Its energy per charge range of $\sim 30 - 6000V$ was subdivided into 32 channels. A more detailed description of the TAUS experiment was presented by Rosenbauer et al. [1989a].

During the active life of the Phobos 2 orbiter, data were obtained by TAUS from four elliptical orbits with low ($h \sim 850km$ above the surface) pericenter, from one elliptical orbit with high ($h \sim 6400km$) pericenter, and from 56 circular orbits quasi-synchronous with the orbit of the Phobos moon ($h \sim 6150km$). For systematic studies of the variations of the Martian plasma boundaries, it is reasonable to use the longest uniform set of TAUS data measured in the circular orbits (February 20 - March 26, 1989). In this period TAUS was operated in a low telemetry rate mode: 1D proton and heavy ion energy spectra (compressed on board from the original 3D and 2D spectra, respectively), and moments of the proton distribution function were provided once in every two minute interval. The energy per charge range was $150 - 6000V$ in these measurements.

The bow shock and magnetopause crossings (sometimes multiple ones) were determined by the specific changes of the charged particle spectra as described by Rosenbauer et al. [1989b], i.e. the Martian bow shock crossings were defined by the sudden decrease of the mean energy and by a broadening in the proton spectra, while the magnetopause separating the shocked solar wind plasma from the Martian magnetosphere was characterized according to TAUS observations by the disappearance of solar wind protons and often accompanied by the appearance of heavy planetary ions.

The solar wind instant proton densities and velocities were derived from the moments of the distribution function computed on board. In order to cross-check these parameters, the densities and velocities determined from on board moment calculations were compared with those determined from 3D raw data for the periods when raw data were also transmitted from board. A good agreement was found.

For the present study, we used proton density and velocity values of the upstream solar wind averaged over a time interval of 20 - 30 min ending/beginning ~ 30 min before/after the inbound/outbound bow shock crossing. This procedure was selected bearing in mind that (i) a few tens of minutes upstream of the Martian bow shock crossing, solar wind deceleration could be observed [Verigin et al., 1991b], (ii) the inbound/outbound magnetopause crossings in the circular orbits occurred about one hour after/before the bow shock crossing, and (iii) the spacecraft was often rotating roughly around the axis pointing towards the Sun with a period of about 10 minutes. In the latter case the instantly measured proton densities were modulated by the s/c rotation and we used only the maximum values while averaging.

Finally, the problem of inflight calibration of proton channel efficiency [Verigin et al., 1991b] is now resolved. The reason for the initial underestimation of proton densities (increasing during the flight) was that the proton exit slit was not completely opened by the piezoelectric actuator. Postcalibration of this slit was performed by using the proton ghosts in the heavy ion channel where the slit was continuously open. The recalibrated TAUS proton densities agreed well with proton number densities obtained by IMP 8 near the Earth for the period when Phobos 2, the Earth, and the Sun were nearly aligned (Sept 21 - Oct 3, 1988).

DATA ANALYSIS

Figure 1 presents the statistics of the bow shock and the magnetopause crossings (the latter is hatched) in aberrated cylindrical solar ecliptic coordinate system (*ase*) as determined from the TAUS data measured in the circular orbits of Phobos 2. Aberration angles were calculated using upstream proton velocity (see above) and the Martian orbital velocity of $24.1 km/s$. Fig. 1 shows the number of bow shock and magnetopause crossings (including multiple ones) in 5° bins of angle measured from the X_{ase} direction.

The essential feature of data presented in Fig. 1 is the significant variability in the location of the bow shock and that of the magnetopause behind the terminator. One of the obvious reasons for such a variability could be the variations in the solar wind ram pressure. Fig. 2 shows the histograms of the logarithmically averaged ram pressure (we used proton dynamic pressure as a proxy of ram pressure) for the same sets of crossings as shown in Fig. 1. It is clearly seen that the solar wind ram pressure was higher on average when the magnetopause was observed close to areomagnetotail axis (X_{ase}) than in the cases when the magnetopause was observed far from the tail axis. This is a firm observational proof for the compressibility of the Martian magnetotail depending on solar wind ram pressure variations. On the other hand, the location of the planetary bow shock seems to be practically independent of the solar wind ram pressure (Fig. 2).

