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The Solar Wind interaction with Mars: locations and shapes of the Bow Shock and the Magnetic Pile-up Boundary from the observations of the MAG/ER experiment onboard Mars Global Surveyor

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Abstract

The Mars Global Surveyor spacecraft was inserted into an elliptical orbit around Mars on September 12, 1997. It includes the MAG/ER instrument with two magnetometers providing in-situ sensing of the ambient magnetic field and an electron reflectometer measuring the local distribution function of the electrons in the energy range of 10 eV to 20 keV. This statistical study deals with the identification and the position of the Bow Shock (BS) and of another plasma boundary, the Magnetic Pile-up Boundary (MPB), proved as permanent by MAG/ER. During the first year of the MGS mission, a total of 290 orbits have been considered to fit the geometric characteristics of these boundaries. The position and shape of these boundaries are compared with previous studies. Good agreement is found with the Phobos 2 observations, suggesting than the mean bow shock and MPB locations are independent of solar cycle phase. The great number of crossings shows that the Bow Shock position and nightside MPB position are highly variable.

Introduction

Previous missions to Mars have established the existence of a Bow Shock but the nature of the interaction with the solar wind (planetary magnetosphere, planetary ionosphere and atmosphere, mass addition to the flow) was not well known. The MAG/ER instrument of MGS has found an upper limit of $2.10^{21} G.cm^3$ on any intrinsic magnetic moment indicating that the interaction of the solar wind with Mars is dominated by the planet's ionosphere and atmosphere [*Acuña et al.*, 1998]. Further, between the Bow Shock and the ionopause, MGS observations have proved the permanent existence of a third plasma boundary: the Magnetic Pile-up Boundary. The solar wind interaction with Mars displays both Venus-like [*Cloutier et al.*, 1999] and comet-like [*Mazelle et al.*, 1999] features. The solar wind plasma with its frozen-in interplanetary magnetic field perceives the dayside ionosphere as an obstacle. Then, the IMF piles up on the front of the obstacle forming a magnetic barrier. The MPB appears as a sharp and thin plasma boundary marking entry into the magnetic barrier region. Mars' MPB is similar to those detected at comets Halley and Grigg-Skjellerup by the Giotto experiments [*Rme et al.*, 1993; *Mazelle et al.*, 1995].

The Phobos 2 encounter with Mars provided, respectively, 126 and 45 crossings of the BS [*Trotignon et al.*, 1993] and the MPB, which was called "planetopause" by *Trotignon et al.* [1996]. During the first year of the MGS mission, 450 and 488 crossings, respectively, of BS and MPB have been identified from a total of 290 orbits. In this paper, the first section is devoted to the identification of the bow shock and the magnetic pile-up boundary from MAG/ER data. Then, the next section explains how these boundaries are fitted and finally, a comparison is made with previous studies.

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MGS Observations

Two redundant triaxial fluxgate magnetometers (MAG) onboard MGS [*Acuña et al.*, 1992] provide fast vector measurements (up to 32 samples/sec) of magnetic fields over the range of $\pm$ 4 nT to $\pm$ 65,536 nT with a digital resolution of 12 bits. The electron reflectometer (ER) measures the local 10 eV - 20 keV electron distribution function in a 360 $\times$ 14 degree disk-shaped field with a time resolution as high as 2 sec.

Figure 1 illustrates an example of Bow Shock and MPB crossings detected by the MAG/ER nearly the dawn - dusk meridian plane on August 12, 1998. We use the Mars-centered Solar Orbital (MSO) coordinate system: the X-axis points from Mars to the Sun, the Y-axis points antiparallel to Mars' orbital velocity and the Z-axis completes the right-handed coordinate system. The magnetic field azimuth (with φ=0 towards the Sun), elevation with respect to the (X, Y) plane and amplitude are plotted in top panels 1, 2 and 3. The last panel shows the electron fluxes for four energy ranges labelled with their geometrical mean energy. The two left vertical bars delimit the time interval when the spacecraft crosses the Bow Shock. The interplanetary magnetic field is initially about 2 nT and then begins to slightly increase (the first vertical bar) to a value of about 16 nT (the second vertical bar) over a period of 10 minutes. During the same time, the electron fluxes, with energy ranges between 11 eV and 300 eV are increasing by a factor 10. Then, between 8:54 and 9:26, the spacecraft is in the magnetosheath region where turbulent magnetic field variations are always observed. At 9:26, the spacecraft crosses another discontinuity. The magnetic field amplitude rises sharply by about a factor 2 over a period of three minutes. This discontinuity corresponds to the Magnetic Pile-up Boundary. The MPB crossings are identified by three simultaneous signatures : a more or less sharp increase of the magnetic field magnitude, a reduction of the electron fluxes greater than 10 eV and a decrease in the fluctuations of the magnetic field. These features on the magnetic field was previously identified in the Phobos 2 data [*Riedler et al.*, 1989]. The electron fluxes drop sharply by about one order of magnitude, typically. This feature in the electrons has been interpreted as a consequence of electron impact ionization by *Crider et al.* [1999]. Next, two dips in the electron fluxes are clearly identified at 9:36 and at 9:50 when the spacecraft is at an altitude of 300 kilometers. These dips correspond to the signature of the ionopause which is not studied in this paper. Outbound, the MGS spacecraft crosses the MPB at $\sim$ 9:55 and the Bow Shock at $\sim$ 10:20.

