GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L18203, doi:10.1029/2005GL023126, 2005

Variability of the altitude of the Martian sheath

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Received 31 March 2005; revised 18 August 2005; accepted 25 August 2005; published 24 September 2005.

[1] Using electron energy spectra, we identify time periods when the Mars Global Surveyor (MGS) spacecraft is in or above the Martian magnetic pileup boundary (MPB). We use more than five years of data to develop a statistical picture of the location of the MPB relative to the MGS mapping altitude near 400 km. We show for the first time that the MPB location is sensitive to interplanetary magnetic field (IMF) orientation and to Martian season, and confirm a dependence upon solar wind pressure. We confirm that crustal magnetic sources raise the altitude of the MPB, and demonstrate that sheath electrons populate magnetic cusp regions in the southern hemisphere. During southern summer strong crustal fields near the subsolar point raise the altitude of the MPB over the entire dayside, implying that Martian crustal fields modify the solar wind interaction globally. **Citation:** Brain, D. A., J. S. Halekas, R. Lillis, D. L. Mitchell, R. P. Lin, and D. H. Crider (2005), Variability of the altitude of the Martian sheath, *Geophys. Res. Lett.*, *32*, L18203, doi:10.1029/2005GL023126.

1. Introduction

[2] The magnetic pileup boundary is a thin boundary in the Martian solar wind interaction that has been observed by several spacecraft at Mars, including Phobos 2, MGS, and Mars Express [*Grard et al.*, 1989; *Acuña et al.*, 1998; *Lundin et al.*, 2004]. A similar feature has been identified at comets [e.g., *Neubauer*, 1989] and at Venus [*Russell et al.*, 1979; *Bertucci et al.*, 2003]. This boundary has been variously termed; here we follow the convention of *Nagy et al.* [2004] and use the term "MPB".

[3] *Nagy et al.* [2004] summarize much of the current understanding of the MPB. It is identified in spacecraft observations as a sharp transition from a plasma regime dominated by compressed solar wind plasma (the sheath) to one significantly affected by planetary ions (the magnetic pileup region). Fits to observed MPB crossings suggest that it is typically located at altitudes of 650–1000 km at the subsolar point and 1200–1600 km at the terminator [*Trotignon et al.*, 1996; *Vignes et al.*, 2000], and variability in its position increases with solar zenith angle (SZA). Particle and field signatures associated with the MPB are observed at higher altitudes in the southern hemisphere, where Martian crustal fields are strongest [*Crider et al.*, 2002].

[4] A number of outstanding questions remain about the nature of the MPB. What is the mechanism of formation? Does the MPB have similarities in behavior or structure to features observed near Earth's magnetopause? How do crustal sources affect the physical structure of the MPB? And what controls its location? Previous studies based on Phobos 2 and MGS data disagree about whether the MPB responds to changes in solar EUV flux and solar wind pressure [*Trotignon et al.*, 1996; *Vignes et al.*, 2000; *Crider et al.*, 2003; *Verigin et al.*, 2004], and a response of the MPB location to changes in IMF direction has not been demonstrated using spacecraft data.

[5] This study focuses on factors controlling the location of the MPB. In this paper, we use electron energy spectra to detect when the MGS spacecraft is in the Martian sheath (in or above the MPB). We report the results of a statistical study during the mapping orbit period of MGS, confirming the response of this plasma boundary to pressure, and showing that its excursion down to 400 km varies with upstream IMF direction and Martian season.

2. Method

[6] Previous studies using MGS pre-mapping data associate the MPB with four separate signatures relative to the surrounding sheath [*Vignes et al.*, 2000; *Bertucci et al.*, 2003]: an increase in magnetic field strength, a decrease in magnetic field fluctuations, an enhancement in magnetic field draping, and a depletion in superthermal electron fluxes. The first is not always obvious during an MPB crossing [*Bertucci et al.*, 2004]. The next two signatures might be used to confirm a crossing of the MPB, but are difficult to use as detection criteria for data from the MGS circular orbit (used in this study), where the spacecraft may spend only very brief periods in the sheath. We use the fourth method in this study.