In order to study the variability of the bow shock quantitatively, we used the traditional procedure of mapping the observed bow shock crossings to the terminator plane. All bow shock crossings recorded by the Phobos 2/TAUS instrument were mapped to this plane by using the hyperbolic shape of the shock surface (eccentricity was taken to be 1.02, focus was located at $X_{ase} = 0.55R_M$ [Slavin et al., 1991]). For each bow shock crossing, the parameter called semilatus rectum was chosen in a way that the surface should pass through the observed bow shock position.

Figure 3 shows the scatter plot of the bow shock terminator distances D_t determined applying the above method as a function of the proton ram pressure. According to these data, the average terminator distance to the bow shock was $2.62 R_M$ with a standard deviation of $\pm 0.39 R_M$. The dependence of the shock terminator distance on ϱv^2 is very weak if any:

$$D_t \sim 6000(\varrho v^2)^{-0.02\pm0.01}. \tag{1}$$

The dashed line in Fig. 3 corresponds to this power dependence.

The mapping approach used for the Martian bow shock crossings cannot be applied for mapping the areomagnetopause crossings because in the latter case the shape of the boundary cannot be considered as invariant since (i) in the magnetotail close to the terminator, the position of the magnetopause shows significant variations and the thickness of the tail is changing by a factor of 2-3 according to the data presented in Fig. 2 , while (ii) observational data available on the dayside magnetopause position imply that the distance to the subsolar point of this boundary r_o is relatively stable, its variations are about ±15%.

The latter peculiarity of the areomagnetopause cannot be considered established as firmly as the former one due to poor statistics of the dayside boundary crossings. Only a few dayside magnetopause crossings have been observed by the orbiters Mars 2 & 3 and Phobos 2. In the first three elliptic orbits, Phobos 2 observed the dayside magnetopause at distances of $\sim 4300 \pm 100 km$ from the center of Mars (see Fig. 5 by Verigin et al. [1991a] and Riedler et al. [1989]), while the proton ram pressure was about 3.6 times higher in the first orbit than in the third one. On January 8, 1972 Mars 2 crossed the subsolar magnetopause at $4500 - 5000 km$ from the center of the planet [Breus and Verigin, 1976] which may be considered as an upper limit of the observed r_o values. The lower limit of r_o can be obtained from theoretical considerations. If r_o were lower than $R_M + 300 km = 3700 km$, the solar wind flow would be absorbed via charge exchange (cross-section of $\sim 10^{-15} cm^2$) in the dense layers of the planetary atmosphere where cold oxygen density is $n \sim 3 \cdot 10^6 cm^{-3}$ [Stewart and Hanson, 1982], and the mean free path for charge exchange is of the order of R_M . This rapid absorption would lead to the disappearance of the detached planetary bow shock (cf. Moon). None of the missions has observed such an effect. On the basis of the above considerations, r_o was taken to be $4300 km \pm 15\%$ for the following quantitative study of the areomagnetotail variability.

We described the variable areomagnetopause shape by applying a first order differential equation with a single free parameter H/r_o [Spreiter et al., 1970]. For each magnetopause crossing we searched for a specific value of H/r_o so that an integration curve beginning at point r_o of the X_{ase} axis should pass through the observed magnetopause position. Then we continued this integration curve far downstream in order to find the asymptotic areomagnetotail diameter D.

Figure 4 presents a scatter plot of magnetotail diameters calculated using the above method as a function of solar wind proton ram pressure. The compression of the areomagnetotail with the increase of solar wind ram pressure is obvious in this figure. The best power fit for the observed dependence of D on ϱv^2 is:

$$D \sim 550(\varrho v^2)^{-1/k}, \tag{2}$$

with a power index of $k \sim 5.9 \pm 0.5$. In Fig. 4 a solid line presents this dependence.

