

INTERPLANETARY MAGNETIC FIELD CONTROL OF THE MARS BOW SHOCK:  
EVIDENCE FOR VENUSLIKE INTERACTION

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**Abstract.** The Mars bow shock location and shape have been determined by examining the PHOBOS spacecraft magnetometer data. Observations show that the position of the terminator bow shock varies with interplanetary magnetic field orientation in the same way as at Venus. The shock is farthest from Mars in the direction of the interplanetary electric field, consistent with the idea that mass loading plays an important role in the solar wind interaction with Mars. We also find that the shock cross section at the terminator plane is asymmetric and is controlled by the interplanetary magnetic field as expected from the asymmetric propagation velocity of the fast magnetosonic wave. Comparing with earlier mission data, we show that the Mars shock location varies with solar activity. The shock is farther from Mars during solar maximum. Thus the solar wind interaction with Mars appears to be Venuslike, with a magnetic moment too small to affect significantly the solar wind interaction.

### Introduction

The solar wind is heated and deflected around a planetary obstacle by a fast shock wave. This shock wave, or bow shock, provides the earliest evidence in the solar wind frame of the approaching obstacle to the flow except for upstream waves. Because the bow shock location and shape are determined by the size and shape of the effective obstacle, a bow shock study can give insight regarding the interaction of the solar wind with the planetary obstacle. In this sense, the bow shock provides a diagnostic of the obstacle properties.

Although it has been noted that the interaction of the solar wind with Mars may be like that of Venus, e.g., with an unmagnetized planetary body having an ionosphere [see Luhmann et al., 1987 and references therein], the question of the existence of an intrinsic magnetic field at Mars is still controversial. Previous missions (before the PHOBOS mission) to Mars (Mariner 4 and Mars 2, 3, and 5) all detected a bow shock [cf. Vaisberg et al., 1990]. However, none of them reached sufficiently low altitudes to conduct the in situ studies of the ionosphere and the solar wind interaction necessary to resolve the controversy. Due to the limited set of data on the Martian ionosphere, the location of the bow shock was exploited to estimate the dimensions of the

obstacle on the dayside [cf. Spreiter et al., 1970]. An obstacle which cannot be much larger than the size of the planet itself was inferred from the bow shock position [e.g., Russell, 1977; Slavin and Holzer, 1981; Vaisberg et al., 1990]. Upper limits were placed on the Martian magnetic moment by different authors (see review by Luhmann et al. [1991]).

One of the main purposes of the PHOBOS magnetic field investigation (Riedler et al., 1989) is to understand the interaction of the solar wind with Mars. Since the periapsis of the PHOBOS spacecraft is significantly above the ionosphere, we cannot directly probe regions where we might expect to see a weak planetary field. Thus, current estimations of the Martian magnetic moment depend very much on understanding the solar wind interaction with the planet. In this paper, we examine the location of the near-terminator bow shock of Mars and determine the shape of the bow shock. This is followed by the examination of interplanetary magnetic field (IMF) control of the shock location. We also compare our shock location results with results from earlier missions.

### Bow Shock Location

The size of the obstacle to the solar wind depends on the size of the planetary intrinsic magnetic moment for the magnetized planets. Thus it is of interest to determine where the bow shock is located. The PHOBOS mission provided three crossings near the subsolar point with the elliptical transfer orbits, and about 100 bow shock crossings in the final circular orbit at close to 2.8 Mars radii. Schwingenschuh et al. [1990] found that the subsolar shock is located at 1.47 Mars radius ( $1 R_M = 3390$  km), close to that obtained by earlier researchers (cf. Table 4 of Vaisberg et al. [1990]).

To determine the location of the terminator bow shock location, we examined 45-s resolution magnetic field measurements of PHOBOS in circular orbits. About 100 crossings were identified. Figure 1 shows the shock crossing radii as a function of time. The difference in radii between the inbound (open circles) and the outbound crossings is due to the noncircularity of the orbit. The orbital eccentricity and semimajor axis were changed several times, notably on March 7, March 15, and March 21, 1989.

