JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. A9, PAGES 17,199–17,204, SEPTEMBER 1, 1994

The relationship between the magnetic field in the Martian magnetotail and upstream solar wind parameters

H. Rosenbauer,[1] M. I. Verigin,[2] G. A. Kotova,[2] S. Livi,[1] A. P. Remizov,[2] W. Riedler,[3] K. Schwingenschuh,[3] N. M. Shutte,[2] J. A. Slavin,[4] K. Szegő,[5] M. Tátrallyay,[5] and T.-L. Zhang[3]

Abstract. Magnetic field data measured by the MAGMA instrument in the Martian magnetotail lobes are compared with the ram pressure of the upstream solar wind observed by the TAUS instrument in the circular orbits of the Phobos 2 spacecraft. High correlation was found between the magnetic field intensity in the Martian magnetotail lobes and the solar wind ram pressure. From this relationship the average flaring angle of the Martian magnetotail was determined as ~13°, and the average magnetosonic Mach number was estimated as ~5. The observed relationship between the Martian magnetotail magnetic field intensity and the solar wind magnetic field reflects the correlation of the solar wind magnetic field to the ram pressure providing a value of ~7 for the average Alfvenic Mach number. The flaring angle obtained for the Martian magnetotail was found to be an intermediate value between the flaring angle of the magnetotail of the Earth and that of Venus at comparable distances.

Introduction

Despite of the success of the Phobos 2 mission in providing a large amount of plasma and magnetic field data in 1989, our understanding of the solar wind interaction with Mars has not changed dramatically [*Slavin et al.*, 1991; *Zakharov*, 1992]. As it was summarized in the reviews of *Gringauz* [1991] and *Luhmann et al.* [1992], the previous missions to this planet had established the existence of the bow shock and the magnetotail and had provided several different estimations for the intrinsic magnetic field of the planet. The nature of the obstacle, however, is not well understood and the origin of the magnetic field in the Martian magnetosphere remains to be an unsolved problem. On the basis of the available information, Mars either presents a hybrid weak intrinsic magnetic field/ionosphere obstacle to the solar wind [e.g., *Axford*, 1991; *Slavin et al.*, 1991] or exibits a purely ionospheric interaction [e.g., *Luhmann and Brace*, 1991].

Since no direct magnetic measurements are available near the surface of Mars, only indirect evidences can be used in order to come closer to the solution of the problem of the intrinsic field: for example, the behavior of the magnetic field in the magnetotail of Mars and the reasons of its variations should be understood. It is also important to determine the shape of the Martian magnetotail and to compare it with that of the Earth and Venus.

[1]Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany.

[2]Space Research Institute, Moscow, Russia.

[3]Institut für Weltraumforschung ÖAW, Graz, Austria.

[4]NASA Goddard Space Flight Center, Greenbelt, Maryland.

[5]KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

Paper number 94JA00946.
0148-0227/94/94JA-00946$05.00

In the papers of *Yeroshenko et al.* [1990] and *Schwingenschuh et al.* [1992] the magnetotail magnetic field direction was compared with the direction of the interplanetary magnetic field. The high correlation between these directions suggested that the induction effects are essential in the solar wind - Mars interaction. On the basis of plasma data analysis, *Verigin et al.* [1993a] revealed that the thickness of the Martian magnetotail varied nearly proportional to the -1/6th power of the solar wind ram pressure. This fact was considered as an evidence of the significant contribution of the intrinsic magnetic field of Mars to the formation of the Martian magnetotail.

In the present paper, plasma and magnetic field data measured in the circular orbits of the Phobos 2 spacecraft (at ~9500 km from the center of the planet) will be analyzed simultaneously. The data were collected in February-March 1989 in a period close to the maximum of the solar activity cycle. Therefore, even in this short time interval, the solar wind ram pressure was varying in a wide range of $10^{-9}-10^{-7}$ dyn/cm^2 providing an opportunity to analyze reliably the properties of the magnetic field in the Martian magnetotail in relation with the parameters of the upstream solar wind. The average flaring angle of the Martian magnetotail will be determined and compared to that of the terrestrial magnetotail and of the induced tail of Venus. The results will be dicussed in terms of the possible origin of the magnetic field in the Martian tail.