[7] Figure 1 shows three energy spectra (#2–4) typical of the Martian sheath and MPB, recorded during an MGS pre-mapping orbit. Spectrum 1, shown for reference, is from a region well below the MPB. It is significantly depleted in electrons with energies between 40 and a few hundred eV relative to the other spectra. Note that the magnitude and energy of the flux enhancements in the sheath/MPB spectra differ for each spectrum; enhancements are most easily recognized relative to fluxes in surrounding energies. We devised a technique to automatically select sheath and MPB spectra from the MGS data set, searching specifically for flux enhancements of a factor of two or more relative to a power law fit between energies outside 15–355 eV. Since our technique depends in part on a reliable estimate of low energy electron fluxes, it was necessary to omit times when photons and spacecraft photoelectrons had direct access to

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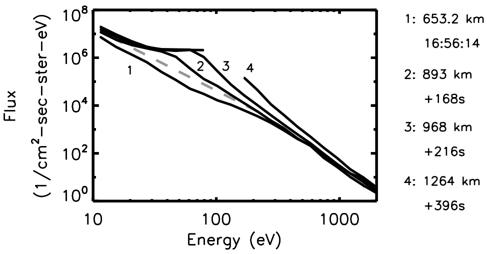

Figure 1. Sheath electron energy spectra from April 10, 1998. Altitude and UT time for each spectrum is indicated. Spectrum 4 saturated the ER instrument energy channels near 100 eV. The dashed line shows a power law fit to spectrum 2.

the instrument aperture. We excluded 6% of all mapping data, primarily at high northern latitudes.

[8] We tested our detection method on pre-mapping data from September 1997 until mid-1999, recorded when MGS was in an elliptical orbit that precessed in local time and periapsis latitude. During this period MGS made observations over a large portion of the solar wind interaction region, including the sheath at most dayside solar zenith angles. We applied our method to all uncontaminated pre-mapping observations (~70% of the data). Orbit-by-orbit examination of the data suggests that the technique successfully identifies most observations made in the sheath or MPB. The statistical results shown in Figure 2 support this statement. Sheath-like spectra are detected 80–100% of the time in the region between the locations of the best-fit bow shock and MPB determined by *Vignes et al.* [2000], and infrequently elsewhere. The majority of detections outside of the nominal sheath boundaries (bow shock and MPB) are valid; the boundary locations determined from magnetometer data have considerable scatter [*Vignes et al.*, 2000]. We estimate that ~5% of spectra are misidentified by the method. In addition to this error, the technique occasionally misidentifies spectra from the Martian tail region, recorded in the optical shadow of Mars. Most of these misidentified spectra are the flux spikes reported by *Mitchell et al.* [2001], which are believed to result from magnetic connection between magnetic cusp regions on the Martian nightside and a source of plasma in the deeper tail or sheath. For this reason we restrict this analysis of MGS mapping data to SZA < 90°.

[9] We take the results of Figure 2 and our orbit-by-orbit inspection as evidence that our technique provides a reasonable means of identifying observations of sheath electrons. We apply this technique to mapping observations from mid-1999 through February 2005. During this time period the MGS orbit was circular (near 400 km altitudes), polar, and fixed in local time at 2am/2pm. For each observation we extract information about the geographic location of MGS, Martian season, and whether sheath plasma was observed.

[10] Additionally, we use MGS magnetometer data to extract information about the upstream pressure and IMF direction for each orbit. We use a proxy method similar to that in *Crider et al.* [2003], and assume that upstream pressure is directly related to magnetic pressure in the Martian interaction region. For a given orbit we exclude observations above crustal sources and with solar zenith angles greater than 110° and fit the remaining field strengths to a cos (SZA) function to estimate the field strength at SZA = 0. Rather than convert this result to an upstream pressure we record only the field magnitude estimate for each orbit. IMF orientation must also be estimated directly from MGS data. For mapping orbits we assume that IMF clock angle is directly related to the orientation of the draped magnetic field near the planet. We define a draping direction as the median direction of the horizontal magnetic field between latitudes 50–60°N (in a latitude band without appreciable crustal magnetization). The local East direction is defined as 0°, and local North as 90°. Both proxies used in this work assume that upstream conditions do not vary over the two hour time span of an MGS orbit. We rely on the statistical nature of our analysis to reduce errors introduced by this assumption.

3. Results

[11] *Crider et al.* [2003] showed using MGS pre-mapping data that the position of the MPB is higher in the southern hemisphere than the northern hemisphere, indicating that crustal magnetic fields influence MPB location. Figure 3 shows that mapping data confirm this result, and further distinguishes between magnetized and non-magnetized regions of the southern hemisphere. The figure is shaded according to the fraction of observations in each 1° × 1° geographic bin having an electron energy spectrum characteristic of the sheath or MPB. The sheath is typically observed 5–20% of the time in mapping data. These percentages agree with those shown in Figure 1 for pre-mapping data near 400 km (≈0.12 R_M) on the dayside. The sheath is less likely to be observed over regions of crustal magnetic field than elsewhere. Over regions of the strongest magnetization sheath plasma can be excluded 100% of the time. Over regions of weaker magnetization (e.g. 0°E, 80°N or 340°E, 20°N) sheath plasma is sometimes observed, but less often than for surrounding regions.