The difference in X location (in Mars solar orbital or MSO coordinates) between the inbound and outbound crossings was used by Schwingenschuh et al. [1990] to calculate an aberration angle of  $3.8^\circ$  which would be caused by a solar wind velocity of 365 km/s in contrast to the actual

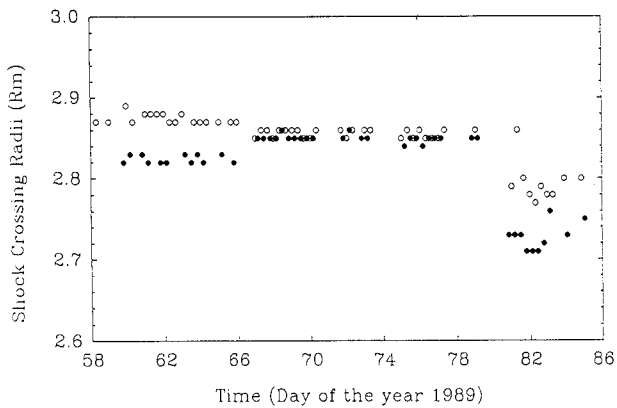


Fig. 1. Bow shock crossing radial distance versus time. The open circles are inbound crossings (dusk), and the solid circles outbound (dawn).

solar wind velocity of 500 km/s. Moreover, the difference in the X location of the shock crossings is due to several factors. First, as mentioned above, the PHOBOS orbit was not perfectly circular. Second, there is a dawn-dusk asymmetry in bow shock location as a result of the prevailing IMF spiral orientation. The quasi-parallel shock dominates the dawnside while the quasi-perpendicular shock dominates the duskside. As a consequence of the varying speed of propagation of the magnetosonic wave, or possibly a kinetic effect, the part of the shock on the quasi-parallel side is closer to the planet than the part on the quasi-perpendicular side [Thomas and Winske, 1990; Zhang et al., 1991]. This effect causes an apparent aberration on the bow shock in the same direction as the motion of Mars perpendicular to solar wind. Therefore one cannot simply use the difference between the dawn and dusk shock distances to calculate the aberration angle of the solar wind. In this study, the aberration angle was calculated using an average measured speed of about 500 km/s solar wind velocity [Schwingenschuh et al., 1991] and average Mars orbital velocity of 24 km/s. This gives an aberration angle of  $2.7^\circ$ , which was used to rotate all data into an aberrated coordinate system. The shock crossings were then extrapolated to the terminator plane using the equation

$$R = \frac{L}{1 + \epsilon \cos(SZA)}$$

where R is the observed planetocentric distance, L the terminator radius,  $\epsilon$  the eccentricity, and SZA the solar zenith angle in the aberrated coordinate system. This gives a median terminator shock radius of  $2.65 R_M$  and eccentricity of 0.80. These values are somewhat different than those obtained earlier by Schwingenschuh et al. [1990] because we used an improved aberration angle and we refined our identification of a number of bow shock crossings. Figure 2 shows the shock terminator radius as a function of time. The straight line is the median shock radius. It is apparent that the location of the terminator bow shock is very variable during the PHOBOS circular orbit phase. This variability could be due to the variation of solar wind plasma properties, such as Mach number, IMF orientation and/or EUV flux

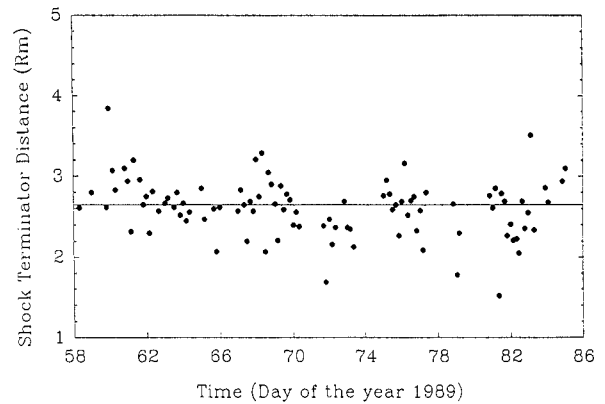


Fig. 2. Location of bow shock extrapolated to the terminator plane using an ellipse focused on the center of Mars with eccentricity of 0.80. An aberration angle of  $2.7^\circ$  has been taken into account. The straight line is the median of the terminator shock distance, which is  $2.65 R_M$ .