DISCUSSION

The Phobos 2/TAUS data obviously revealed the dependence of the areomagnetopause position on solar wind ram pressure (Figs. 2 and 4). The power index for the best fit curve turned to be $k \sim 5.9$. The close coincidence of this index with $k = 6$ for a dipole geomagnetic field implies that an intrinsic dipole magnetic field can be an important factor in the interaction of Mars with the solar wind plasma which is significantly contributing to the pressure balance.

This new argument in favour of the essential contribution of an intrinsic areomagnetic field to the solar wind deflection around the planet seems to complete the earlier proposed argument by Gringauz [1981] and by Whang and Gringauz [1982] which was based on the relative thickness of the Martian magnetotail as compared to Venus. The good statistics of the areomagnetotail crossings by Phobos 2 provides a stronger observational evidence for this argument (see also Rosenbauer et al. [1989b] and Verigin et al. [1991a]).

Figure 5 presents the summary statistics of the inbound and outbound magnetopause crossings determined from TAUS data measured in the circular orbits of Phobos 2 (cf. Fig.1). This figure also shows all data available on the location of the magnetopause in the induced tail of Venus at $1 - 3$ planetary radii downstream of the terminator (from Fig. 12 by Saunders and Russell [1986], and from Fig. 7 by Luhmann et al. [1991]) scaled by the planetary radius. When comparing the two sets of data, one can conclude that (i) the diameter of the Martian magnetotail close to the terminator is 1.5 - 2 times thicker on the average than that of Venus (in planetary radius) and that (ii) the observed positions of areomagnetopause crossings are essentially more spread than the magnetopause crossings at Venus. These two observational facts can hardly be explained without the contribution of an intrinsic magnetic field which can produce a larger and softer obstacle in the solar wind flow than a purely ionospheric hard obstacle.

The power index $k = 6$ in relation (2) for the purely dipole magnetic obstacle is obtained from the theoretical consideration of the pressure balance at the magnetopause: $\varrho v^2 \sim B^2/8 \sim (M/r^3)^2$, where M is the dipole moment and r is the magnetopause dimension. In this case the variations in the solar wind ram pressure control the location of the magnetopause and that of the bow shock through the same power law and the shape of both discontinuities remains invariant. Several observational studies on the motion and the shape of the terrestrial magnetopause and bow shock [e.g., Spreiter et al., 1966; Binsack and Vasiliunas, 1968; Bezrukikh et al., 1976; Sibeck et al., 1991, etc.] confirmed these theoretical expectations at least for solar zenith angles less than $\sim 120°$.

The relative motion of plasma boundaries seems to be completely different at Mars where observations revealed a significant magnetotail compressibility with $1/k = 0.170 \pm 0.015$ in expression (2), while the bow shock position was practically independent of ϱv^2 (see relation (1) and Figs. 2 and 3). This latter observation was earlier reported by Schwingenschuh et al. [1990b] analyzing bow shock crossings obtained by the magnetic experiment MAGMA and preliminary uncalibrated ϱv^2 data of TAUS. The very weak dependence of the Martian bow shock terminator position on the solar wind ram pressure is similar to the case of Venus [Tatrallyay et al., 1983].

How is it possible to explain the simultaneously observed high compressibility of the areomagnetotail and the weak dependence of the bow shock terminator position on solar wind ram pressure? It can occur if the variations of the subsolar point are very limited (see the previous section). On the basis of Fig. 4 by Spreiter et al. [1970] (Mach number was 8 and specific heat ratio was 5/3 in their hydrodynamic model) the bow shock terminator position D_t can be approximated by the following empiric relation:

$$\frac{D_t}{r_o} \sim \frac{7}{4} + \frac{4}{15}(\frac{D}{r_o} - 2). \tag{3}$$

This expression can be used to determine the expected dependence of D_t on ϱv^2 when this shock was formed upstream of an obstacle with a fixed nose position r_o and with a magnetotail thickness of D determined by expression (2). In Fig. 3 a solid line shows this calculated dependence.

Expected and observed bow shock positions are in good agreement within the large range of bow shock variations (Fig. 3). This agreement provides an indirect observational evidence for our assumption discussed above that the position of the subsolar magnetopause is relatively stable.

