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ASYMMETRIES IN THE LOCATION OF THE VENUS AND MARS BOW SHOCK

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Abstract. An examination of observations of the position of the terminator bow shock at Venus and Mars shows that the terminator bow shock varies with the angle between the local bow shock normal and the upstream magnetic field, θ_{BN}. The part of the shock on the quasi-parallel side is closer to the planet than the part on the quasi-perpendicular side, a result which had been suggested by an earlier computer simulation by Thomas and Winske [1990]. This bow shock asymmetry is observed to be larger at Mars than at Venus.

Introduction

Analyses of Pioneer Venus Orbiter (PVO) data have revealed many features of the solar wind interaction with a planetary ionosphere. Our current understanding of the solar wind interaction with an ionosphere is that the obstacle to the solar wind consists of a magnetic barrier produced by shielding currents carried by the ionosphere, modified by the comet-like pickup of cold planetary ions [Luhmann, 1986]. This obstacle deflects the oncoming supersonic solar wind around the planet so that a bow shock is formed. PVO has monitored the location of the Venus bow shock for a complete solar cycle, returning information on both the size and shape of the bow shock.

Earlier studies [cf. Russell et al., 1988] showed that the solar EUV flux and solar wind magnetosonic Mach number exert strong control on the size of the terminator bow shock, while the orientation of the interplanetary magnetic field (IMF) controls the asymmetry of the terminator bow shock. The shock radius increases as the magnetosonic Mach number decreases. Since the magnetosonic velocity depends on the angle between the magnetic field and the shock normal, this velocity varies with position along the shock surface. Therefore the magnetosonic Mach number of the shock is position dependent. One might expect an asymmetrical cross section of the bow shock as a result. Russell et al. [1988] confirmed that this asymmetry, first reported by Romanov [1978], is found in the Venus terminator bow shock. They showed that the terminator bow shock location depends on the clock angle which is the angle between the direction of the upstream magnetic field component transverse to the solar wind flow, and the radial vector to the shock encounter as projected into the terminator plane. However, the magnetohydrodynamic (MHD) effect is not the only factor leading to this asymmetry, since the ion pickup process could be effective [e.g., Phillips et al., 1986]. Moreover, at both Venus and Mars ion gyro radii can be a significant fraction of the thickness of the magnetosheath so that kinetic effects may also be important.

In our recent study of the Venus subsolar bow shock we showed that there is a dependence of the subsolar bow shock radius on cone angle (the angle between the IMF and the solar wind flow direction) [Zhang et al., 1990]. As illustrated in Figure 1, the cone angle is the angle between the magnetic field and the solar wind flow direction. The subsolar bow shock is further from Venus when the cone angle is larger. In the subsolar region, the cone angle is approximately equal to the angle between the shock normal and upstream field, i.e., θ_{BN}. Shocks with θ_{BN} less than 45° are called quasi-parallel, while those with θ_{BN} larger than 45° are called quasi-perpendicular. Thus the large cone angle corresponds to a quasi-perpendicular subsolar shock and small cone angle to a quasi-parallel subsolar shock. The clock angle, as we define it here, is the angle between the radius vector to the spacecraft and the magnetic field both projected in the YZ plane orthogonal to the solar wind flow. Russell et al. [1988] reported that the Venus bow shock was smallest for clock angles close to 0° and 180°. In their bow shock simulation, Thomas and Winske [1990] report that the bow shock is closer to the planet on the quasi-parallel side than on the quasi-perpendicular side. In this paper we examine whether this bow shock asymmetry is present near the terminators at Venus and Mars.

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Venus Bow Shock Asymmetry

The location of the terminator bow shock is determined from PVO magnetometer 12-s resolution magnetic field data. Here we use cases when the spacecraft trajectory is nearly perpendicular to the shock at the crossings near the terminator, and use conic section fits to project them to the terminator plane. This study involves about 2000 bow shock crossings which cover the years from 1979 to 1988.

To calculate the angle between the shock normal and the upstream magnetic field, θ_{BN}, we use an average shock shape which is a conic section with an eccentricity of 0.66 [Zhang et al., 1990]. We calculate the angle between IMF and the shock normal at the point of crossing and extrapolate the location of this crossing to the terminator using an eccentricity of 0.66. Figure 2 shows all extrapolated terminator shock positions as a function of θ_{BN}. The medians of the shock radii for 10° θ_{BN} intervals are shown in Figure 3. Apparently, the terminator bow shock radius increases as θ_{BN} increases. However, the dependence is complicated by the effects of the