Bow shock and magnetic pile-up boundary fits

From September 12, 1997 to August 29, 1998, 450 Martian Bow Shock crossings and 488 MPB crossings are identified. The

Table 1. Martian shock fit parameters from MGS - Phobos 2 observations

	X_0 (R_M)	ε	L (R_M)	R_{SD} (R_M)	R_{TD} (R_M)	α[a]	N[b]
This study (Direct fit method)	0.64 ± 0.02	1.03 ± 0.01	2.04 ± 0.02	1.64 ± 0.08	2.62 ± 0.09	4°	450
This study (Slavin's method)	0.72	1.02 ± 0.02	1.93 ± 0.01	1.67 ± 0.03	2.56 ± 0.06	4°	450
Slavin et al. (Phobos 2, 1991)	0.55	1.01	2.07	1.58	2.57	3.2°	94
Trotignon et al. (Phobos 2, 1993)	0.50	1.02	2.17	1.57 ± 0.03	2.63	4°	126

[a]Aberration angle considered.
[b]Number of crossings used.

difference comes from a few data gaps far from the periapsis and because sometimes, when the angle between the shock surface normal and upstream interplanetary magnetic field becomes small, the determination of the bow shock location is complicated. First the shock locations are expressed in an aberrated solar ecliptic system (X', Y', Z'), so that the X' axis is opposite to the mean solar wind flow direction in the Mars frame of reference assuming a 4 degree aberration. Then, in order to fit these boundary positions, the approach of [*Slavin and Holzer*, 1981] was first used. The fits of these positions are represented by conic sections. Expressed in polar coordinates, assuming a cylindrical symmetry along the X' axis, the equation of the shock surface is $r=L/(1+\varepsilon cos\theta)$ where the polar coordinates (r, θ) are measured about the focus which is located at (X_0,0,0), L is the semi-latus rectum and ε is the eccentricity.

The focus is allowed to move along the X' axis and for each focus location, linear regression in 1/r - cos θ space to least square fit the observation are performed. The best fit was chosen by the best linear correlation coefficient. However, this method is not appropriate for the MPB data set because most of MGS MPB crossings identified are near the terminator or on the dayside. Thus, when linear regressions in 1/r - cos θ space are made, the boundary crossings which occur far from Mars have not the same weight in the linear regressions than those which occur near Mars. Because of the nonuniform coverage, another slightly different method is used. First, the time interval when the spacecraft crosses one boundary is assumed to correspond to the apparent layer of this boundary. Then, for the boundary crossing positions used in the fit, a random location is considered in this time interval. Second, the three parameters of the conic (ε, L, X_0) are allowed to vary simultaneously. For each set of these three parameters, the root mean square for all crossings to the conic considered is determined. Then the best fit is chosen with the lowest rms. These two previous points are repeated a great number of times in order to determine the conic parameters with their uncertainties.

The axisymmetric bow shock crossings are displayed in Figure 2. The black solid curve is a fit to all MGS shock crossings with the direct fit method, while the black dashed curved is the fit obtained with Slavin's method. As can be seen in Figure 2, a large variability of the bow shock position is found. In order to compare the position of the two shock fits, two parameters have been determined : R_{SD} which is the conic stand-off distance along the X' axis and R_{TD} which is the conic stand-off distance along the Y' axis:

$$R_{SD} = X_O + \frac{L}{1+\varepsilon} \quad (1)$$

$$R_{TD} = sin\varphi \frac{L}{1+\varepsilon cos\varphi} \quad (2)$$

where φ is, from the focus, the polar coordinate of the conic terminator stand-off distance to the X' axis. The fits from MGS data, obtained with two different methods, are quite similar. The conic parameters are given in Table 1.