[12] A few regions above crustal magnetic sources contain sheath plasma as much or more often than surrounding areas. These regions, most notably a linear feature from 150–210°E, 50°S and a large feature centered at 195°E, 25°S, are located where the measured magnetic field is strong and radial. They are magnetic cusps, where solar wind electrons have access to the Martian ionosphere near crustal fields. The presence of these regions demonstrates

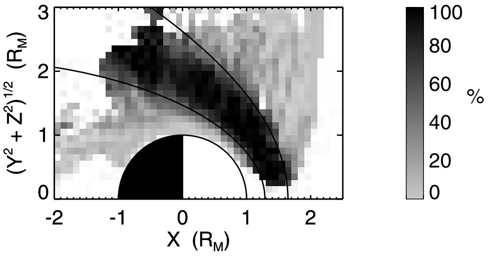

Figure 2. Percentage of sheath-like electron spectra measured by MGS in its pre-mapping orbit as a function of location in cylindrical coordinates. Independent fits to the location of the bow shock and MPB by *Vignes et al.* [2000] are shown for reference. 1R_M ≈ 3400 km.

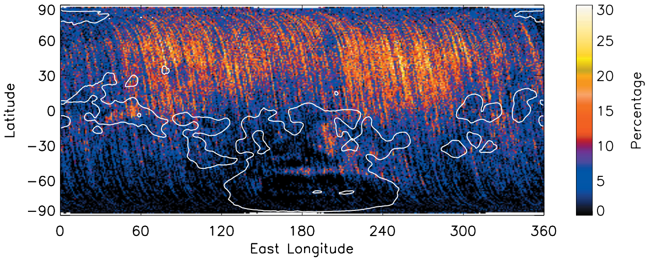

Figure 3. Percentage of sheath-like electron spectra in dayside mapping data as a function of geographic location. 20 nT field magnitude contours derived from nightside data are overlaid for reference.

that the shielding of portions of the atmosphere from the solar wind by crustal fields depends upon both their strength and orientation.

[13] Far from crustal fields Figure 3 shows a clear hemispheric asymmetry, with sheath plasma observed more often in the north. This effect may be due to the southern crustal magnetic fields, but the effect is seen even near 0°E, when the strongest sources are on the Martian nightside. The asymmetry is more likely due to the ellipticity of the MGS mapping orbit, which creates a 65 km altitude difference between observations at high northern latitudes and high southern latitudes. Therefore, when a hemispherically symmetric MPB is near apoapsis altitude, sheath plasma is only detected in the northern hemisphere (where apoapsis occurs). At the highest northern latitudes (60–90°N) the sheath is seen less often than at lower latitudes, despite the fact that MGS is located at higher altitudes in these regions. This effect results from the flared shape of the MPB, which is lower at the stagnation point of the solar wind flow than near the flanks of the interaction region. In the polar MGS mapping orbit low latitudes are closer to the stagnation point than high latitudes.

[14] Several factors control variability in the position of the MPB above a given region. We demonstrate the influence of three of those factors in Figure 4, which shows the percentage of sheath observations over the entire dayside as a function of time, upstream pressure proxy, and draping direction. Though absolute percentages vary for different geographic regions as shown in Figure 3, the relative trends evident in Figure 4 are present for all regions.

[15] Figure 4a shows the likelihood of observing sheath plasma as a function of time. Allowing for errors of up to 5% in our detection method, seasonal effects are clearly evident, with periodicity corresponding to Mars' orbital period. MGS is in the sheath more often when the Martian subsolar latitude is in the northern hemisphere (i.e. $L_S = 0$–180), and less often at other times. The probability is statistically indistinguishable from 0% during seasons when the strong southern crustal sources are closest to the subsolar point, indicating that as crustal fields move closer to the subsolar point they effectively keep sheath plasma from reaching 400 km at all dayside locations. Also notice that there is a hint of a long term variation, which could be attributed to changes in solar EUV flux over the solar cycle. As EUV flux declines from 2001–2004 the amount of photoionization at Mars should also decline, decreasing ionospheric densities and moving the solar wind interaction closer to the planet. This situation should increase the probability of observing sheath plasma, as shown in the panel. Such an effect would contradict the results of *Vignes et al.* [2000], and support the suggestion of *Trotignon et al.* [1996].