The quite stable position of the subsolar point of the Martian magnetopause and unambiguous induction effects observed by the Phobos 2/MAGMA magnetic experiment in the areomagnetotail [Yeroshenko et al. 1990; Schwingenschuh et al., 1990b] indicate that the planetary atmosphere/ionosphere is also playing an essential role in the interaction of the solar wind with Mars.

Another consequence of the stable subsolar areomagnetopause position can be the dependence of the bow shock terminator position on the angle between the shock normal and the upstream interplanetary magnetic field discussed by Zhang et al. [1991a]. This effect was earlier observed at Venus (Tatrallyay et al. [1983]) where there is a rigid ionospheric obstacle, but it completely disappears in the large amplitude motions of the terrestrial bow shock where there is a compressible magnetosphere. From the statistics of the Martian bow shock crossings presented in Fig. 1, it appears that in the inbound leg of the circular orbits, the bow shock was most frequently observed at 5°-10° lower solar zenith angles than in the outbound leg. This angular difference corresponds to a difference of $800 - 1600 km$ in the mean terminator position of the bow shock between the dusk and dawn side of the planet.

The spiral interplanetary magnetic field geometry suggests that Phobos 2 could observe quasiperpendicular shocks more often in the inbound leg, while quasiparallel shocks were more frequent in the outbound leg as it was also discussed by Zhang et al. [1991b]. Thus, the observed asymmetry in the shock terminator positions can be related to the different speed of magnetosonic and Alfven disturbances propagating perpendicular and parallel to the interplanetary magnetic field, respectively. This asymmetry between the inbound and outbound shock positions quantitavely corresponds to the difference of $1000 - 2000 km$ in the terminator position of quasiparallel and quasiperpendicular bow shocks as determined by Zhang et al. [1991a] and it can be considered as an indirect support of their observations.

CONCLUSIONS

The first quantitative study of the Martian magnetopause variability based on 3D solar wind proton spectra measured by the TAUS spectrometer on board Phobos 2 in its 56 circular orbits revealed the clear and strong dependence of the location of the areomagnetopause on solar wind ram pressure.

The power index k in the expression $D \sim (\varrho v^2)^{-1/k}$ describing the dependence of the Martian magnetotail thickness D on solar wind ram pressure turned to be $k \sim 5.9 \pm 0.5$. The close coincidence of this index with $k = 6$ for the dipole geomagnetic field and the large areomagnetotail thickness compared to the planetary diameter suggests that an intrinsic dipole magnetic field can be an important factor in the solar wind plasma interaction with Mars.

On the other hand, the terminator position of the bow shock turned to be practically independent of solar wind ram pressure. This observation can be explained by the stable position of the nose point of the magnetopause. This incompressibility of the subsolar Martian magnetopause and unambiguous induction effects observed by the Phobos 2/MAGMA magnetic experiment in the areomagnetotail indicate that the induced magnetic field also plays an essential role in the solar wind interaction with Mars.