Instrumentation and Data Description

The present analysis is based on the plasma measurements performed by the TAUS energy-spectrometer and magnetic field data measured by the MAGMA magnetometer on board Phobos 2. The TAUS spectrometer had a field of view of ~40°×40° centered on the nominal aberrated solar wind direction (~5° off the solar direction in the ecliptic plane) which was divided into 8×8 channels for angular resolution. The 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.* [1989]. The MAGMA magnetometer had a range of ±100 nT with a resolution of 0.05 nT and returned data at a rate of one vector in every 1.5 or 45 s depending on the telemetry mode of the spacecraft [*Aydogar et al.*, 1989].

The Phobos 2 mission provided data from four elliptical orbits with low pericenter ($h \approx 850$ km above the planet's surface), from one elliptical orbit with high pericenter ($h \approx 6400$ km) and from a number of circular orbits ($h \approx 6150$ km) quasi-synchronous with the orbit of the Phobos moon. Here the uniform set of data measured in the circular orbits (February 20 - March 26) is considered. During this time interval, TAUS provided one proton spectrum in the energy range of 150–6000 eV and one set of proton moments in every 2 min, while MAGMA measured one magnetic field vector in every 45 s. Most of the time, the Phobos 2 spacecraft was rotating instead of being three-axis stabilized. The angle between the rotation axis and the Sun-Mars line sometimes approached ~20° according to TAUS data. Thus only the magnitude of the magnetic field vector (B) and the components parallel ($B_{\|}$) and perpendicular ($B_{\perp}$) to the Sun-Mars line are available for the analysis.

The crossings of the plasma boundaries near Mars (bow shock and magnetopause) are indicated by specific changes in the measured magnetic field and plasma parameters [*Rosenbauer et al.*, 1989; *Riedler et al.*, 1989]. The bow shock crossings are identified by a jump in the magnetic field and a sudden decrease of the mean energy as well as a broadening in the proton spectra. The magnetopause crossings are determined by the disappearance of solar wind protons as measured by TAUS and by an increase in the magnitude of the magnetic field.

In order to study the dependence of the magnetic field of the Martian magnetotail on solar wind parameters, those inbound or outbound legs of the circular orbits were selected when both plasma and magnetic field data were available and the location of the bow shock and the location of the magnetopause were recorded on the same pass. Forty-two inbound and twenty-seven outbound legs satisfied these criteria. The upstream solar wind parameters were determined by averaging proton density and velocity values over a time interval of 20–30 min ending (beginning) ~30 min before (after) the inbound (outbound) bow shock crossing as it was done in the paper by *Verigin et al.* [1993a]. Average interplanetary magnetic field values were derived for nearly the same time interval in the upstream region. In the tail lobes the average field values were taken for time intervals (~15 min) of fairly stable field close to the boundary. Three inbound passes (March 13, ~1500–1800 UT; March 23, ~1400–1700 UT; March 26, ~1100–1300 UT) and one outbound pass (March 8, ~1800–2100 UT) were excluded from our study since in these orbits the $B_{\|}$ component of the magnetic field vector changed sign very close to the magnetopause position. This means that the neutral sheet was crossed very close to the magnetopause and it is impossible to determine the proper tail lobe magnetic field value reliably. For the inbound pass of midday on March 10 the upstream parameters observed later on the outbound leg were used since the solar wind seemed to change significantly during the ~1 hour while the spacecraft was flying from the bow shock to the magnetopause. Altogether, 39 inbound and 26 outbound passes are analyzed in the present study.

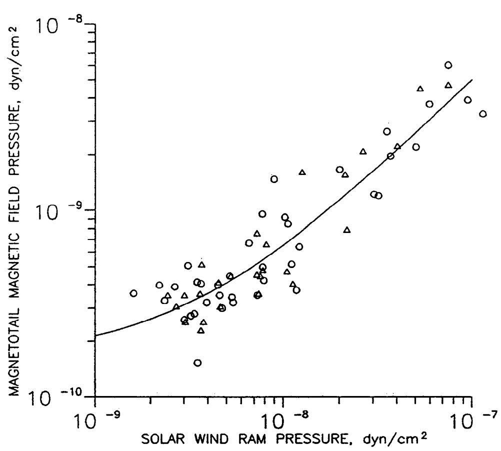

Figure 1. The magnetic pressure in the Martian magnetotail versus the ram pressure of the upstream solar wind. Circles mark data from the inbound legs, triangles mark data from the outbound legs. The solid line is the regression line.

