Observations of the latitude dependence of the location of the martian magnetic pileup boundary

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[1] We report observations that show the dependence of the altitude of the magnetic pileup boundary (MPB) at Mars on planetary latitude. As seen by the Mars Global Surveyor Magnetometer/Electron Reflectometer instrument, the MPB is further away from Mars on average at southern latitudes than at northern latitudes. The data are consistent with a MPB distance mapped to the terminator plane that does not vary with latitude in the northern hemisphere, but increases with increasing southern latitude in the southern hemisphere. We also report increased variability in the MPB distance within the longitude range 90–270° E. longitude in the southern hemisphere which is the region that contains the strongest crustal magnetic fields. These trends are most obvious in a planet-fixed coordinate system, indicating a planet-fixed driver of the MPB location. The proposed mechanism is the local diversion of shocked solar wind flow by crustal magnetic fields. *INDEX TERMS:* 2780 Magnetospheric Physics: Solar wind interactions with unmagentized bodies; 6225 Planetology: Solar System Objects: Mars; 5443 Planetology: Solid Surface Planets: Magnetospheres (2756); 2459 Ionosphere: Planetary ionospheres (5435, 5729, 6026, 6027, 6028)

1. Introduction

[2] The magnetic pileup boundary (MPB) is a permanent feature of the solar wind interaction with Mars. It is located downstream of the bow shock and upstream of the ionopause. In Mars Global Surveyor (MGS) Magnetometer/Electron Reflectometer (MAG/ER) data, it appears as a layer in which magnetic fields measured by MAG increase over a short vertical drop [*Vignes et al.*, 2000]. Simultaneously, the electron fluxes measured by the ER attenuate in a manner consistent with electron impact ionization of the oxygen and hydrogen exosphere by solar wind electrons [*Crider et al.*, 2000]. Coincident with this location, wave activity in MAG data declines with decreasing altitude.

[3] Previously, instruments onboard PHOBOS-2 detected a boundary in a location consistent with the MPB location when comparing their respective fits [*Trotignon et al.*, 1996; *Vignes et al.*, 2000] as shown in Figure 1. The PHOBOS-2 fit is based upon 45 crossings near solar maximum whereas the MGS fit is based on 488 crossings during low solar activity. PHOBOS-2 instruments ASPERA [*Lundin et al.*, 1989] and TAUS [*Rosenbauer et al.*, 1989] saw the MPB (then called "planetopause") as a termination in solar wind proton flux in the same position as the magnetometers sensed an increase in magnetic field values [*Riedler et al.*, 1989]. These attributes indicate that the solar wind protons are interacting through charge exchange with the planetary exosphere. We put this together with the complementary MGS observations of electron impact ionization and wave activity and the MPB appears to be the transition to the region in which the planetary exosphere becomes substantial in determining the plasma properties.

[4] It is important to note that the MPB is neither a pressure balance boundary nor an impenetrable obstacle to the solar wind flow. ER data show the presence of solar wind electrons everywhere above the ionopause [*Mitchell et al.*, 2000]. Therefore, the solar wind electrons and magnetic field do penetrate the MPB. The MPB simply marks the transition from shocked solar wind plasma to flow lines mass-loaded by exospheric ions. That is, the MPB delimits where a flow line that has interacted substantially with the exosphere is tangent to a flow line that has not. As such, any parameter that affects the solar wind flowlines' locations or the exospheric properties will affect the position of the MPB.

[5] Here we investigate the effects that the strongly magnetized regions of Martian crust have on the solar wind interaction with Mars. The magnetic pressure in these localized regions of strong magnetic fields is high enough to balance the solar wind pressure at high altitudes [*Acuña et al.*, 1998]. However, these are highly localized features. Elsewhere the solar wind flow is deflected by the Martian ionosphere. In effect, the mini-magnetospheres protrude into the shocked solar wind flow around Mars and locally divert it to altitudes higher than the nominal ionopause height. The result is that Mars represents an asymmetric obstacle to the incident solar wind flow. This work will show that the unusual obstacle shape is reflected in the position of the MPB.

2. MGS Observations

[6] We analyze the position of the MPB from MGS MAG data using the aerobraking and science phasing orbital periods. These data are from the time period of Sept. 1997–Nov. 1998. During this time, the polar, elliptical orbit of MGS evolved slowly in period, local time, and latitude of periapsis. This allowed sampling over a large range of positions in planet-fixed, solar-ecliptic, and IMF-related coordinates.