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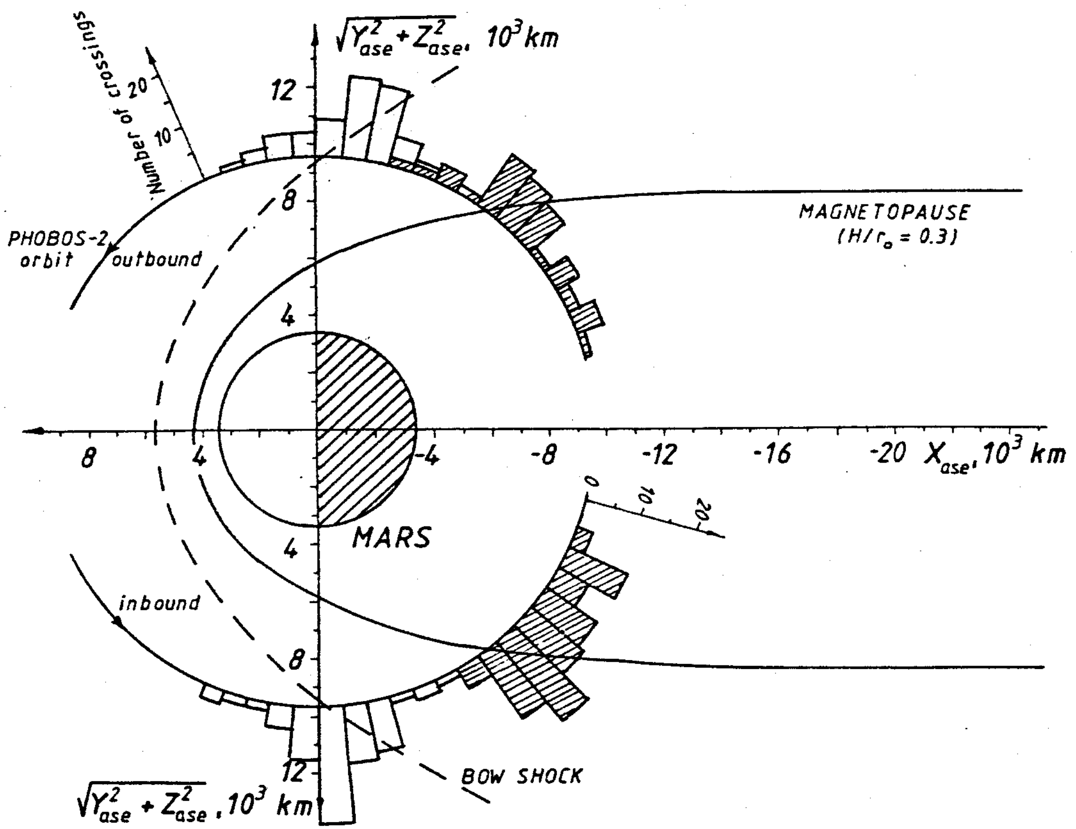

Fig. 1. Statistics of inbound (bottom) and outbound (top) crossings of the Martian bow shock and magnetopause (the latter is hatched) as determined by TAUS data measured in the circular orbits of Phobos 2 in aberrated cylindrical solar ecliptic coordinate system (*ase*). The number of the bow shock and the magnetopause crossings (including multiple ones) is shown in 5 deg bins measured from the X_{ase} direction. The dashed and solid line corresponds to the bow shock and the magnetopause, respectively according to Spreiter et al. [1970] with $r_o = 4300 km$ and $H/r_o = 0.3$.