Data Analysis

Figure 1 presents the relation between the Martian magnetotail magnetic field pressure $B_t^2/8\pi$ and the ram pressure of the upstream solar wind ρV^2. In order to describe the obviously strong dependence of the magnetotail field pressure on the ram pressure, the condition of pressure balance for planetary magnetotails was used [*Spreiter and Alksne*, 1969]:

$$B_t^2/8\pi = K(\rho V^2)\sin^2\psi + p \tag{1}$$

where ψ is the flaring angle of the magnetotail (i.e., the complementary angle of the angle between the exterior normal to the magnetopause surface and the flow direction of the solar wind; K is a constant (usually taken as 0.88 for an adiabatic flow with a ratio of specific heats γ=5/3) which will be taken equal to 1 in order to take account for alpha particles since proton density will be used further as a proxi of solar wind density [*Spreiter*, 1976; *Slavin et al.*, 1980]; p includes the pressure of the interplanetary magnetic field and the difference between the thermal pressure of the upstream solar wind and the thermal pressure inside the magnetotail. The method of least squares applied for the data in Figure 1 provides $\sin^2\psi = 0.049 \pm 0.004$ and $p = (1.7 \pm 0.3) \times 10^{-10}$ dyn/cm^2. This relation means that the average angle ψ typical for the Martian magnetotail at the Phobos 2 orbit is equal to $\arcsin\sqrt{0.049} \approx 13°$. Assuming that the main contribution to the value of p is the external thermal and magnetic pressure of the solar wind and taking the average ram pressure as 8×10^{-9} dyn/cm^2 (see Figure 2), the average magnetosonic Mach number M_{ms} can be estimated as $M_{ms} \approx \sqrt{\rho V^2/\gamma p} \approx 5$ during the Phobos 2 mission.

Figure 2 shows the component of the Martian tail lobe field perpendicular to the Sun-Mars line versus the magnitude of the same field. The tangent of the slope angle of the regression line $B_{\perp} = (0.29 \pm 0.02)B_t$ gives an estimate for the sine of the specific "draping angle" (~17°) of the magnetic field in the Martian magnetotail. If the direction

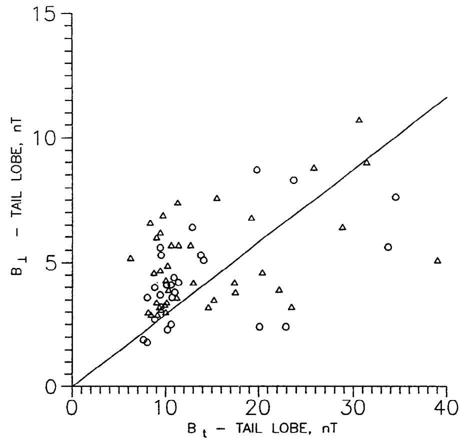

Figure 2. The Martian magnetotail field component perpendicular to the Sun-Mars line versus the total magnetic field magnitude. The solid line is the regression line determining a draping angle of ~17°. Data are marked as in Figure 1.

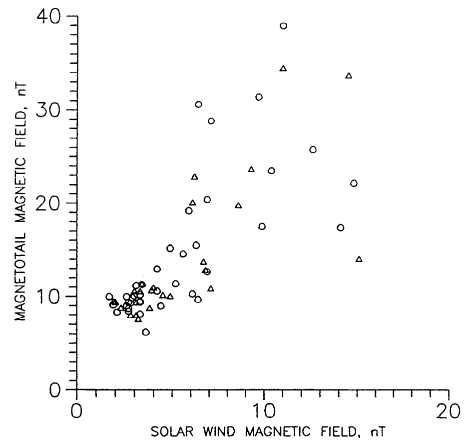

Figure 3a. The magnitude of the Martian magnetotail magnetic field versus the upstream solar wind magnetic field intensity. Data are marked as in Figure 1.