[7] The MPB has a thickness of tens - hundreds of km. We use the bottom of the boundary for the work presented here. Plotted in Figure 2 are Mars-centric distances from 777 MGS MPB crossings as a function of solar zenith angle (SZA). The MPB distance is dependent on the SZA and is well described by a conic section, such as the fit shown [*Vignes et al.*, 2000]. The observed scatter in the

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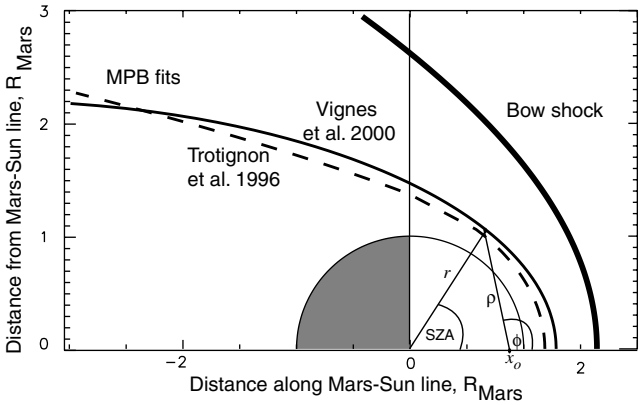

Figure 1. Fits to the magnetic pileup boundary assuming axial symmetry are shown from Phobos-2 data (dashed line) and MGS data (solid line). The Sun is to the right. Also shown are the relationship of the coordinate system used in (1) to the standard coordinates of distance, *r*, and solar zenith angle, SZA.

plot is due to other factors, such as changes in solar wind conditions, exospheric densities, the obstacle boundary, etc. In order to unravel these effects, we must first remove the SZA dependence.

[8] We invoke a mapping function to project the observed MPB distance to a common SZA. The distances from the points in Figure 2 are mapped by a conic section using the parameters from *Vignes et al.* [2000] to the distance expected that the boundary would occur in the terminator plane, or 90° SZA, by:

$$\rho = \frac{L}{1 + \epsilon \cos\phi} \tag{1}$$

where ϕ is the angle from the Sun-Mars line with the origin at a point (x_o, 0) with x_o at 0.78 R_M, ρ is the distance, L is the semilatus rectum, and $\epsilon = 0.90$ is the eccentricity. The coordinates are shown on Figure 1 for reference. We hold ϵ and x_o constant and determine the L value required for the spacecraft position (ρ, ϕ). Using the derived L, we then find the distance at the terminator given x_o, L, and ϵ. We stress that this mapping method is only used as a way to compare data from all solar zenith angles and makes no suggestion about the actually variation in the MPB distance at the terminator. An alternative method of would be to look at the difference in the measured MPB position and the average location at the same solar zenith angle. This alternative method would give an increasing deviation at high solar zenith angles, as can be seen in Figure 2.

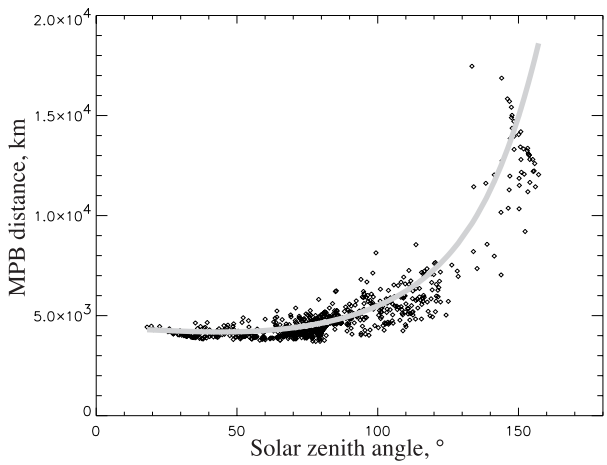

Figure 2. The actual MPB crossing distance is plotted by solar zenith angle. Superposed on the data points is the fit to the MPB position from *Vignes et al.* [2000].

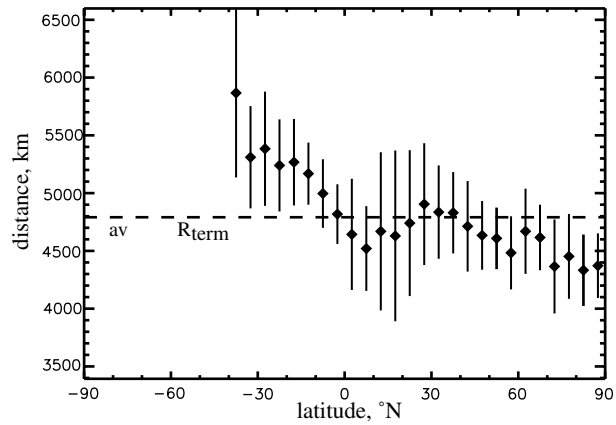

Figure 3. We average the MPB crossing distance mapped to the terminator plane in 5° latitude bins. The error bars show one standard deviation from the average for each bin.

