The Martian magnetosheath: how Venus-like?


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Abstract

The planets Mars and Venus, because of their weak global magnetic fields, have small-scale magnetosheaths amenable to detailed analysis and model comparisons. In this paper we examine some of the similarities and contrasts between the Venus and Mars cases based on Pioneer Venus Orbiter (PVO) magnetometer observations from the PVO prime mission, and Mars Global Surveyor magnetometer observations obtained during the MGS Science Phase Orbits (March-September, 1998). The combination of a mass-loaded magnetohydrodynamic magnetosheath model and a data-based model of the Martian crustal fields is used to illustrate the differences produced by the presence of the Martian crustal fields. While Venus at solar maximum exhibits a nearly classical magnetosheath formed by the solar wind interaction with a practically impenetrable blunt body, Mars in late 1998 represents a complicated obstacle whose own magnetic fields complicate this simplicity within at least several hundred km of the nominal obstacle boundary inferred from the bow shock position. In particular, the results suggest the presence of a thick inner magnetosheath boundary layer when the strong southern hemisphere crustal fields are located on the sunward hemisphere. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The solar wind interactions of Venus and Mars are dominated by their magnetospheres. These weakly magnetized planets thus call special attention to the regions of disturbed interplanetary plasma flow and magnetic field surrounding planetary obstacles. At Venus, most of the plasma and magnetic field observations along the Pioneer Venus Orbiter (PVO) elliptical orbit are remarkably well-described by a gas-dynamic model of fluid flow around an impenetrable blunt body with a convected, frozen-in magnetic field (e.g. Spreiter and Stahara, 1992; Luhmann et al., 1997 and references therein). This simple picture was particularly appropriate around the solar maximum period of PVO’s primary mission. Under such conditions of high solar EUV flux, the thermal pressure of Venus’ ionosphere is generally sufficient to balance the incident solar wind pressure at an altitude where inter-particle collisions are infrequent (∼ 300 km subsolar). The resulting narrow ionopause current layer forms a sharp boundary between the solar wind and ionosphere (e.g. Elphic et al., 1981), providing a natural laboratory for testing the fluid picture of planetary magnetosheaths without the complications of interactions with planetary magnetic fields.

Using the large PVO data set, including the solar wind plasma measurements (e.g. Intriligator et al., 1979), magnetosheath field measurements (Russell et al., 1979), and ionospheric thermal plasma measurements (Bruce et al., 1979), along a highly inclined, elliptical orbit whose ∼ 150 km altitude peripause circled the planet at ∼ 15° North latitude once a Venus year, it was possible to study steady solar wind conditions from the over 5000 orbits for statistical global studies. For example, the average, global 3D magnetosheath field draping was reconstructed and compared to models (Phillips et al., 1986). Analysis of the transition to the magnetohydrodynamic regime in the inner magnetosheath, the “magnetic barrier” adjacent to the ionopause, revealed the thickness of the layer where the magnetic pressure of the compressed interplanetary field dominates the magnetosheath pressure (Zhang et al., 1991). The asymmetries in the magnetosheath cross section due to magnetohydrodynamic (MHD) forces could be demonstrated (Russell et al., 1988), as could the effects of subsolar quasi-periodic bow shock-generated waves converted into the magnetosheath.
The Martian magnetosphere, in contrast, has thus far escaped similar close scrutiny. Few early flybys well above the obstacle boundary by Soviet/Mars 3 and 5 spacecraft provided magnetosheath plasma and field measurements that, like the Venus observations, compared favorably to the gas dynamic/forefield model (Russell et al., 1984). However, the elliptical transfer orbits of Phobos-2 that probed the magnetosheath to the lowest altitude yet of \( \approx 850 \) km altitude, followed by over 50 crossings of the wake magnetosheath in a circular orbit at \( \approx 2.7 \) Mars radii, suggested complications. In particular, the average inferred widths of the inner boundary of the magnetosheath in the wake, or magnetosheath boundary, had a larger diameter than expected from scaling of the Venus case (noticed in earlier Mars data by Vaisberg and Strohov, 1986; see Verigin et al., 1993 for Phobos-2 results, and also Luhmann and others, 1991). Another difference was the variability of the measured bow shock and magnetosheath/magnetotail boundary locations (e.g., Verigin et al., 1993). While these could arguably have resulted from finite solar wind ion gyroradii effects at Mars, which solar wind parameter studies and the subsolar magnetosheath thickness indicate should play a role (Breicht and Ferantze, 1991; Breicht, 1997), the first measurements by the Mars Global Surveyor (MGS) at altitudes below several hundred kilometers (Acuna et al., 1999; Connerney et al., 1999) revealed the main cause of departures from a Venus-like magnetosheath.