[Russell et al., 1988]. Also this variability could be due to solar wind dynamic pressure variations if there exists an intrinsic magnetic field or possibly due to the large gyroradii of reflected ions [Moses et al., 1988]. The IMF control of the terminator shock location is the subject of the present investigation.

#### Interplanetary Magnetic Field Control

The study of the solar wind interaction with Venus showed that the neutral atmosphere plays an important role. Photoionization, charge exchange with solar wind protons, and impact ionization convert substantial numbers of the neutral atmospheric particles, mostly oxygen, above the ionopause into ionized atoms. These ions are picked up by the  $E = -V \times B$  convection electric field of the solar wind. They have been observed by the Pioneer Venus plasma analyzer [Mihalov and Barnes, 1982; Moore et al., 1990]. Mass loading slows down the solar wind because of momentum conservation. The effect of mass loading on the bow shock position is expected to be most important for situations when the IMF and solar wind flow are perpendicular since the electric field is at its maximum and the velocity of the picked-up ions at its maximum at this time. It has been shown that the position of the Venus terminator bow shock depends on the cone angle, which is the angle between the direction of the solar wind and IMF [Alexander et al., 1986; Russell et al., 1988]. This appears to be in accord with simulations [Belotserkovskii et al., 1987] but has yet to be confirmed by other groups. Figure 3 shows the Mars terminator shock location as a function of cone angle. The straight line shows the least squares fit to the shock position. In constructing this plot, we only used data from periods when the spacecraft was inertially stabilized so that the IMF direction is well determined. There are only 27 data points available in this spacecraft mode. While this plot shows an apparent effect of the cone angle on the shock location at Mars as we found at Venus, the correlation coefficient is only 0.1. The average shock location seems to be farther from

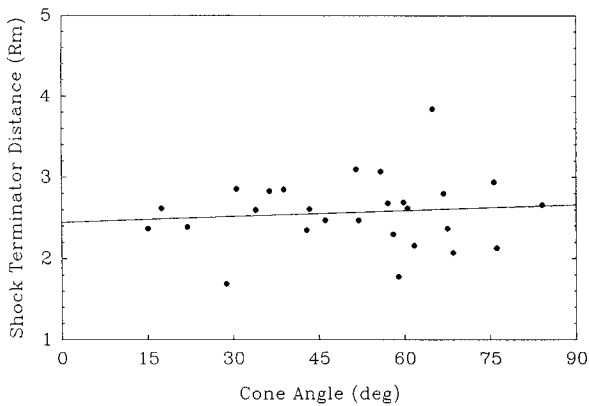


Fig. 3. The cone angle dependence of the location of the terminator bow shock. The cone angle is the angle between the direction of the interplanetary magnetic field and the average solar wind flow direction. Solid circles give the shock position during the inertially stabilized observing session. The straight line is the linear best fit of the 27 individual measurements.

the center of Mars when the IMF is perpendicular to the solar wind (large cone angle). While we expect mass loading due to oxygen to be less at Mars than at Venus [Russell et al., 1983], we note that evidence for mass loading due to hydrogen has been found at Mars which is not seen at Venus [Russell et al., 1990].

It has been found that at Venus the shock is farther from the planet in the hemisphere of locally upward convection electric field than in the opposite hemisphere [Alexander et al., 1986; Russell et al., 1988]. Here, north-south refers to the directions perpendicular to the upstream transverse IMF direction. This bow shock location asymmetry has been attributed to the asymmetric mass loading of the magnetosheath by large-gyroradius picked-up oxygen ions. Figure 4 shows the terminator distance versus the IMF clock angle which is here defined as the angle between the radius vector through the spacecraft and the upstream magnetic field projected on the terminator plane. Again we used data only from inertially stabilized sessions. Also shown in this display are medians of the north and south shock radii, respectively. The median north shock location lies at  $2.68 R_M$  while the south shock location lies at  $2.47 R_M$ . Thus there is a  $0.21 R_M$ , or 8%, difference in the shock locations, with the shock at the greater distance in the northern hemisphere where the picked-up ions go upward. This number is the same as the 8% difference at Venus during solar maximum [Alexander et al., 1986].