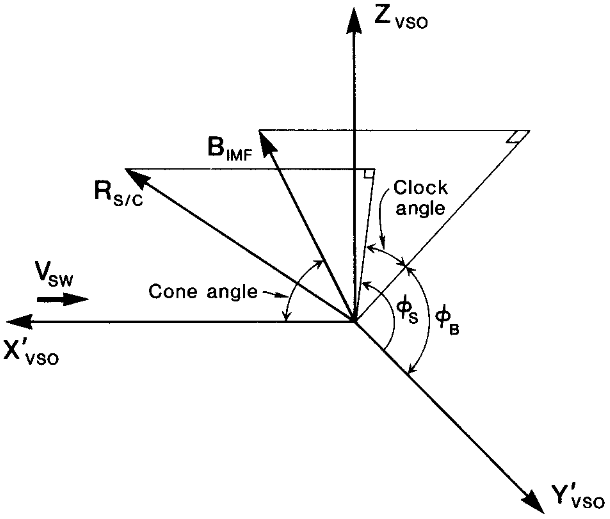

Fig. 1. The coordinate system used in this analysis. The X'-direction is antiparallel to the average solar wind flow direction and Y is approximately opposite planetary motion. The cone angle is the angle between the magnetic field and the average flow direction. The clock angle is the difference between the projected angles of B and R on the YZ plane.

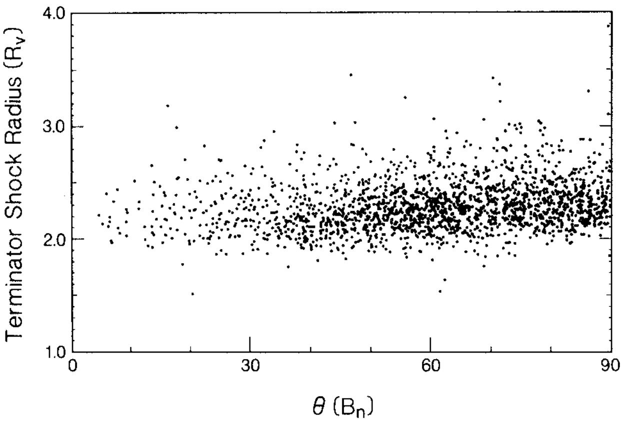

Fig. 2. Location of Venus bow shock extrapolated to terminator plane using an ellipse centered on planet with an eccentricity of 0.66. The average aberration of the solar wind of 5° is used here.

clock angle and cone angle mentioned above [Russell et al., 1988] which both may vary systematically when θ_{BN} changes. Thus Figure 3 may not represent solely a θ_{BN} effect but rather include some cone angle and clock angle effects. To eliminate these effects we proceed as follows.

We first divide the observations into three bins according to clock angle, defining "north" as 22.5° < clock angle < 157.5°, "south" as -157.5° < clock angle < -22.5°, and "equator" as the rest. Due to the near polar orbit of PVO, and the fact that the IMF usually lies near the equatoral plane, there are no small θ_{BN} shock crossings in the polar region. Therefore, we use only equatorial observations to avoid orbital bias in this study.

Similarly, by using observations for small ranges of IMF cone angles, one can exclude any effects of ion pickup. We expect that there will be minimum ion pickup effects when the interplanetary electric field is smallest, i.e., at small cone angles, and largest when the interplanetary electric field is greatest. We divide the equatorial shock crossings into three groups according to cone angle: 0°-30°, 30°-60°, and 60°-90°. Considering the geometry of the equatorial shock and the IMF, small cone angle crossings correspond to large θ_{BN}, and large cone angle crossings correspond to intermediate θ_{BN}. Only intermediate cone angle crossings include both large and small θ_{BN}, or in other words, only intermediate cone angle crossings provide a statistically significant range of angles for this study. Figure 4 illustrates the θ_{BN} effect for the equatorial terminator shock at intermediate cone angles. The quasi-parallel terminator shocks have a mean radius of 2.21 R_V and median of 2.18 R_V (R_V ~6052 km). The quasi-perpendicular shocks have a mean radius of 2.31 R_V and median of 2.27 R_V. Thus there is about 0.1 R_V, or 600 km, asymmetry in the terminator bow shock due the IMF direction relative to the local shock normal.

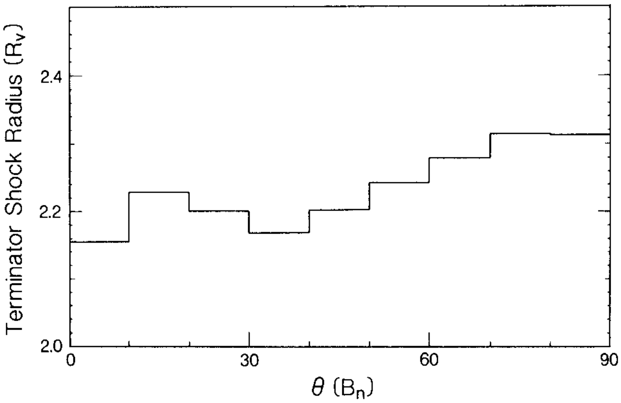

Fig. 3. The medians of the shock position every 10° in θ_{BN}.