The observed Martian crustal magnetic fields should both contribute to the pressure balance in the solar wind interaction, making a bumpy magnetopause/ionopause hybrid inner magnetospheric boundary, and produce cup-like features where the magnetosheath plasma can penetrate to lower altitudes is happens in the region of the Earth's magnetospheric cusps (Mitchell et al., 2001). These will affect the appearance of the magnetosheath in complicated ways that like the Venus case depend on solar wind pressure and EUV flux, but unlike Venus will also depend on the subsolar planetary longitude and interplanetary magnetic field orientation. Here we consider some of the Martian magnetosheath's contrasts to Venus as observed by the MAE/MA/ER magnetometer during the elliptical science phasing orbits. Our goal is to both identify a subset of well-behaved MGS passes that can be used for future modeling efforts, and to suggest what future sophisticated numerical simulations might find in light of the observations.

2. Description of the data set used

The MGS MAG/ER data from the science phasing orbits constitute the largest data base obtained to date on the magnetic field in the Martian magnetosheath. The data used here are available in the Planetary Data System Planetary Plasma Interactions modellative (Walker et al., 1996; Connerney and Acuna, 2000). They consist of 0.75 s time resolution magnetic field vector components in both Mars Solar Orbital (MSO) coordinates (equivalent to GSE at Earth), and planetary or geographical coordinates. The PVO data consist of 0.25 s measurements in the Venus Solar Orbital (VSO) system, comparable to the MSO system. Here we average both data sets to 1 s in order to focus on gross characteristics, and use the magnetic field data in the comparable MSO and VSO coordinate systems that are appropriate for magnetosheath analyses. Spacecraft orbit information is also included in the MGS MAG/ER archive, with separate tables giving the subsolar planetary latitude and longitude at periastris as well as the periapsis's latitude and longitude. The archived science phasing orbit cover the several-month period from March 26, 1999 to September 23, 1999. During this time interval, MGS was in near-polar orbit with its periastris between ~ 60°-85° North latitude. The MGS orbital period of ~ 12 h and the ~ 24-h Martian day (Sol) combine to produce periodic sampling of the north polar region about 180° of longitude apart on sequential orbits. The periapsis altitudes range between ~ 70 and 178 km for this MGS orbit phase. Fig. 1a summarizes the planetary latitude, longitude, altitude and solar zenith angle coverage. Along the MGS orbit, the magnetosheath is typically entered and exited within ~ 60-80 minutes of periapsis. As shown by the sample orbit trajectories in Fig. 1b, the high inclination orbit scans latitudes relatively smoothly, but is confined to a rather narrow longitude range on a single pass.

Limitations of this data set for magnetosheath studies include a lack of solar wind bulk plasma measurements, and the restricted latitude and local time coverage at low altitudes. The MGS sampling of the magnetosheath gives a primarily polar, near-terminator view. Nevertheless, the planet's rotation and interplanetary magnetic field (IMF) rotations produce a range of solar wind interaction perspectives. There is also some difficulty in determining the prevailing IMF orientation because of the combination of ~ nT spacecraft fields, comparable in strength to the ~ 3-5 nT IMF at Mars, and the restricted near-planet data acquisition periods. In these cases, the IMF orientation can be inferred from the stronger, compressed magnetosheath field if the field draping is taken into account. For our analyses below, we examine a selected subset of orbits that exhibit approximatively Gaussian magnetosheath field draping, both with and without strong crustal fields near periapsis. As our goal is to illustrate the first-order effects of the crustal fields, we avoid orbits where interplanetary field variations or waves from either the foreshock or other physical processes appear to be present.
3. Models for comparisons and interpretation

