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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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The location of the Martian magnetopause and that of the bow shock are studied on the basis of three-dimensional 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 D on the solar wind ram pressure: $D \sim (\varrho v^2)^{-1/k}$, the power index turned out to be $k \sim 5.9 \pm 0.5$. The close coincidence of this index with $k = 6$ for a dipole geomagnetic field, and the large areomagnetotail thickness compared with the planetary diameter, suggest that an intrinsic dipole magnetic field is likely to 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 magnetotail 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 may be related to the relatively stable position of the subsolar magnetopause.

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

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.

Although the early missions of the 1960s (Mariner 4) and 1970s (Mars 2, 3, and 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 of the dependence of their location on solar wind ram pressure has been performed. The compression of the Martian magnetosphere with the increase of ϱv^2 was demonstrated qualitatively by the Faraday cup data on 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 and 5 orbiters which were not cross-calibrated.

Only the Phobos 2 mission provided good statistics in order to study the variations of the magnetopause and the bow shock location. Recently, several authors have analyzed the dependence of the Martian bow shock terminator position on different parameters [e.g., *Schwingenschuh et al.*, 1990, 1992; *Zhang et al.*, 1991a,*b*]. However, the variations of the location of the areomagnetopause have not been investigated, even 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 will be compared with that of the Martian bow shock.

INSTRUMENTATION AND OBSERVATIONAL DATA

The TAUS ion spectrometer on board Phobos 2 was designed to measure three-dimensional spectra of protons and alpha particles, and two-dimensional spectra

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of heavy ions separately. The instrument had a field of view of ~40°×40° centered on the nominal aberrated solar wind direction (~5° deviation from the solar direction in the ecliptic plane) and divided into 8×8 channels for angular resolution. Its energy per charge range of ~30–6000 V 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 ($h \sim 850$ km above the surface) pericenter, from one elliptical orbit with high ($h \sim 6400$ km) pericenter, and from 56 circular orbits quasi-synchronous with the orbit of the Phobos moon ($h \sim 6150$ km). 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 to March 26, 1989). In this period, TAUS was operated in a low telemetry rate mode: one-dimensional proton and heavy ion energy spectra (compressed on board from the original three-dimensional and two-dimensional spectra, respectively), and moments of the proton distribution function were provided once in every 2-min interval. The energy per charge range was 150–6000 V 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.* [1989*b*]; 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 three-dimensional raw data for the periods when raw data were also transmitted from on 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 (1) a few tens of minutes upstream of the Martian bow shock crossing, solar wind deceleration could be observed [*Verigin et al.*, 1991*b*], (2) the inbound (outbound) magnetopause crossings in the circular orbits occurred about 1 hour after (before) the bow shock crossing, and (3) the spacecraft was often rotating roughly around the axis pointing toward the Sun with a period of about 10 min. In the latter case the instantly measured proton densities were modulated by the spacecraft rotation, and we used only the maximum values while averaging.

Finally, the problem of in-flight calibration of proton channel efficiency [*Verigin et al.*, 1991*b*] 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

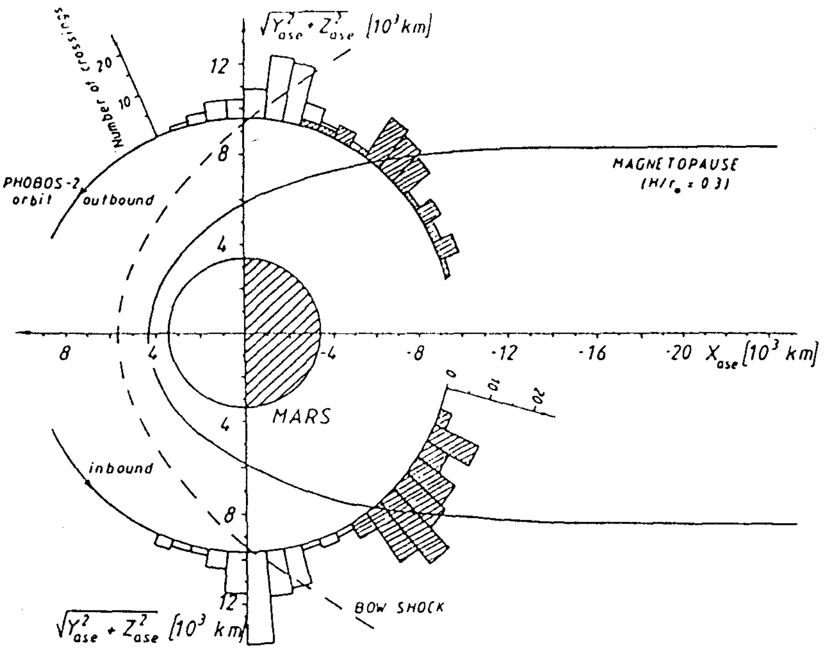

Fig. 1. Statistics of inbound (bottom) and outbound (top) crossings of the Martian bow shock and magnetopause (the latter are hatched) as determined by TAUS data in the circular orbits of Phobos 2 in aberrated cylindrical solar ecliptic coordinate system (ase). The number of the bow shock and the magnetopause crossings (including multiple ones) is shown in 5° bins measured from the X_{ase} direction. The dashed and the solid line correspond 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.