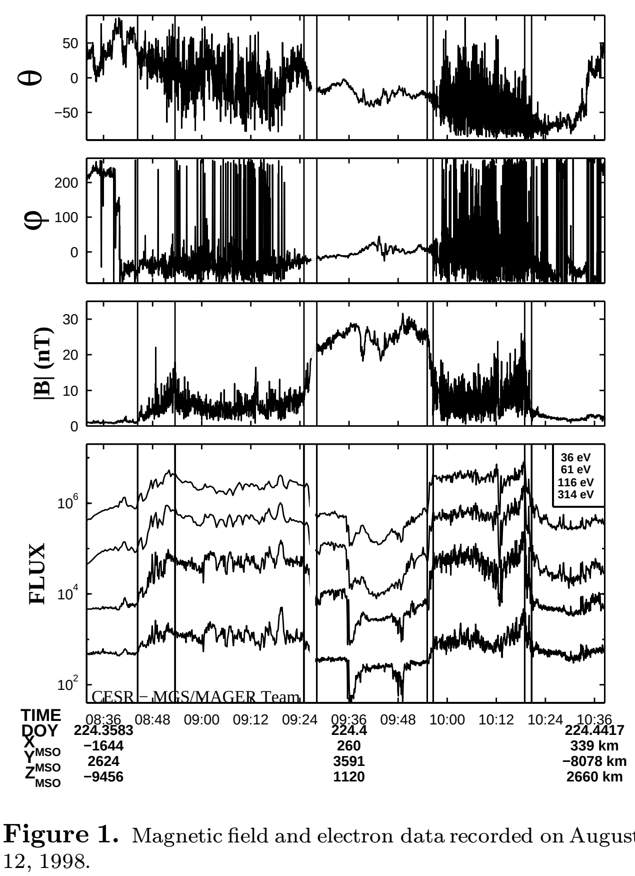

Figure 1. Magnetic field and electron data recorded on August 12, 1998.

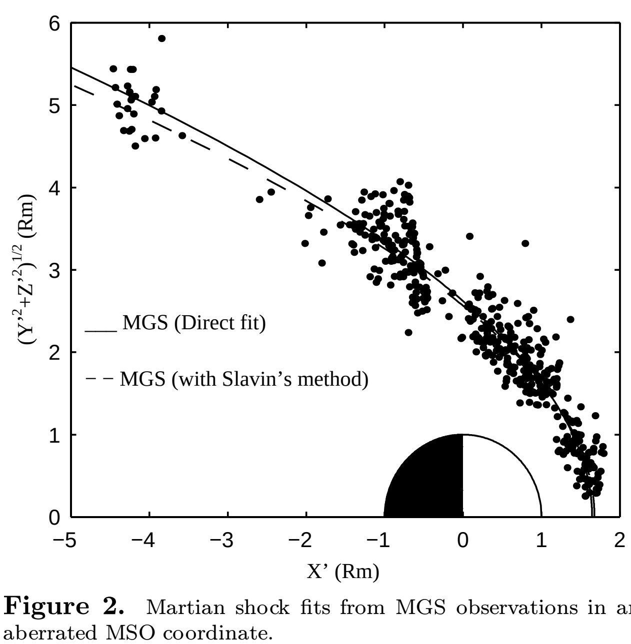

Figure 2. Martian shock fits from MGS observations in an aberrated MSO coordinate.

Table 2. Martian MPB fit parameters from MGS - Phobos 2 observations

	X_0 (R_M)	ε	L (R_M)	R_{SD} (R_M)	R_{TD} (R_M)	α	N
This study (Direct fit method)	0.78 ± 0.01	0.90 ± 0.01	0.96 ± 0.01	1.29 ± 0.04	1.47 ± 0.08	4°	488
Trotignon et al. (Phobos 2, 1996)	0.58 (dayside)	0.75	1.06	1.19	1.37	4°	45
	1.60 (nightside)	1.01	0.49				

The axisymmetric MPB crossings are displayed in Figure 3. There are no data for MPB crossings below 20 degree solar zenith angle. Then, using the direct fit method, the extrapolation of the fit at low solar zenith angle gives a subsolar location higher than expected. Thus, the direct fit method is used plus one more condition to choose the best fit : the distance difference between the closest point of the fit to Mars and the subsolar point must be less than 0.05 Martian radius. This degree of liberty is consistent with the mean fluctuation of MPB crossings positions for solar zenith angle less than 50 degree. The black solid curve is the fit obtained to all MGS MPB crossings using this method. The fit obtained using Slavin's method to the MGS MPB crossings is not good due to the bias artefact mentioned earlier. MPB crossings in the night hemisphere are more variable than in the dayside hemisphere. The conic parameters are given in Table 2.