Venus and Mars present smaller obstacles to the solar wind flow than Earth's magnetosphere, allowing a spacecraft to make a complete transit of the magnetosheath while the IMF is effectively steady. As mentioned above, Spreiter and Stahara's (1980, 1992) gas dynamic frozen field magnetosheath model has been compared with observations from both Venus and Mars. Since that early model was developed, progress has been made on more physically complete simulations. In particular, 3D MHD treatments of the solar wind interaction with a conducting sphere, with some models including the mass loading from the ionization of the upper atmosphere (Tanaka, 1993; Calzo a
mass-loading is that the field lines are more strongly draped in the mass-loaded magnetosheath. Both of these models are used in the present study. Fig. 2b shows north and south polar views of the Parker et al. (2000) (hereafter referred to as Parker) crustal field model, with the north-south dichotomy associated with the southern hemisphere outer region clearly visible. Because the science phasing orbit sampling of this crustal field near periapsis was limited to the north polar region, this orbit phase missed the largest crustal field effects on the magnetosheath, but on the other hand allows interpretation of the observations in terms of separate crustal field and magnetosheath models as will be shown below.

4. Magnetosheath passes compared to models

Fig. 3 illustrates the different characteristic magnetosheath sampling geometries of MGS and PVO orbits. The MGS orbits are designated by their day number, 1998, and periapsis number, while the PVO orbits are given their assigned orbit number. The orthogonal views of the orbits in the solar orbital coordinate system show the basic differences between the MGS and PVO perspectives. The PVO periapsis at ~15° North latitude circles the planet over a Venus year, providing inner magnetosheath sampling in a near-equatorial band including the subsolar region. Because the IMF at low heliographic latitudes typically lies close to the solar equatorial plane, PVO usually crosses the magnetosheath drapes field on an almost perpendicular trajectory in both subsolar and terminator regions unless the IMF is highly inclined. In contrast, MGS repeatedly observes the most-draped, or ‘polar’ region of the magnetosheath where mass-loading appears to have considerable influence on the field orientation (see Fig. 2a).

Of the three PVO orbits included in Fig. 3, the more subsolar periapsis examples (orbits 432, 438) were chosen because they represent the cases that so successfully fit the gas-dynamic frozen field model in early studies, and represent the prototypical PVO view of the Venus magnetosheath in a region not well-sampled at Mars. The third, near-terminator orbit 801, was selected because it occurred at an unusual time when the IMF at Venus was inclined almost 90° to the ecliptic, providing a good analogy to the usual MGS perspective for comparison. Figs. 4a–c show the measured time series of the magnetic field vector components from the PVO magnetometer, at a time resolution of 15 s. Corresponding simulated flights through the Lyon magnetosheath model were carried out by experimenting with the scaling and IMF direction until a reasonable fit was found. The drop in field magnitude around periapsis in these cases represents PVO’s entry into the ionosphere, or into the conducting sphere obstacle in the case of the model. Both mass-loaded and unloaded models were examined, but only the best fitting model is plotted. Models without mass loading were found to best fit the more subsolar
perihelion orbits 432 and 438, while the mass-loaded model best fit the terminator perihelion, high inclination IMF orbit 201.