2.1. Latitude Dependence

[9] We take the mapped terminator distance using (1) from every MGS MPB crossing, average over 5° latitude bins, and plot the results in Figure 3 together with error bars representing plus and minus one standard deviation. One single crossing south of 40°S is excluded. If the crustal magnetic fields do affect the boundary position, it should appear as a change in the observed distance and/or variability at southern latitudes because the crustal sources are concentrated there [*Acuña et al.*, 1999]. Inspection shows a general trend of increasing distance with increasing southern latitude in the southern hemisphere. The northern hemisphere data are consistent with a horizontal line fit within the error bars. Sampling errors preclude interpretation of small scale features in this plot. Nevertheless, Figure 3 reveals that the data can not be fit by a single horizontal line through all latitudes. Therefore, the MPB altitude has a dependence on planetary latitude in which the southern hemisphere data clearly display an increase in the average MPB distance mapped to the terminator plane compared to the northern hemisphere. The average value for dayside southern

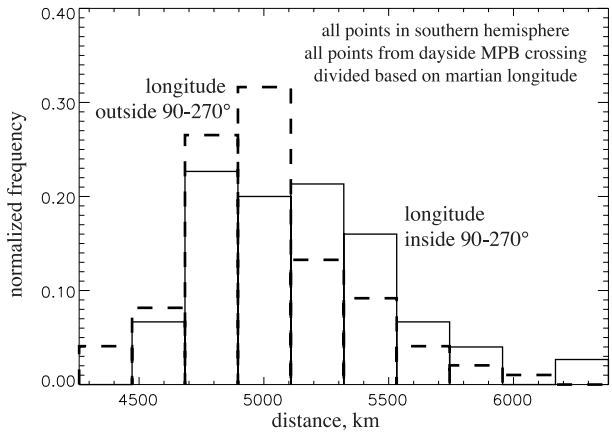

Figure 4. Two histograms show the distribution of the terminator distance of the MPB by longitude range. The average location is close to the same for the two distributions. However, the distribution is narrower in the region without crustal magnetic fields (dashed line) than the 90–270° longitude range (solid line) which has strong fields.

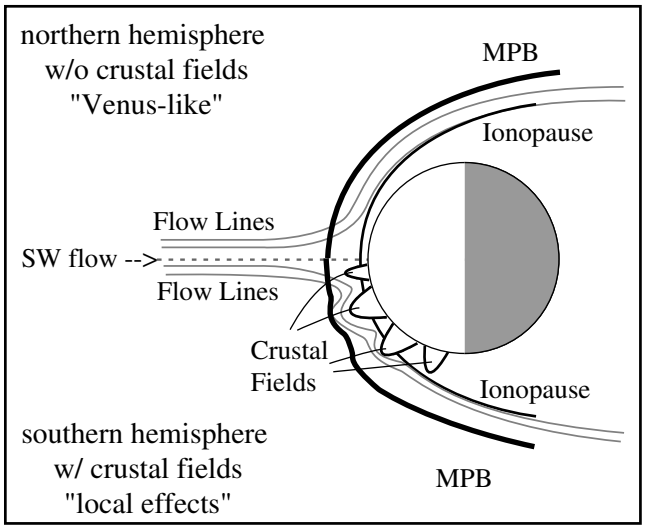

Figure 5. Cartoon showing how the crustal fields divert the shocked solar wind flow around Mars. The northern hemisphere flow lines follow the ionopause around the planet. In the southern hemisphere, the lowest flow line is lofted to higher altitudes to go around the mini-magnetospheres.

hemisphere crossings is 200 km higher than for dayside northern hemisphere crossings.

[10] It is important to consider external factors that might influence the statistics here. We assume that short time scale variations due to changing solar flux and solar wind dynamic pressure from orbit to orbit average out in statistical analysis of 777 samples. Longer time scale variations due to seasonal and solar cycle effects could affect the data. Fortunately, by having MPB crossings from both inbound and outbound spacecraft passes, both the northern and southern hemispheres were often sampled in the same orbit. This allows us to assume that both hemispheres are sampled under roughly similar conditions. Inspecting the time evolution of the MPB crossings over 60% of a Martian year, we see no distinct seasonal effect in the MPB position. Neither do we observe an effect due to the rising solar cycle in the period of observations.

[11] Although there are MPB crossings at all northern latitudes, due to the spacecraft orbit there are no MPB crossings at high southern latitude where the strongest crustal fields occur. Therefore, we can not currently determine how the trend continues in the vicinity of the strongest magnetic fields.