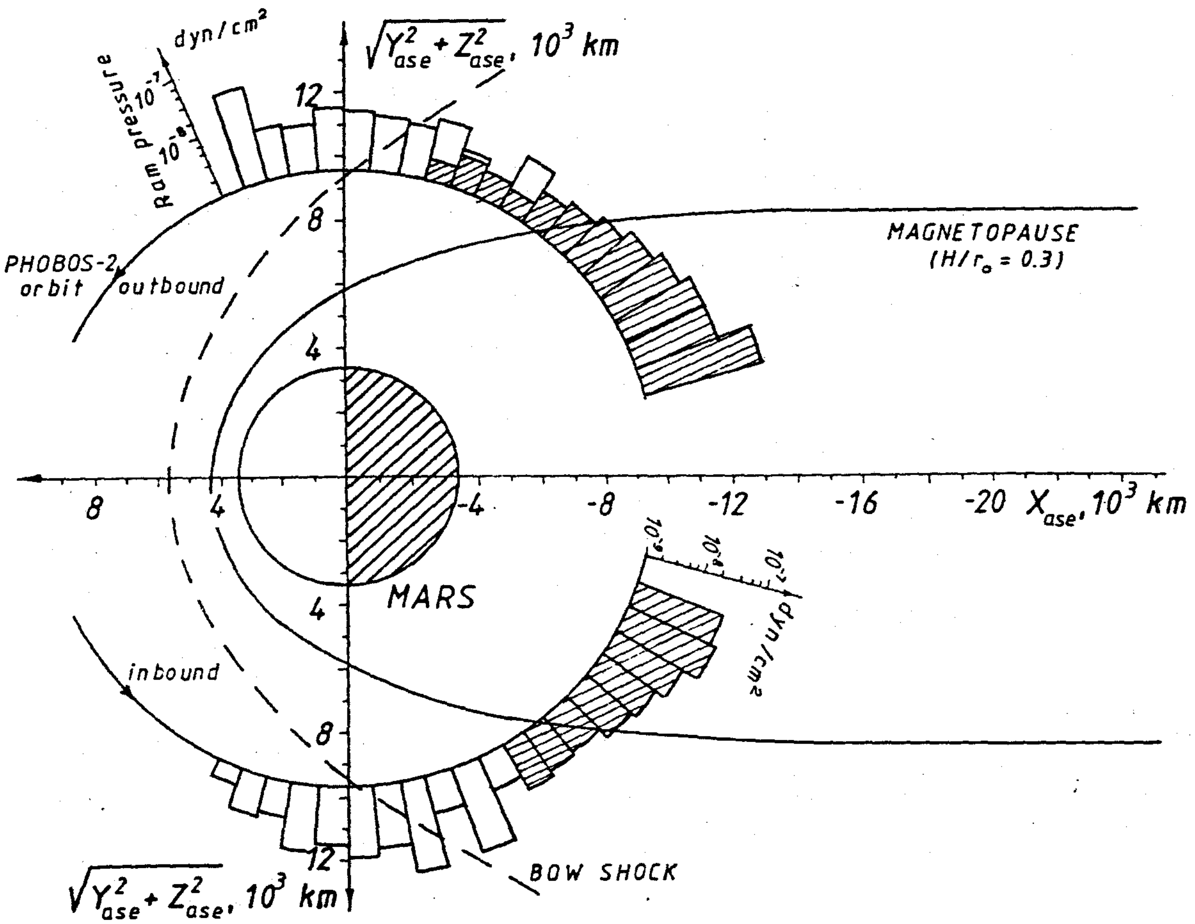

Fig. 2. Histograms of the logarithmically averaged solar wind ram pressure for the same bins as in Fig. 1.