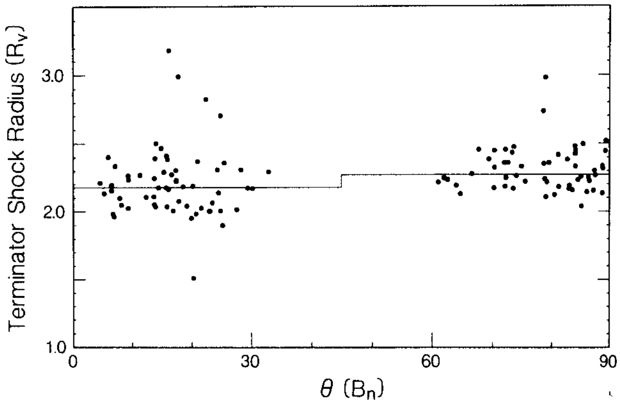

Fig. 4. Equatorial Venus terminator bow shock radii vs. θ_{BN} for intermediate cone angles. The medians of the quasi-parallel and quasi-perpendicular shock locations are shown also.

Mars Bow Shock Asymmetry

Data obtained with the magnetometer on board the Phobos-2 spacecraft can be used in a similar study for Mars. The Martian bow shock, as observed by the Phobos-2 spacecraft, has been reported by Schwingenschuh et al. [1990]. Their study shows the Martian bow shock is quite variable. They found that the median terminator crossing lies at 2.72 Mars radii (Rm ~ 3390 km). In this study, we will make some slight improvements over the earlier study. Firstly, we utilize high resolution plots to determine the shock crossing time. Secondly, we pick the center of the shock ramp instead of the foot as the shock location. Third, we use the ephemeris of the Phobos spacecraft to extrapolate each point to the terminator plane. Lastly, we use an aberration angle of 2.7° due to the 24 km/s orbital velocity of Mars around the Sun. This angle corresponds to a solar wind velocity of 500 km/s which was appropriate for this period [Schwingenschuh et al., 1991]. We find that the terminator bow shock radius is 2.65 Rm and the eccentricity is 0.80. Thus, the Martian bow shock location is similar to that of Venus at the subsolar point when scaled by the planetary radius, but it is significantly larger at the terminator. The reason for this difference is beyond the scope of this paper but may lie in the different scale heights of the atmospheres of these 2 planets.

The terminator bow shock locations as a function of θ_{BN} are shown in Figure 5. Both three-axis stabilized data and despun data are shown. Of 97 shock crossings, there are 29 data points from three-axis stabilized orbits and 70 from despun data. The dotted line in Figure 5 shows the linear regression fit of the three-axis stabilized data. The dashed line shows the fit to the despun data. The solid line shows the fit to all 97 crossings. We find the shock radius increases with increasing θ_{BN} for both the three-axis stabilized data which have the greatest accuracy, and the data we have despun which are less accurate. Considering all 97 shock crossings, the quasi-parallel shocks have a mean radius of 2.48 Rm and median of 2.46 Rm, while the quasi-perpendicular shocks have a mean radius of 2.68 and median of 2.67 Rm. Therefore we find the difference or asymmetry is about 0.20 Rm.

Conclusions

For both Venus and Mars we find the terminator bow shock is asymmetric in the sense predicted by Thomas and Winske [1990], that is, the quasi-parallel shock is closer to the planet than the quasi-perpendicular shock. At Venus, this asymmetry is about 0.1 R_V. At Mars it is around 0.2 R_m. Thomas and Winske [1990] find that this asymmetry decreases as the shock radius increases relative to the gyroradius. The solar wind ion gyroradius at Venus is about 300 km, and at Mars, ~1000 km, while the radius of curvature of the shock at Venus is roughly twice that at Mars. Therefore our observations are consistent with the simulation results. However, due to the rather small data set of Mars bow shock data, this consistency can only be said to be suggested by the observations. We cannot determine in this analysis whether this effect is due to kinetic effects as found in the hybrid model of Thomas and Winske [1990] or due to the difference in Mach number parallel and perpendicular to the magnetic field.

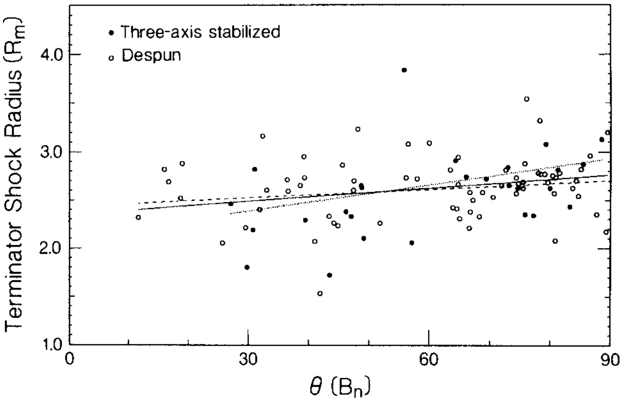

Fig. 5. Mars terminator bow shock location as a function of θ_{BN}. Solid points show the three-axis stabilized data, while circle points are despun data. Dotted line is the linear regression fit for the three-axis stabilized data. Dashed line is the fit for despun data. Solid line is the fit for all 97 data points.

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