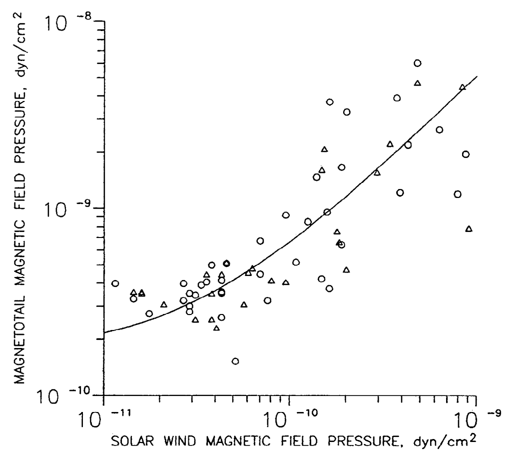

Figure 3b. The pressure of the Martian magnetotail magnetic field versus pressure of the the upstream solar wind magnetic field. Data are marked as in Figure 1. The solid line shows the relation between ${B_t}^2/8\pi$ and ${B_{sw}}^2/8\pi$ as determined from (1) applying $M_A = 7$.

of the magnetic field in the Martian tail lobes is parallel to the surface of the magnetopause, this value can be considered as another estimate of the flaring angle. It is in a fairly good agreement with the previously estimated value of ψ bearing in mind that in most of the circular orbits, the spacecraft was rotating around an axis pointing not exactly towards the Sun. It is worthy of note, however, that the slightly smaller value of the estimate of the flaring angle compared to the estimate of the draping angle might also indicate either the existence of a magnetic field component normal to the magnetopause surface of the Martian magnetotail or the twisting of the magnetotail lobe field [*Verigin et al.*, 1993b].

According to Figures 3a and 3b, there is a rather high correlation between the external interplanetary magnetic field B_{sw} and the internal field inside the Martian magnetotail B_t measured aboard the Phobos 2 spacecraft. However, a high correlation was also observed between the upstream magnetic field magnitude and the ram pressure of the solar wind (see Figure 4). The regression line ${B_{sw}}^2/8\pi = (0.0098 \pm 0.0008)\rho V^2$ determined from the observed data in Figure 4 provides the average Alfvenic Mach number as

$$M_A = \sqrt{0.5\rho V^2/({B_{sw}}^2/8\pi)} \approx 7.$$

The solid curve in Figure 3b represents the relation ${B_t}^2/8\pi = 5{B_{sw}}^2/8\pi + 1.7 \times 10^{-10}$ obtained from (1) taking into account the value of $M_A = 7$. This curve also fits the data fairly well. It seems to be obvious that the observed correlation between the tail lobe magnetic field of Mars and the interplanetary magnetic field is a consequence of the correlation between the upstream magnetic pressure and the ram pressure in the time period of the observations (see Figure 4).

Discussion

On the basis of the large amount of data collected in the circular orbits of the Phobos 2 spacecraft, it is possible to compare the magnetic field inside the Martian magnetotail with the parameters of the upstream solar wind at ~1.5 AU from the Sun. While the mean subsolar distance of the Martian magnetopause (R_{ss}) is likely to be about ~4300 km from the center of the planet [e.g., *Verigin et al.*, 1993a], the Phobos 2 spacecraft observed the magnetopause at a distance of ~2 R_{ss} downstream of the planet. The quantitative analysis of the data revealed that the pressure balance equation (1) properly describes the observed relation between the magnetic field pressure in the Martian magnetotail lobes and the solar wind ram pressure. The flaring angle of the Martian magnetotail ψ turned out to be about 13° at ~2 R_{ss} downstream of the planet.

In the followings the observed relationship between the magnetic pressure in the Martian tail and the conditions in the upstream solar wind at Mars will be compared with similar relations observed for the magnetotail of the Earth which has a strong intrinsic dipole magnetic field and for the magnetotail of Venus which has no intrinsic field.