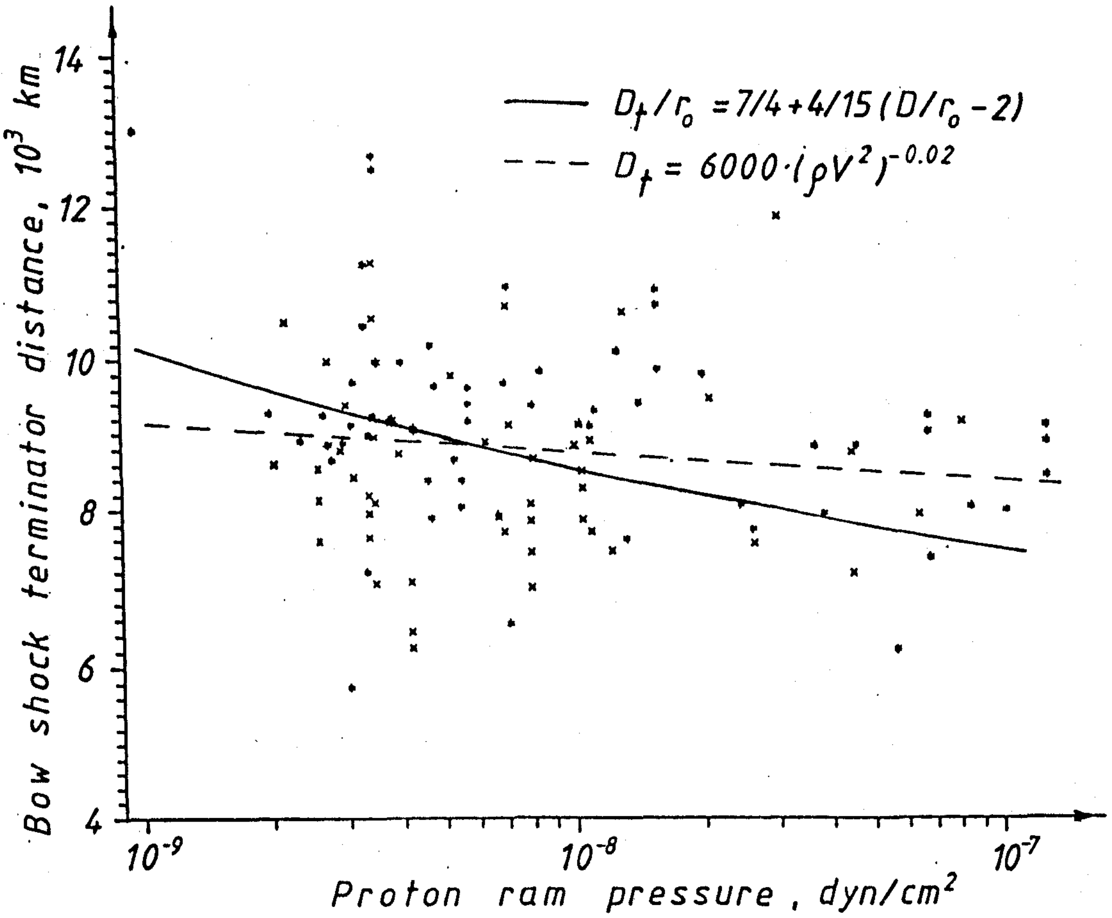

Fig. 3. Terminator positions of the bow shock in the inbound (*) and in the outbound (x) leg of the Phobos 2 circular orbits as a function of the upstream solar wind ram pressure. The power law fit given by relation (1) is presented by the dashed line. The expected dependence of the terminator position of the bow shock on ϱv^2 according to expressions (2 and 3) is shown by the solid line.