2.2. Longitude Dependence

[12] The crustal magnetic fields have a small spatial scale length and are concentrated in one region in planetary latitude and longitude. We look for a longitude dependence by inspecting the difference in the MPB location inside and outside of the region of strong crustal fields. There are 174 dayside MPB crossings in the southern hemisphere of which 76 are between 90–270° E. longitude, the region of strongest crustal fields. MGS sampling in planetary longitude was essentially randomly distributed in time. Figure 4 shows the histograms of the MPB distance mapped to the terminator plane from the two longitude ranges. Although the averages of the distributions are fairly close together, 5180 km near the crustal fields and 5040 km outside of the region, the distribution for the passes over crustal fields is much broader. It has a standard deviation of 490 km vs. 340 km away from the crustal fields. This shows increased variability of the MPB position due to the presence of the strong crustal fields.

3. Discussion

[13] Although solar wind pressure variations are expected to account for most of the scatter about the average location, this effect is superposed on a structure to the MPB in planetary latitude. A planet-fixed driver is indicated by the average MPB location in planetocentric coordinates. Specifically, the structure in latitude and longitude suggests that the driver is the crustal magnetic fields. We propose the following mechanism to explain the relationship.

[14] In order to understand the effects of the crustal magnetic sources, let us consider first the flow of the solar wind around Mars away from the sources. Without crustal magnetic fields, the solar wind is diverted around the Martian ionosphere, much like the situation at Venus. The top half of Figure 5 depicts the geometry in the Venus-like case. The flow lines that approach Mars near the sub-flow point follow the ionopause as it naturally flares to higher altitude with increasing solar zenith angle. The MPB forms upstream of the ionosphere, delimiting the transition from plasma that has not interacted significantly with the planetary exosphere from the plasma that has. The MPB altitude in this region will vary with external drivers that affect exospheric and flow properties.

[15] However, the obstacle shape is complicated by the presence of localized regions of strongly magnetized crust that exist predominantly in the southern hemisphere of Mars [*Acuña et al.*, 1999]. They are observed at altitudes up to several hundred km higher than the nominal ionopause height and have horizontal scale lengths also on the order of several hundreds of km. The magnetized, shocked solar wind flow must be diverted around these protrusions as it encounters them, as illustrated in the bottom half of Figure 5. The lowest flow line, which would have followed the ionopause around the planet in the northern hemisphere, is diverted to higher altitudes in the southern hemisphere because of the crustal fields.

[16] The redirection of flow lines alters where the MPB will be observed because flow lines that interacted with the exosphere are moved to higher altitudes over the anomalies. Because the crustal fields are concentrated south of the Martian Dichotomy Boundary, we expect the position of the MPB to be higher on average in the south. In addition, the flow in the Martian magnetosheath is subsonic, which allows the flow to adjust downstream of the mini-magnetospheres. Therefore, the flow lines and MPB return to their nominal altitudes behind the protrusions. This predicts a larger scatter in MPB altitudes where crustal fields are present. Whereas the MPB is expected to vary in altitude in the northern hemisphere due to external parameters, the MPB altitude in the southern hemisphere will additionally have a planet-fixed altitude driver as the crustal fields rotate under the Sun. A similar dependence on bow shock position due to crustal magnetic fields is exhibited in MHD models of the solar wind interaction with Mars [*Liu et al.*, 2001].

4. Conclusions

[17] We observe in MGS MAG data that the magnetic pileup boundary is further from Mars in the southern hemisphere than in the northern hemisphere on average. This effect is evident from studying the latitude dependence of the observed crossings mapped to the corresponding distance at a common solar zenith angle.

[18] In addition, we report a longitude dependence on the variability of the position of the MPB. In the longitude range containing large crustal fields in the southern hemisphere, there is a wider spread in the observed MPB positions than in all of the northern hemisphere as well as in the southern hemisphere in the longitude range away from the strong crustal sources.

[19] The spatial position of the MPB depends on the size and shape of the obstacle to the solar wind flow and on the solar wind flow parameters. Therefore, the position responds to changes in

solar wind, atmospheric, and ionospheric parameters as well as to the motion of the planet-fixed protrusions to the flow. These relations between the MPB location and planet-fixed spatial coordinates are observed assuming that perturbations in the MPB location due to solar wind and exospheric conditions average out in the statistical treatment.

[20] Both the latitude and longitude dependence of the position of the Martian MPB are consistent with the solar wind flow being diverted to higher altitudes due to the presence of strong paleomagnetic fields at Mars. Having data at high southern latitudes is required to firmly establish this effect.

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