In the paper by *Nakai et al.* [1991] the dependence of the geotail lobe magnetic field on the ram pressure of the solar wind is presented based on the data of the ISEE 1 spacecraft, the lobe field strength being normalized to a

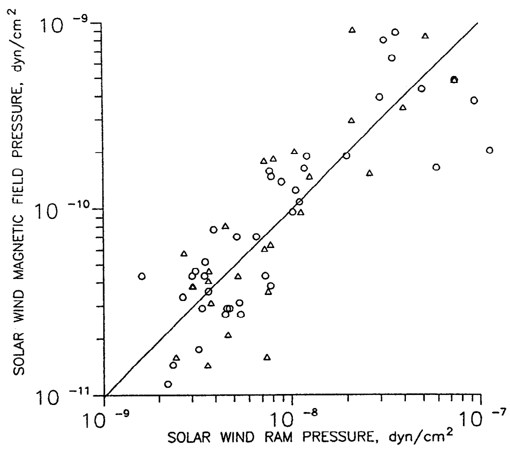

Figure 4. The solar wind magnetic field pressure versus the solar wind ram pressure. The solid line is the regression line providing a value of $M_A \approx 7$.

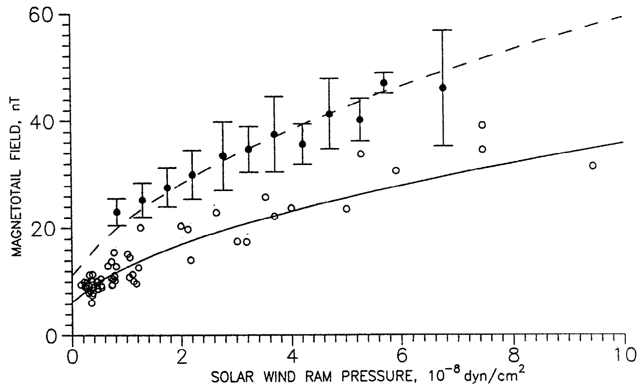

Figure 5. Magnetotail field intensity versus solar wind ram pressure for the Earth and for Mars (solid circles with error bars mark ISEE 1 data from Figure 9 of *Nakai et al.* [1991], open cirlces represent Phobos 2 data). The ISEE 1 data are normalized to the distance of 20 R_E downstream of the planet. The pressure balance relation is shown: dashed line for ISEE 1 data $B^2/8\pi = 0.134\rho V^2 + (5 \times 10^{-10})$, solid line for Phobos 2 data $B^2/8\pi = 0.049\rho V^2 + (1.7 \times 10^{-10})$.

distance of $\sim$20 R_E (Earth radii) downstream of the Earth in the tail. Since the subsolar magnetopause distance at the Earth is about 10 R_E, the distance of 20 R_E corresponds to 2 R_{ss} downstream of the planet. Thus these data refer to about the same relative distance in the tail where the Phobos 2 spacecraft observed the magnetopause and they can be directly compared with the above discussed Martian data. In Figure 5, both sets of data are plotted together (ISEE data are taken from Figure 9 of *Nakai et al.* [1991]), and they obviously split into two different curves. The dashed line represents the regression curve ${B_t}^2/8\pi = (0.134 \pm 0.006)\rho V^2 + (5 \times 10^{-10})$ dyn/cm^2 for the terrestrial data providing a flaring angle of $\psi \approx 22°$. This value is larger than the average flaring angle of $\psi \approx 13°$ obtained for the magnetotail of Mars at the same distances (at $\sim$2 R_{ss} downstream of the planet).

The above presented pressure balance equation was determined assuming that the value of $p \approx nk(T_e+T_i)+{B_{sw}}^2/8\pi$ (n is the density, T_e and T_i is the temperature of electrons and ions, respectively) is $\sim$3 times greater near the Earth than it is around Mars. Indeed, the solar wind density is decreasing as r^{-2} (r is the distance from the Sun), the electron and proton temperatures are decreasing roughly by 1.3 times from the orbit of the Earth to the orbit of Mars [*Bame et al.*, 1992; *Gazis and Lazarus*, 1983]. Therefore the thermal pressure decreases roughly by 3 times from the Earth to Mars. The magnitude of the solar wind magnetic field is $\sim$1.7 times smaller near Mars compared to the value at the Earth [*Smith and Barnes*, 1983], therefore the magnetic field pressure is $\sim$3 times smaller.