Overall, the Lyon models show good agreement with these examples from PVO. The question is whether such agreement can be found at Mars where the obstacle is so much more complex. Fig. 5a shows a set of five MMS orbits including the three examples in Fig. 3, but plotted in the planetary coordinate system, and superposed on the Parker model of the crustal fields. These five orbits were selected because they appeared to occur during steady solar wind conditions for which an IMF might be determined from the magnetometer data, and included a combination of perihelion where the strongest northern hemisphere crustal fields were either directly beneath the spacecraft, or largely avoided. Another view of the crustal field sampling, shown by projection of the same orbit segments on the Parker 200 km model field map, is shown in Fig. 5b. In this plot, the spacecraft position is shown with a time resolution of 15 s. Comparison with the information in Fig. 1h gives a sense of the rate at which altitude is increasing away from perihelion.
Figs. 6a-g show the results of attempts to replicate the higher altitude MGS data with simulated flights through the scaled and rotated mass-loaded Lyon magnetosphere model, and with flights through the Pidcock crustal model for the low altitude portion. (A check using the unrotated Lyon model was carried out to confirm the better agreement with the mass-loaded model.) The passes labeled D0Y 208 Peri 2 (Fig. 6a) and D0Y 181 Peri 1 (Fig. 6b) are most analogous to the PVO orbit 801 case in that the near-polar magnetospheric field contributions were weak, while the magnetosphere exhibited a fairly classical magnetospheric draping behavior. As can be seen from Figs. 6a and b, the magnetosphere model approximates the MGS observations away from periapsis, but in spite of the absence of strong magnetic anomalies beneath the spacecraft at periapsis, a thick inner magnetospheric boundary layer appears to be present. This layer is probably the same as the magnetic pile-up boundary layer reported in both Phobos-2 transfer orbit observations (Biedert et al., 1999) and MGS observations (Vigae et al., 2000). Its properties may result from the induced magnetization of the ionosphere at high altitudes (e.g. Shingawa and Cremers, 1999), from strong inner magneto- spheric mass-loading (e.g. Nagy et al., 1995), or from a complicated boundary layer formation process involving both local planetary ion production and the solar wind interaction with the crustal fields. Indeed, the strong southern hemisphere features were facing the Sun during the times of these passes, favoring a direct solar wind interaction with the southern hemisphere crustal fields. Unfortunately, it is difficult to make observational comparisons with corresponding passes with the southern hemisphere fields in the wake because, under those circumstances, MGS always flies over the northern hemisphere crustal fields during the science phasing orbit.

The three MGS orbits in Figs. 6c-e represent fairly well-behaved passes when the northern hemisphere crustal fields were crossed at periapsis. The comparisons with the magnetosphere and crustal field models suggest that one can roughly approximate the observed signature with a linear combination of the two in this part of the magnetosphere of Mars. The departures from a good fit to the combination indicate either a problem from neglect of the Sun Mars component of the IMF in the magnetosphere model, time-dependent solar wind features that were not accounted for, or perturbations introduced into the magnetosphere by the solar wind interaction with the crustal fields. These comparisons nevertheless illustrate the fair quality of agreement with the classical picture for at least
the northern hemisphere of the Martian magnetosphere. As mentioned above, the strong southern hemisphere crustal fields are generally in the terminator to wake local time sector when the northern hemisphere fields are directly below the spacecraft at periapsis. If our conjecture that the boundary layer is strongest when the southern hemisphere anomalies are subsolar is correct, it would be consistent with the presence of a less apparent boundary layer at the times of these observations.

The last MGS orbits selected, DOY 209 Peri 2 in Fig. 6f and DOY 218 Peri 2 in Fig. 6g, are of special interest because they occurred when the IMF at Mars was unusually large. This circumstance, coupled with only weak to moderate crustal fields at periapsis, suggests these passes should again be comparable to the PVO orbit 801 case in Fig. 4c. MGS pass 209 Peri 2 was also used by Cloutier et al. (1999) for a Venus comparison, but those authors believed crustal fields contributed to what was observed near periapsis, and compared the observations to a more subsolar PVO pass through the Venus magnetosheath akin to the PVO orbits 432 and 438 shown earlier (see Figs. 3 and 4a,b). The draping signature in the MGS observations is consistent with the magnetosheath model, but the field pile-up must be due to either enhanced induced field in the ionosphere, and/or some extraordinary mass-loading effect or nonlocal crustal field interaction effect. As during the passes shown in Figs. 6a and b, when an inner magnetosheath boundary layer in excess of the magnetosheath and crustal...
models was observed, the strong southern hemisphere crustal fields were on the sunlit face of Mars during periapsis. However, this was not the case during periapsis. The orientation of the planet with respect to the incident solar wind is not a unique predictor of an enhanced inner magnetospheric field. Large IMF, and/or its relative solar wind conditions, also alter the appearance of the solar wind interaction.