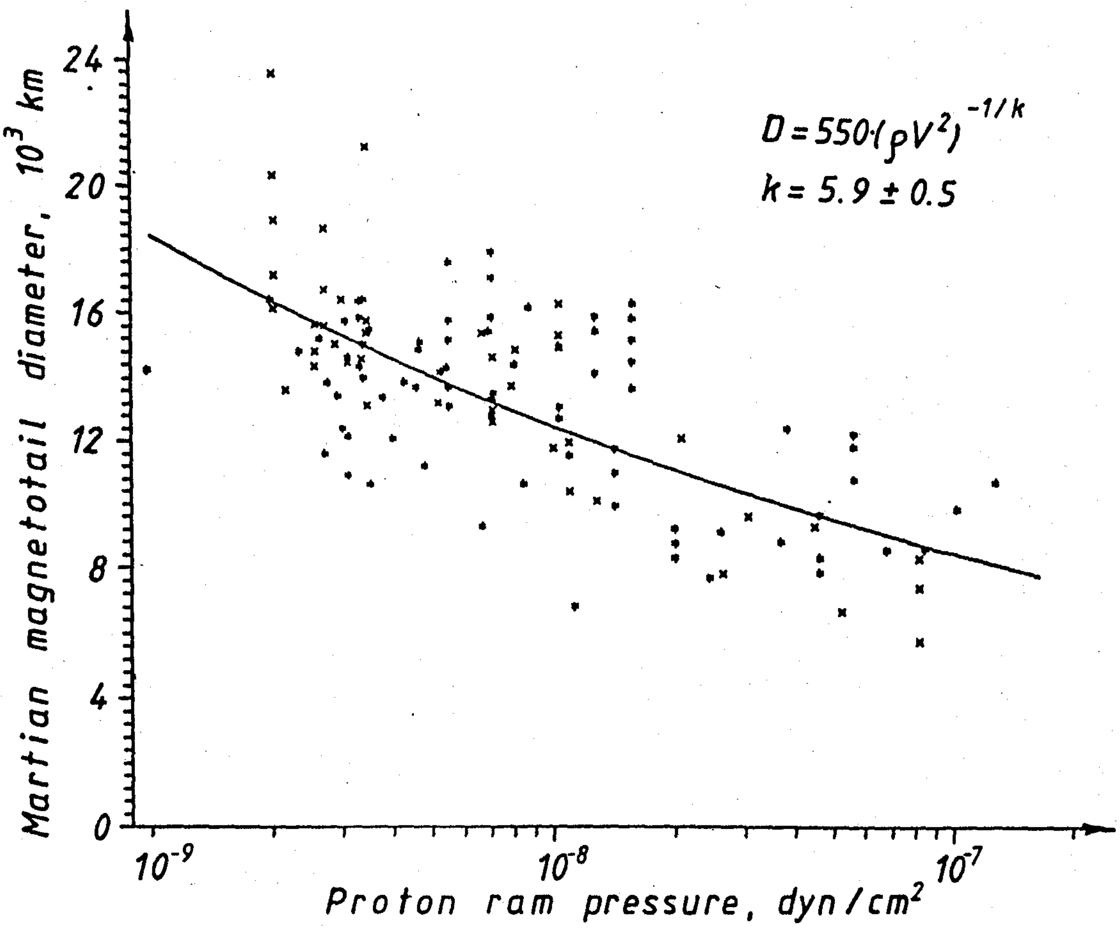

Fig. 4. Scatter plot of the magnetotail diameter extrapolated from the inbound (*) and outbound (x) magnetopause crossings of Phobos 2 as a function of the upstream solar wind ram pressure. Power law fit is shown by the solid line.

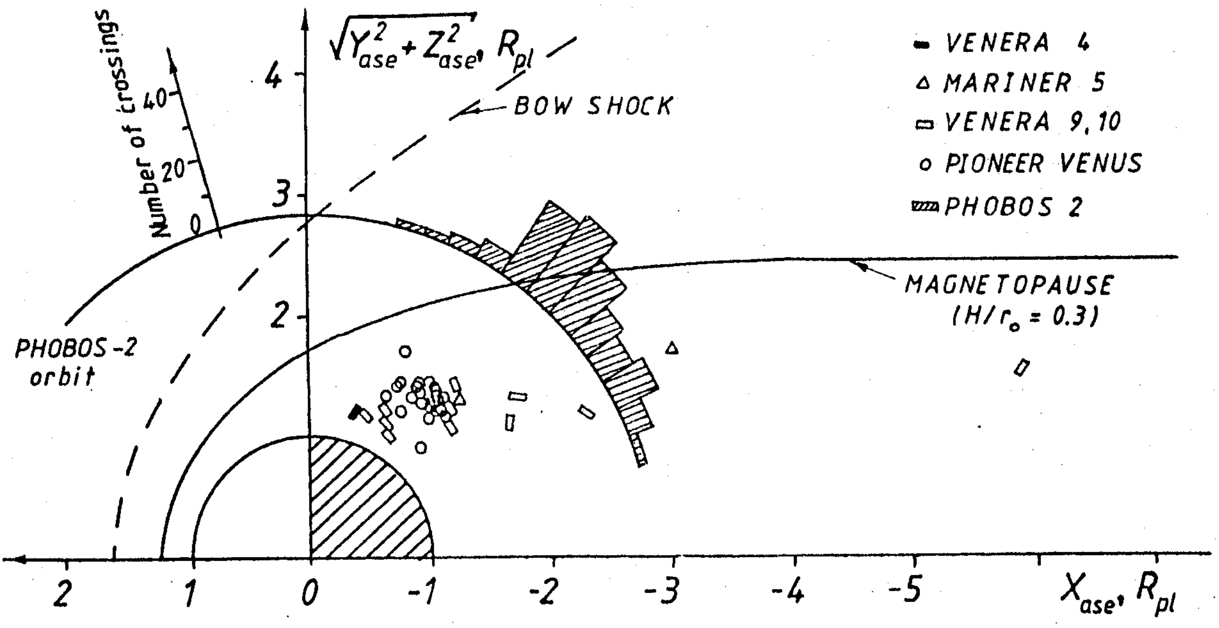

Fig. 5. Summary statistics of the inbound and outbound magnetopause crossings as determined by TAUS data in the circular orbits of Phobos 2. All available data on the location of the magnetopause of Venus at 1 – 3 planetary radii downstream of the terminator (from Fig. 12 by Saunders and Russell [1986] and from Fig. 7 by Luhmann et al. [1991]) are also presented scaled by the planetary radius.

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