The Phobos 2 data can also be compared with another set of data obtained near the Earth. *Ohtani and Kokubun* [1990] analyzed IMP 8 data measured in 1978–1982. Figure 6 presents the IMP 8 data normalized for the distance of 30 R_E ($\sim$3 R_{ss}) downstream of the planet (from Figure 8 of *Ohtani and Kokubun* [1990]). In Figure 6 the curve shows the relation given by (1) where the value of p is the same as for the ISEE 1 data (see Figure 5) and the value of $\sin^2\psi$ is 0.038$\pm$0.002 corresponding to $\psi \approx 11°$. This value of ψ determined from the IMP 8 data applying the method of least squares is nearly the same as the flaring angle obtained for Mars at $\sim$2 R_{ss} downstream of the planet. Figure 7 shows both sets of data collected by Phobos 2 and IMP 8. The coincidence is obviously very good between the two data sets. This comparison shows that the flaring angle of the Martian magnetotail at 2 R_{ss} downstream of the planet is approximately equal to that of the terrestrial magnetotail at a distance of 3 R_{ss} downstream of the Earth. This means that the magnetotail of Mars scaled by R_{ss} is narrower than the magnetotail of the Earth in the same units.

On the other hand, the magnetotail of Venus scaled by R_{ss} is narrower than the magnetotail of Mars [*Verigin et al.*, 1991]. On the basis of the analysis of the magnetic field data obtained by Phobos 2 and by the Pioneer Venus Orbiter at $\sim$1.3 R_V downstream of the planet (R_V is the radius of Venus and $R_V \approx R_{ss}$), *Luhmann et al.* [1991] obtained the value of $\sim$9.5° for the local draping angle in the Venus magnetotail. Since the flaring angle is not likely to be larger than the draping angle, both the flaring angle and the draping angle of the Venus magnetotail seem to be smaller than those for Mars at comparable distances downstream of the planet.

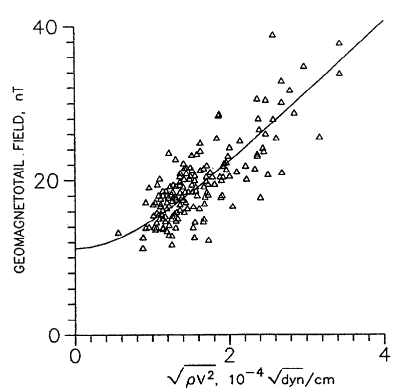

Figure 6. Magnetic field intensity in the terrestrial magnetotail versus the square root of the upstream solar wind ram pressure (IMP 8 data from Figure 8 of *Ohtany and Kokubun* [1990]). The data were normalized to the distance of 30 R_E downstream of the planet. The solid line represents the relation ${B_t}^2/8\pi = 0.038\rho V^2 + (5 \times 10^{-10})$.

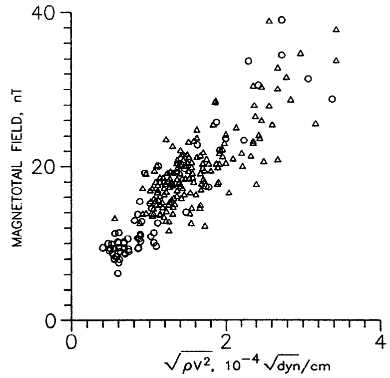

Figure 7. Magnetic field intensity in the magnetotail versus the square root of the upstream solar wind ram pressure. Triangles mark the IMP 8 data of Figure 6, circles represent the Phobos 2 data.

The intermediate values for the relative thickness and flaring of the magnetotail of Mars in comparison with those values for Venus and the Earth mean that both the ionospheric pressures and the intrinsic magnetic field may contribute to the solar wind deflection around Mars.

In the paper of *Luhmann et al.* [1991] the average magnetic field magnitudes in the tail lobes are compared to the interplanetary field magnitudes at Venus and Mars (Figure 5 of *Luhmann et al.* [1991]). The authors considered the positive correlation between these fields as an indication suggesting that both tails are induced magnetotails. In the solar wind, however, a correlation between the interplanetary magnetic field and the ram pressure of the solar wind can often be observed (e.g. Figure 4). Consequently, the correlation between the Martian magnetotail field and the solar wind field seems to be the result of the dependence of the tail magnetic field on the ram pressure of the solar wind.