Another type of asymmetry in the Venus bow shock position is a magnetic pole-equator asymmetry in the terminator plane that makes the shock cross section elliptical [Alexander et al., 1986]. The shock diameter is larger across the polar direction than across the equatorial direction. In order to determine if this is also true at Mars, we replot in Figure 5 the terminator bow shock location as a function of clock angle, but mix the north and south pole data to improve the statistics. Hence the clock angle  $0^\circ$  here refers to the equator, and  $90^\circ$  to the pole,

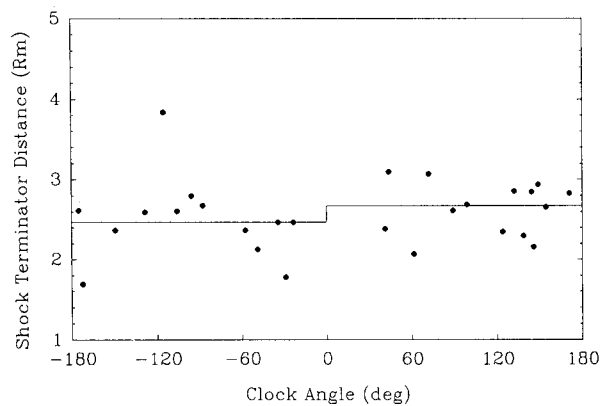


Fig. 4. The terminator shock location as a function of IMF clock angle. The clock angle is measured from the projection of the interplanetary magnetic field onto the terminator plane. Positive clock angle corresponds to north, and negative to south, in a magnetic coordinate system where the projected field defines the equator. Solid lines show the median positions.

regardless of whether it is in the north or south. Figure 5 shows that there is a pole-equator asymmetry at Mars as at Venus. Although the correlation coefficient is only 0.3, the correlation is significant at the 80% level. This asymmetry could be due to either the quasi-parallel shock/quasi-perpendicular shock effect described earlier or to a mass-loading effect. To distinguish between them, a larger data set is needed to separately analyze the shock shape for different solar EUV intensities, for example.

One can argue that the above results prove that the mass-loading effect is important in controlling the Martian bow shock location, but the existence of competing MHD effects leaves some ambiguity. Since the number of ions produced in the magnetosheath varies with solar activity through changes in the EUV intensity and exospheric density, one may expect that the Martian bow shock location would also change during the solar cycle as at Venus [Alexander et

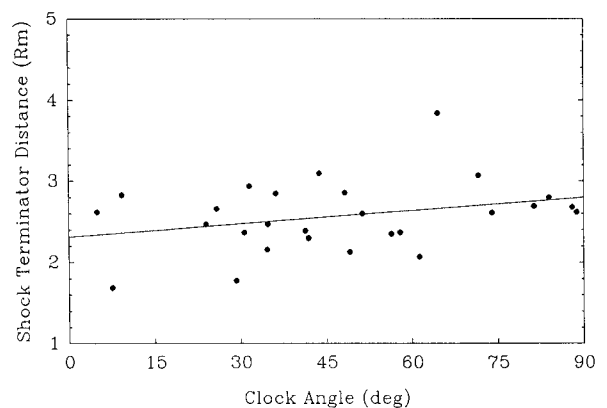


Fig. 5. The clock angle dependence of the terminator shock location. Here small clock angle is near the equatorial region, and large clock angle is near the polar region, in the magnetically defined coordinate system.

al., 1986; Russell et al., 1988]. Figure 6 shows conic section fits to the location of the Martian bow shock in aberrated cylindrical coordinates [Russell et al., 1991]. Also drawn in Figure 6 are the shocks for 1972/1974 as determined from the Mars 2, 3, and 5 spacecraft data [Vaisberg et al., 1990], and the Venus bow shock at solar maximum and solar minimum [Zhang et al., 1990]. Note that the PHOBOS data were obtained near solar maximum, and Mars 2, 3 and 5 data in the declining phase of solar activity. The Mars and Venus bow shocks both vary in location with solar activity and vary comparable amounts for comparable changes in solar activity. Thus, mass-loading effects on the Mars bow shock position appear certain.