[16] Figure 4b shows the percentage of sheath observations as a function of our upstream pressure proxy. As upstream pressure increases, sheath plasma is more often able to penetrate to 400 km altitudes. These results from mapping data confirm those of *Crider et al.* [2003] from MGS pre-mapping data and of *Harnett and Winglee* [2003] using a Hall MHD simulation, but contradict the results of *Trotignon et al.* [1996] using Phobos 2 plasma wave data. We note that Phobos 2 yielded far fewer dayside crossings of the MPB, and their results may have been affected by a geographic sampling bias.

[17] Figure 4c shows the percentage of sheath observations as a function of IMF draping direction. When the subsolar latitude is in the southern hemisphere relatively few sheath spectra are observed, consistent with the results of Figure 4a. During these times, our data do not allow us to infer any variability with IMF direction. When the subsolar latitude is in the northern hemisphere, however, we can conclude that there is such a variation. Sheath plasma is observed less often when the draped field points locally southwest at 50–60° North latitude. The histogram peaks near 0° (locally eastward). This is the first demonstration that IMF direction affects the MPB, though previous investigators [e.g., *Brecht and Ferrante*, 1991; *Crider et al.*, 2003] have proposed such an effect.

4. Discussion

[18] Our detection method does not specifically identify the MPB in MGS observations, but instead identifies observations of sheath plasma. We are careful to interpret our results as demonstrating variability in the access of sheath electrons to 400 km altitudes. Since the MPB is generally considered to be the inner boundary of the sheath, it is likely that we have also demonstrated the variability in

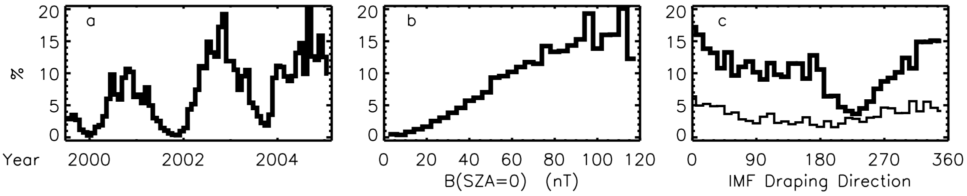

Figure 4. Histograms of frequency of sheath-like spectra as a function of (a) time, (b) upstream pressure proxy, and (c) IMF draping direction for times when the subsolar latitude was in the northern hemisphere (thick line), or in the South (thin line).

its position relative to 400 km. *Harnett and Winglee* [2003] assert that the MPB does not form at all above the southern crustal magnetic sources, and that a thicker current region analogous to a magnetopause forms in those regions instead. We make no distinction between the MPB and a mini-magnetopause in this work; it remains to be seen whether other signatures associated with MPB and magnetopause crossings behave in the same way as the electron energy spectrum.

[19] It is often suggested that the solar wind interaction at Mars is essentially that of an unmagnetized body perturbed locally by crustal magnetic fields [*Nagy et al.*, 2004]. Our results demonstrate the degree to which strong crustal fields influence this interaction. We showed that sheath plasma is often observed in magnetic cusps on the Martian dayside, suggesting that the MPB/magnetopause is either permeable to solar wind electrons in regions of radial magnetic field or quite "lumpy". Support comes from the ASPERA-3 experiment on Mars Express, which has observed solar wind particles down to 270 km altitudes [*Lundin et al.*, 2004]. And during southern summer crustal fields prevent sheath plasma from accessing 400 km altitudes over the entire dayside.

[20] We showed in Figure 4c that the MPB altitude in the northern hemisphere at 2pm is controlled in part by the IMF draping direction. The effect may be hemispherically asymmetric, resulting from Hall currents [*Brecht and Ferrante*, 1991], or from mass loading of the plasma flow past the planet [e.g., *Nagy et al.*, 2004]. If the observed effect is instead global, another explanation must be provided. Discrimination between these three possibilities is complicated by the fixed mapping orbit of MGS, the strong southern crustal fields, and uncertainty in extrapolating draping direction to upstream IMF orientation.

[21] Our results give a statistical picture of how the lower boundary of the Martian sheath responds to different parameters in the solar wind interaction. In many ways the boundary behaves like a magnetopause, moving up and down according to upstream pressure, the strength of the planetary field, and IMF direction. Our analysis is possible because MGS has made so many observations from a fixed orbit. But several orbital parameters (SZA, local time, latitude, and altitude) are convolved in this orbital configuration. Ongoing analysis of MGS pre-mapping data and future analyses of data returned from the Mars Express spacecraft will continue to reveal the variability in the location of the MPB throughout the entire interaction region.

[22] **Acknowledgments.** D. Brain thanks J. Luhmann, K. Maezawa, and M. Øieroset for useful discussions. This research was supported through NASA grant NNG04GL35G-05/06.

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