Conclusions

The relation between the magnetic field measured by the MAGMA experiment in the Martian magnetotail and the upstream solar wind ram pressure provided by the TAUS instrument has been studied here. On the basis of the two data sets collected aboard the Phobos 2 spacecraft in 39 inbound passes and 26 outbound passes through the boundary of the Martian magnetotail, a dependence of the magnetotail lobe magnetic field on the solar wind ram pressure was found which can be expressed as follows:

$$B_t^2/8\pi = 0.049(\rho V^2) + (1.7 \times 10^{-10}) \text{ dyn/cm}^2.$$

From this expression it follows that the average flaring angle of the Martian magnetotail was $\sim$13° at $\sim$2 R_{ss} downstream of the planet and the estimated average magnetosonic Mach number was $\sim$5 in the time interval when Phobos 2 collected the data.

The dependence of the Martian magnetotail magnetic field intensity on the upstream solar wind magnetic field reflects the correlation between the solar wind magnetic field and the ram pressure indicating that the average Alfvenic Mach number was $\sim$7 during the Phobos 2 measurements.

While the average flaring angle of the Martian magnetotail at $\sim$2 R_{ss} downstream of the planet is smaller than that of the terrestrial magnetotail at the same downstream distances, it is approximately equal to the flaring angle of the geotail at $\sim$3 R_{ss} downstream of the Earth; that is, the Martian magnetotail scaled by R_{ss} is narrower than the terrestrial magnetotail in the same units. The tail field of Venus, however, is more severely draped close to the planet than that of Mars.

This comparison of the Martian magnetotail with the Venusian and terrestrial tail probably implies that both the ionospheric pressures and the intrinsic magnetic field are contributing to the solar wind deflection around Mars.

Acknowledgments. This work was supported by the International Science Foundation under Grant N MQU000 and by the Hungarian Grant OTKA 1813.

The Editor thanks A. Bürgi and another referee for their assistance in evaluating this paper.

References

Axford, W.I., A commentary on our present understanding of the Martian magnetosphere, *Planet. Space Sci., 39*(1/2), 167-173, 1991.

Aydogar, O., K. Schwingenschuh, G. Schelch, H. Arnold, G. Berghofer, and W. Riedler, The Phobos fluxgate magnetometer (MAGMA) instrument description, *Rep. IWF-8904*, Aust. Acad. of Sci., Graz, 1989.

Bame, S.J., J.L. Phillips, D.J. McComas, J.T. Gosling, and B.E. Goldstein, The ULYSSES solar wind plasma ivestigation: Experiment description and initial in-ecliptic results, in *Solar Wind Seven, COSPAR Colloquia Ser.*, vol. 3, edited by E. Marsch and R. Schwenn, pp. 139-142, Pergamon, New York, 1992.

Gazis, P.R., and A.J. Lazarus, The radial evolution of the solar wind, in Solar Wind Five, *NASA Conf. Publ. 2280*, 509-519, 1983.

Gringauz, K.I., What was known about the Martian magnetosphere before Phobos-2 mission, *Planet. Space Sci., 39*(1/2), 73-74, 1991.

Luhmann, J.G. and L.H. Brace, Near-Mars space, *Rev. Geophys., 29*, 121-140, 1991.

Luhmann, J.G., C.T. Russell, K. Schwingenschuh, and Ye. Yeroshenko, A comparison of induced magnetotails of planetary bodies: Venus, Mars, and Titan, *J. Geophys. Res., 96*(A7), 11,199-11,208, 1991.

Luhmann, J.G., C.T. Russell, L.H. Brace, and O.L. Vaisberg, The intrinsic magnetic field and solar wind interaction of Mars, in *Mars*, edited by H.H. Kieffer, B.M. Jakovsky, C.W. Snyder, M.S. Mattheus, pp. 1090-1134, University of Arizona Press, Tucson, 1992.

Nakai, H., Y. Kamide, and C.T. Russell, Influences of solar wind parameters and geomagnetic activity on the tail lobe magnetic field: a statistical study, *J. Geophys. Res., 96*(A4), 5511-5523, 1991.