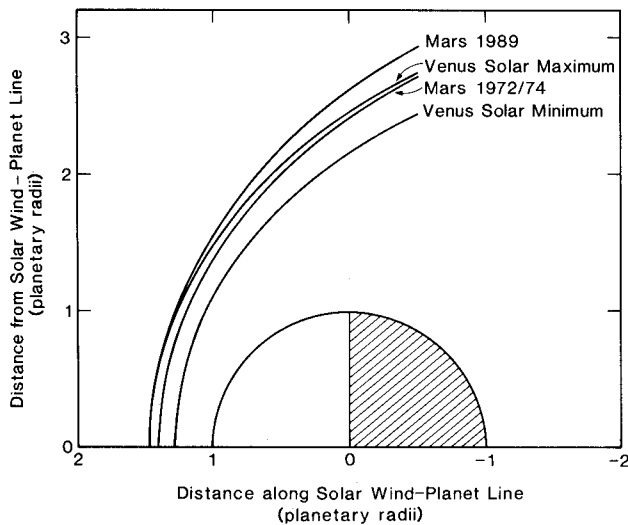


Fig. 6. Location of Venus and Mars bow shock in aberrated cylindrical coordinates. All shock locations have been fit with simple planet-centered conic sections.

### Discussion and Conclusions

As mentioned earlier in this paper, the bow shock position provides a tool to understand the nature of the solar wind obstacle at Mars. A subject of controversy for many years has been the question of whether Mars is magnetized or stands off the solar wind through a Venuslike interaction. To resolve this issue completely, in situ measurements from low-altitude spacecraft are required. Nevertheless, our study provides indirect evidence that the solar wind interacts primarily with the ionosphere at Mars, as at Venus, rather than with an intrinsic field.

Yeroshenko et al. [1990] reported that the magnetotail of Mars is very sensitive to the direction of the interplanetary magnetic field. Their study suggested that Mars has an induced magnetotail like that of Venus, which further reinforces the present conclusion concerning the ionospheric nature of the obstacle. One additional way to infer the nature of the obstacle is to study the compressibility of the bow shock. If there is a small intrinsic field which stands off the solar wind at low altitude, one would expect the bow shock location to exhibit a sixth root dependence upon solar wind ram pressure

[e.g., Slavin and Holzer, 1982]. Ionospheres, in contrast, are far less compressible and exhibit only a very weak dependence on solar wind ram pressure. Schwingenschuh et al. [1991] recently examined the compressibility of the Mars bow shock. They found that at Mars there is only a very weak dependence of the shock location on solar wind dynamic pressure, as at Venus. Thus, four independent pieces of observational information (the bow shock position dependence on the IMF, the solar cycle effect, the apparent incompressibility of the obstacle, and the induced magnetotail), all point to consistent conclusions.

We note that observationally we find similar dependences of the radius of the bow shock of Venus and Mars on the location of the observation relative to the projected IMF direction, i.e., on the clock angle of the observer relative to the magnetic field. When the observation is made in the direction of the interplanetary electric field, the bow shock is further away from the planet than in the opposite hemisphere. This asymmetry is in contrast to that found by Brecht [1990], who found in a non-mass-loaded hybrid code that the clock angle of the most distant bow shocks was dependent on the size of the planet. It was on the same side as we have found it for a Mars-sized planet and opposite our findings for a Venus-sized planet. This difference may be associated with the expected mass loading by picked-up ions.

In summary, we find that the interplanetary magnetic field controls the bow shock location at Mars in the same way as it does at Venus. Both Venusian and Martian bow shock cross sections are elliptical. Mass loading may be important in the solar wind interaction with Mars since there is a north-south asymmetry, cone angle dependence, and solar activity dependence of the shock position. Together with the previously reported induced magnetotail and very weak bow shock compressibility, the present results further support the idea that the intrinsic magnetic moment of Mars is too weak to affect significantly the solar wind interaction.

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