Discussion

Figure 4 represents MGS BS and MPB fits with fits from previous study on Phobos 2 data obtained by allowing the focus to lie along the symmetry axis [*Slavin et al.*, 1991; *Trotignon et al.*, 1993]. For the BS, there is a close agreement between fits from MGS and Phobos 2 observations : the terminator stand-off distance is nearly the same, but the subsolar stand-off distance is slightly greater for MGS results. The conic parameters given in Table 1 confirm these observations. As mentioned earlier in this paper, the bow shock position is highly variable and some MGS crossings occurs closer to Mars than the *Slavin et al.* [1991] and *Trotignon et al.* [1993] fits. But, the MGS mission took place during a period of solar activity lower than during the Phobos 2 mission: the sunspot number during the Phobos 2 mission was between 140 and 180 while during the first year of MGS mission, it was between 30 and 90. However Phobos 2 and MGS fits are nearly identical. This could suggest than the mean bow shock location is independent of solar cycle phase which is different from the solar wind interaction with Venus. Moreover, MGS Bow Shock crossing locations are highly variable with respect to the mean shock position.

The MPB appears as a standing boundary which marks the entry in the magnetic barrier region. The MPB is determined from the MAG/ER data by an increase of the magnetic field amplitude, a decrease in the turbulence of the magnetic field and a decrease of electron fluxes. The magnitude of the field also sharply increases during dayside MPB crossings. Two major features characterize this plasma boundary: the nightside crossing positions of this boundary are more variable than the dayside crossing position, and the nightside crossing positions are not easily identifiable. For X' ≤ -2 R_M, the MPB appears as a weak and gradual transition in the night hemisphere, which is at least partly due to the crossing geometry along the orbit on the flanks (more tangential) and is sometimes poorly defined. In this case, it is not included in this study. In Figure 4, the MPB fit with the new method is slightly farther from Mars than the Martian "planetopause" surface given by *Trotignon et al.* [1996] for X' ≥ -2 R_M. The MPB fit is about 300 km above the position found by *Trotignon et al.* [1996] in the dayside hemisphere at the subsolar position (see Table 2). However, *Trotignon et al.* [1996] have only 4 boundary crossings in the dayside hemisphere, making it difficult to compare the dayside results from the two data sets; however, there is a quite good agreement for the nightside hemisphere. This could suggest than the mean MPB location is also independent of solar cycle phase. From Phobos 2 observations, it is known that the MPB is also characterized by a change in the ion composition (Note than MGS has no ion measurements onboard). This boundary is not clearly foreseen by classical MHD models. However, the formation of an "Ion Composition Boundary" was observed in a collisionless 2D bi-ion fluid plasma model made by *Sauer et al.* [1994]. Future modelling effort must used multi-fluid approach or kinetic treatment.

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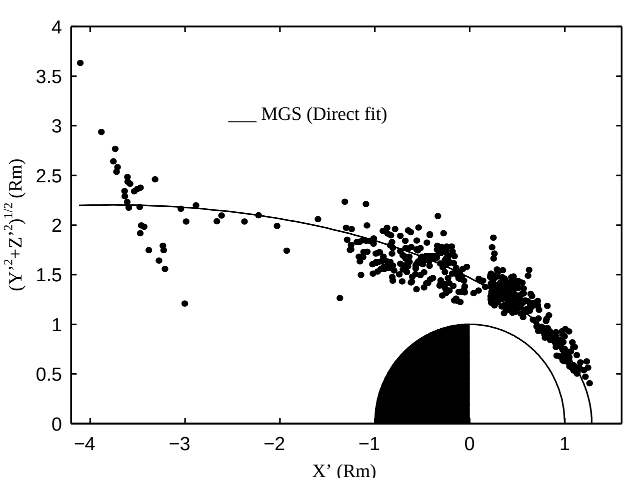

Figure 3. Martian MPB fit from MGS in an aberrated Mars-centered Solar Orbital (MSO) coordinate.

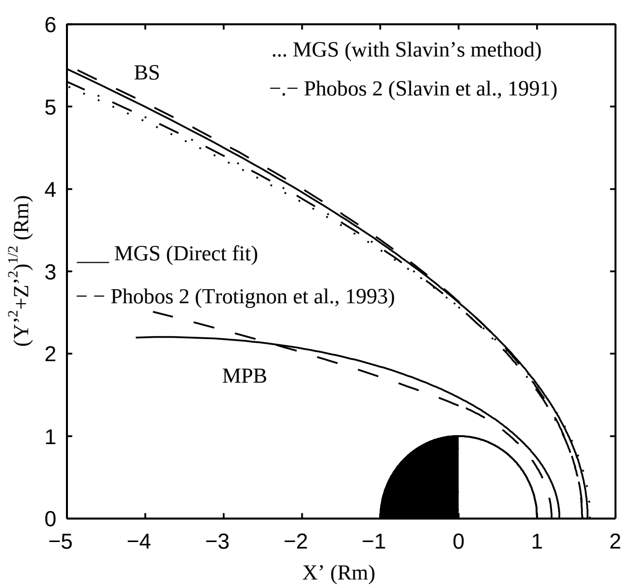

Figure 4. Martian BS and MPB fits from MGS and Phobos 2 in an aberrated MSO coordinate.

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