These individual MGS orbit analyses raise the question of how far from Mars one can detect the effects of the crustal fields. To investigate this from the science planning orbit perspective, statistics were compiled on the strength of radial fields observed in various altitude intervals over the Martian surface. Radial fields are a good indicator of features of planetary origin because the draped inner magnetospheric fields are largely horizontal, except in the wake region. While the present analysis is limited to the field behavior in the terminator region, it gives a sense of where one expects classical magnetosphere models to best fit observations. The contour plots in Fig. 7 show the statistics of the radial field in selected altitude intervals. These illustrate that the effects of the crustal fields in the northern hemisphere are clear in the 200–250 km altitude range, but by 400–450 km the effects are largely absent. A higher altitude interval (4000–1650 km) that is still in the magnetosphere is included because as the altitude increases, the region sampled by MGS moves southward where the stronger southern hemisphere crustal fields might produce high altitude perturbations. In the science planning orbits, the spacecraft rose rapidly away from the planet so that the southern crustal fields effects were not seen before the spacecraft left the magnetosphere. Other MGS orbit phases will be useful for determining the extent of the strong southern crustal fields' effects in the southern hemisphere magnetosphere.
5. Discussion

A possible interpretation of what is observed at Mars as opposed to Venus or MGS pass 99-208 Periapsis 2 is based on the idea that reconnection between the draped magnetosheath field and crustal magnetic fields produces a boundary layer akin to that between the Earth’s magnetosphere and magnetosheath. This boundary layer is in part made up of transient remnants of reconnecting flux tubes and magnetopause flux tubes adjusting to the latter (e.g., Le et al., 1996 and references therein). At Mars such a layer should be more disorganized because of the relatively complicated magnetic field.
merging geometries that must exist with the patchy crustal fields (Mitchell et al., 2001) and the presence of substantial ionospheric effects. Nevertheless, the basic concept of a layer containing a mixture of reconnecting magnetosheath and planetary field flux tubes is similar.

To demonstrate the variety of possible merging scenarios between the Martian crustal fields and the interplanetary field, one can add a uniform "IMF", representing magnetosheath fields that might penetrate into the ionosphere, to the Parker model. This pedagogical device is often used with a dipole field to illustrate how IMF merging with Earth's magnetic field produces different topological connections between the magnetosphere and the IMF, depending on the IMF orientation. Field line projections were calculated for the case where 90° planetary longitude is at the subsolar point (here referred to as the Central Meridian or CM), and the viewer is looking at Mars from the Sun.

Fig. 8 displays the crustal field alone from this perspective, which places the strong southern hemispheric fields on the lower right. With the addition of the IMF, the merging geometry over the highly magnetized southern hemisphere and the weaker magnetized northern hemisphere regions can then be compared in one view. Fig. 9a shows the results of vacuum superposition of northward, southward, eastward and westward external fields of 4 nT magnitude and the Parker model. The field lines were initiated from uniformly spaced grids of points at the right and left sides of the box for the east (B_y = +4 nT) and west (B_y = −4 nT) IMF cases, and from the top and bottom for the north (B_z = +4 nT) and south (B_z = −4 nT) cases.

As for the global dipolar magnetospheres, there are regions of open (to interplanetary space) and closed magnetic field that depend on the IMF orientation. The dotted regions on the planet show the overall pattern of open regions for
Fig. 7: Statistics of absolute radial field strength in sheets at altitude for the 1200-scope observing orbits. Contours separate fields of (0.0, 0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, and 30.0) nT average magnitude. The large areas of medium grey indicate zone singularities. The effect of the northern hemispheric strong reversal field is clearly visible as the light patches around zero longitude in the 200–250 km range, but is gone by 400–500 km. The much stronger southern reversal field is not apparent in the higher altitude 1600–1800 km interval, just before M0 begins to have the central magnetosphere. The lower left panel shows the Parker model map for comparison.