Ohtani, S. and S. Kokubun, IMP 8 magnetic observations of the high-latitude tail boundary: locations and force balance, *J. Geophys. Res., 95*(A12), 20,759-20,769, 1990.

Riedler, W., et al., Magnetic field near Mars: First results, *Nature, 341*(6243), 604-607, 1989.

Rosenbauer, H., et al., Ions of martian origin and plasma sheet in the martian magnetotail: Initial results of TAUS experiment, *Nature, 341*(6243), 612-614, 1989.

Rosenbauer, H., et al., The study of three dimensional distribution functions of the main solar wind ions - protons and alpha-particles in Phobos mission. TAUS experiment (MPK instrumentation), in *The Instrumentation and Meth-*

ods in Space Research (in Russian), edited by V. M. Balebanov, pp. 30-43, Nauka, Moscow, 1989.

Schwingenschuh, K., et al., The Martian magnetic field environment: Induced or dominated by an intrinsic magnetic field?, *Adv. Space Res.*, *12*(9), 213-219, 1992.

Slavin, J.A., et al., The solar wind interaction with Venus: Pioneer Venus observations of bow shock location and structure, *J. Geophys. Res.*, *85*(A13), 7625-7641, 1980.

Slavin, J.A., K. Schwingenschuh, W. Riedler, Ye. Yeroshenko, The solar wind interaction with Mars: Mariner 4, Mars 2, Mars 3, Mars 5, and Phobos 2 observations of bow shock position and shape, *J. Geophys. Res.*, *96*(A7), 11,235-11,241, 1991.

Smith, E.J. and A. Barnes, Spatial dependences in the distant solar wind: Pioneers 10 & 11, in Solar Wind Five, *NASA Conf. Publ. 2280*, 521-535, 1983.

Spreiter, J.R., Magnetohydrodynamic and gasdynamic aspects of solar wind flow around terrestrial planets. A critical review, in Solar Wind Interaction with the Planets Mercury, Venus and Mars, *NASA Spec. Publ. 397*, 135-149, 1976.

Spreiter, J.R. and A.Y. Alksne, Effect of neutral sheet currents on the shape and magnetic field of the magnetosphere, *Planet. Space Sci.*, *17*, 233, 1969.

Verigin, M.I., et al., Ions of planetary origin in the martian magnetosphere (Phobos-2/TAUS experiment), *Planet. Space Sci.*, *39*(1/2), 131-137, 1991.

Verigin, M.I., et al., The dependence of the Martian magnetopause and bow shock on solar wind ram pressure according to Phobos 2/TAUS ion spectrometer measurements, *J. Geophys. Res.*, *98*(A2), 1303-1309, 1993a

Verigin, M.I., J.G. Luhmann, and C.T. Russell, On the Venus ion magnetotail structure, in *Plasma Environments of Non-Magnetic Planets, COSPAR Colloquia Ser.* vol. 4, edited by T.I. Gombosi, pp. 259-264, Pergamon, Oxford, 1993*b*.

Yeroshenko, Ye., W. Riedler, K. Schwingenschuh, J.G. Luhmann, M. Ong, and C.T. Russell, The magnetotail of Mars: Phobos observations, *Geophys. Res. Lett.*, *17*(6), 885-888, 1990.

Zakharov, A.V., The plasma environment of Mars: Phobos mission results, in *Venus and Mars: Atmospheres, Ionospheres, and Solar wind Interactions, Geophys. Monogr. Ser.*, vol. 66, edited by J. G. Luhmann, M. Tatrallyay, R. O. Pepin, pp. 327-344, AGU, Washington, D.C., 1992.

G. A. Kotova, A. P. Remizov, N. M. Shutte, and M. I. Verigin, Space Research Institute, Profsoyuznaya 84/32, 117810 Moscow, Russia.

S. Livi and H. Rosenbauer, Max-Planck-Institut für Aeronomie, D-W3411 Katlenburg-Lindau, Germany.

W. Riedler and K. Schwingenschuh, Institut für Weltraumforschung ÖAW, Inffeldgasse 12, A-8010 Graz, Austria.

J. A. Slavin, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

K. Szegő and M. Tátrallyay, KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest P.O. Box 49, Hungary.

(Received November 15, 1993; revised April 6, 1994; accepted April 7, 1994.)