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 (September 21 to October 3, 1988).

DATA ANALYSIS

Figure 1 presents the statistics of the bow shock and the magnetopause crossings (the latter are 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. Figure 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 Figure 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. Figure 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 Figure 1. It is clearly seen that the solar wind ram pressure was higher on average when the magnetopause was observed close to magnetotail axis (X_{ase}) than in the cases when the magnetopause was observed far from the tail axis. This is firm observational proof for the dependence of the compressibility of the Martian magnetotail on solar wind ram pressure variations. On the other hand, the location of the bow shock does not appear to vary significantly with the solar wind ram pressure, as shown in Figure 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, and focus was located at $X_{ase} = 0.55\ R_M$ [*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 by applying the above method as a function of the solar wind 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, if any, is very weak:

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

The dashed line in Figure 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. Indeed, 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 Figure 2, while observational data available on the dayside magnetopause position imply that the distance to the subsolar point of this boundary r_o is relatively stable, and its variations are about ±15%.

The latter peculiarity of the areomagnetopause cannot be considered to be as firmly established as the former one owing to poor statistics of the dayside boundary crossings. Only a few dayside magnetopause crossings have been observed by the orbiters Mars 2 and 3

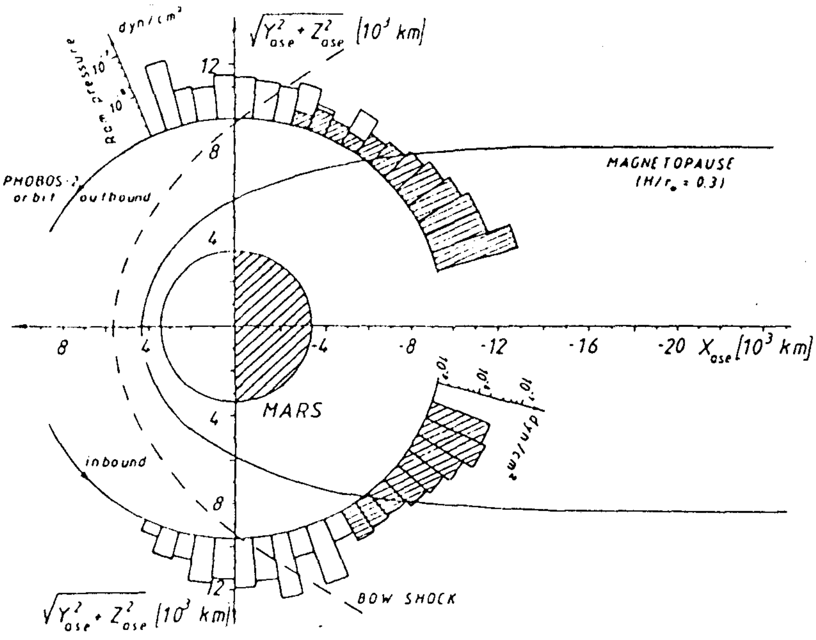

Fig. 2. Histograms of the logarithmically averaged solar wind ram pressure for the same bins as in Fig. 1.

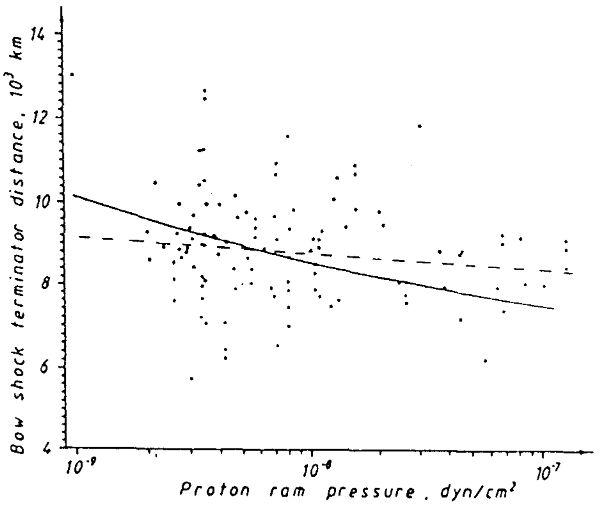

Fig. 3. Terminator positions of the bow shock in the inbound and outbound leg of the Phobos 2 circular orbits as a function of the upstream solar wind ram pressure. The power law fit given by relation (1) is presented by the dashed line. The expected dependence of the terminator position of the bow shock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