Fig. 8: Plot of the Parker Mars crustal field model, with the 90° longitude CM taken as the origin. Corresponding magnetic field lines, started from a uniform grid on the surface, are shown from the same perspective on the right.

each case. These areas, which represent where in the upper atmosphere one might detect magnetosheath particles entering from above, became larger if a stronger penetrating external field is present, and smaller if it is weaker. The pattern details also depend on the externally imposed field strength, and of course on the crustal field distribution with which the external field merges. An interesting aspect of these diagrams is that the field line geometry resembles what would be obtained by adding the uniform fields to a weak global dipolar field aligned along Mars’ spin axis, as shown by Fig. 9b. The meaning of this resemblance is not clear. It is apparently a property of the extrapolated Purucker et al. (2000) model that at large distances where the higher order magnetic sources to dominate, an approximately rotation axis-aligned dipole persists. If real, it could be an underlying signature of the original magnetizing Martian dynamo field that left its strongest imprint on the southern hemisphere crust, and is still weakly affecting the solar wind interaction.

These simple superpositions of course neglect the external field damping from the diverging flow of the shocked solar wind plasma around the crustal magnetic field/ionospheric obstacle. In a rudimentary attempt to illustrate the damping effect, we can instead add the Lyon magnetosheath model field to the Parker model. Although realistic distortions of the field due to the dynamics and plasma physics of the interaction require at the very least a global MHD simulation approach, this is an interesting exercise for training one’s intuition in interpreting the data and for motivating more rigorous numerical treatments.

Two cases are shown in Fig. 10. Both assume the IMF is northward and 4 nT magnitude, but one places the strong crustal fields in the central meridian facing the Sun, while
the other places them in the solar wind wake. The accuracy of the field line tracing is limited close to the planet because of the 0.01 Mars radius step size used in the integration. Some field lines are started on a spherical grid 300 km above Mars, while a second (interplanetary) set originates on a rectangular grid that lies perpendicular to the IMF in the equatorial plane. Perhaps the most important point made by these displays is that field lines rooted in Mars contribute to the magnetosheath in numbers that depend on the planetary longitude at the subsolar point. Not surprisingly, when the strong southern hemisphere fields are in the subsolar region, more field lines merging with the magnetosheath drop off fields occur. This more extensive merging creates a ballooned region in the inner magnetosheath where the other originating on Mars become part of the inner magnetosheath. Thus the strength of the magnetosheath boundary layer must
depend on where it is noon on Mars. There is also certainly dependence on the IMF orientation, but we do not explore that aspect here because of the limitations of this simplified description.

6. Concluding remarks

It should be noted that the examples of MGS magnetosheath data discussed in this paper are a small sample of what is available from the archived science processing efforts, and represent the best-behaved subset. There are many passes where the Martian magnetosheath field appears to be tremendously variable, and is unlikely, based on statistics of IMF orientation behavior, that there are all cases of upstream wave convection from a quasiparallel subsolar bow shock. More likely, the typically distorted-looking magnetosheaths result from the combination of solar wind and IMF variations during a pass, solar wind ion kinetic effects, and the fact that the Martian obstacle to the solar wind is neither smooth and symmetric nor impenetrable as most magnetosheath models assume.

It will require some extremely sophisticated numerical modeling with both 3D MHD and/or global hybrid simulations to obtain a better sense of the dominating factors under various conditions. Moreover, it will require unusually large amounts of computer time to consider the different combinations of solar wind/IMF conditions and planet/Sun aspects that can occur in the Mars solar wind interaction. If these models confirm what was inferred from the present limited study, they will find the inner Martian magnetosheath includes a variable strength boundary layer containing remnants from IMF merging with the crustal magnetic fields on the subsolar hemisphere. The strength of that boundary layer will be greatest when it is daytime over the strong southern hemisphere crustal fields.

It is indeed fortunate that the almost ideal magnetosheath at Venus was studied first. A much more extensive survey of the Mars solar wind interaction is expected from the NOZOMI and Mars Express missions. The present results suggest how important it will be to have a good numerical simulation of the plasma interaction with the crustal fields in order to interpret the observations.

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