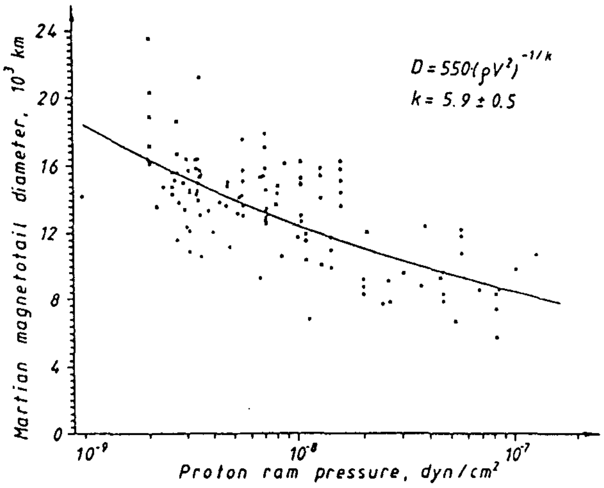

Fig. 4. Scatter plot of the magnetotail diameter extrapolated from the inbound and outbound magnetopause crossings of Phobos 2 as a function of the upstream solar wind ram pressure. The power law fit is shown by the solid line.

and Phobos 2. In the first three elliptic orbits, Phobos 2 observed the dayside magnetopause at distances of ~4300±100 km from the center of Mars at solar zenith angles between 35° and 75° [see *Verigin et al.*, 1991a, Figure 5; *Riedler et al.*, 1989], while the solar wind 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 at a solar zenith angle of ~35° [*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 $n \sim 3 \times 10^6$ 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. None of the missions has observed such an effect. On the basis of the above considerations, r_o was taken to be 4300 km±15% for the following quantitative study of the magnetotail variability.

We describe 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 magnetotail 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 magnetotail 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

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

with a power index of $k \sim 5.9 \pm 0.5$. In Figure 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 (see Figures 2 and 4). The power index for the best fit curve turned out 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 may 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 favor 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 magnetotail crossings by Phobos 2 provides stronger observational evidence for this argument (see also *Rosenbauer et al.* [1989*b*] 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. Figure 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 *Saunders and Russell*, 1986, Figure 12; *Luhmann et al.*, 1991, Figure 7] scaled by the planetary radius. When comparing the two sets of data, one can conclude, first, that the diameter of the Martian magnetotail close to the terminator is 1.5–2

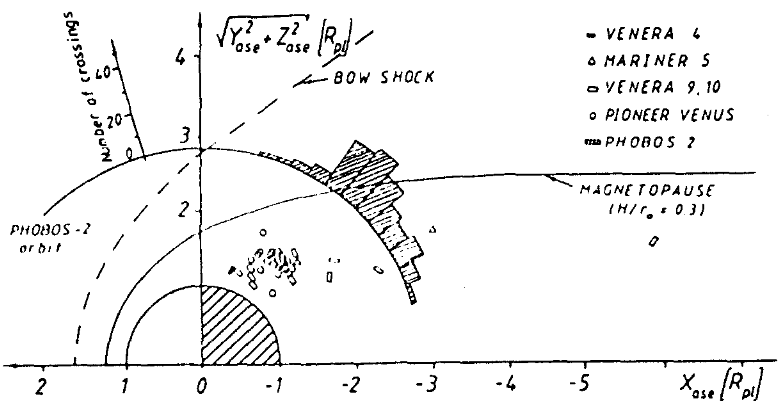

Fig. 5. Summary statistics of the inbound and outbound magnetopause crossings as determined by TAUS data in the circular orbits of Phobos 2. All available data on the location of the magnetopause of Venus at 1−3 planetary radii downstream of the terminator are also presented (from *Saunders and Russell*,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

times thicker on average than that of Venus (in planetary radius) and, second, that the observed positions of areomagnetopause crossings are essentially more spread out than the magnetopause crossings at Venus. It seems to be difficult to explain these two observational facts 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: $\varrho v^2 \sim B^2/8\pi \sim (M/r^3)^2$, 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 of the motion and the shape of the terrestrial magnetopause and bow shock [e.g., *Spreiter et al.*, 1966; *Binsack and Vasyliunas*, 1968; *Bezrukikh et al.*, 1976; *Sibeck et al.*, 1991] confirmed these theoretical expectations at least for solar zenith angles less than ~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 Figures 2 and 3). This latter observation was earlier reported by *Schwingenschuh et al.* [1992] in 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 magnetotail and weak dependence of the bow shock terminator position on solar wind ram pressure in the case of Mars? It can occur if the variations of the subsolar point are very limited, as suggested by the observations discussed earlier (see the previous section). On the basis of Figure 4 of *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:

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

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 Figure 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 (Figure 3). This agreement provides 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 magnetotail [*Yeroshenko et al.* 1990; *Schwingenschuh et al.*, 1992] 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 may 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 Figure 1, it appears that the bow shock was most frequently observed at 5°−10° lower solar zenith angles in the inbound leg of the circular orbits 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 duskside and the dawnside of the planet.

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

CONCLUSIONS

The first quantitative study of the Martian magnetopause variability based on three-dimensional 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 magnetopause 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 out 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 magnetotail thickness compared to the planetary diameter suggest that an intrinsic dipole magnetic field is likely to be an important factor in the solar wind plasma interaction with Mars.

On the other hand, the terminator position of the bow shock turned out 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 magnetotail indicate that the induced magnetic field also plays an essential role in the solar wind interaction with Mars.

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