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POSITION AND SHAPE OF THE VENUS BOW SHOCK: PIONEER VENUS ORBITER OBSERVATIONS

J.A. Slavin, R.C. Elphic and C.T. Russell
IGPP, University of California, Los Angeles, California 90024
J.H. Wolfe
Ames Research Center, Moffett Field, California 94035
D.S. Intriligator
Physics Department, University of So. California, Los Angeles, California 90007

Abstract. In this study magnetometer data from the Pioneer Venus Orbiter is used to examine the position and shape of this planet's bow shock. Utilizing crossings identified on 86 occasions during the first 65 orbits a mean shock surface is defined for sun-Venus-satellite angles of 60-110°. Both the shock shape and variance in location are found to be very similar to the terrestrial case for the range in SVS angle considered. However, while the spread in shock positions at the earth is due predominantly to the magnetopause location varying in response to solar wind dynamic pressure, ionopause altitude variations can have little effect on total obstacle radius. Thus, the Cytherean shock is sometimes observed much closer to or farther from the planet than previously predicted by gasdynamic theory applied to the deflection of flow about a blunt body which acts neither as source nor sink for any portion of the flow.

Introduction

Planetary bow shocks provide the outermost evidence of the deflection of the solar wind by a planet. Since the shock position and shape are determined by the size and nature of the planetary obstacle, bow shocks are a major source of information concerning the interaction of the solar wind with the planets, and hence their properties. Of the large objects in the solar wind probed thus far only the earth's moon has been found to possess sufficiently small magnetic moment and low electrical conductivity to absorb the solar wind to the point of not forming a bow shock (e.g., Schubert and Lichtenstein, 1974). In situ observations have demonstrated that the solar wind is diverted by magnetopause surfaces at Mercury (Ness et al., 1974), Earth (Sonett et al., 1960), and Jupiter (Smith et al., 1974) while the nature of the interaction at Mars is a matter of controversy with the shock crossings by Mariner 4 (Smith, 1969), Mars 2, Mars 3 (Dolginov et al., 1973), and Mars 5 (Dolginov, 1976) subject to varying interpretations (Russell, 1979; Intriligator and Smith, 1979). The Pioneer Venus Orbiter (PVO) has confirmed the conclusions of earlier American and Soviet missions (see Siscoe and Slavin, 1979) that the solar wind is stood-off by the Venusian ionosphere through the formation of an ionopause (Russell et al., 1979a; Wolfe et al., 1979, Brace et al., 1979).

For a "hard" obstacle (i.e. time stationary and not acting as a source or sink) the position and shape of the shock are a function of the magnetosheath flow which is then determined only by interplanetary conditions and the position of the boundary deflecting the flow (e.g. Spreiter et al., 1966). At planets where intrinsic magnetic fields stand-off the solar wind, such as the Earth and Mercury, the shock position is not constant due to both the changing interplanetary parameters and the variation in obstacle height in response to those changes (e.g. Fairfield, 1971; Slavin and Holzer, 1979). By comparison the change in subsolar ionopause altitude with varying solar wind conditions should be relatively small due to the exponential dependence of pressure on height in the ionosphere and the low ratio of ionospheric depth to planetary radius (Wolff et al., 1979). Accordingly, the hard obstacle model of the Venus solar wind interaction predicts that this shock should exhibit less variation in position relative to the planet than is the case at the Earth. However, a number of theoretical studies (Michel, 1971; Wallis, 1973; Cloutier, 1976; Perez-de-Tejada and Dryer, 1976) as well as observational studies (Russell, 1977; Romanov et al., 1977) have indicated that the ionosphere as influenced by its environment may be acting as a sink and/or a source for the magnetosheath with the possibility of giving rise to an effective viscosity at the interface between the two plasmas (Perez-de-Tejada, 1979). Such effects may be examined indirectly by studying the position and structure of the Venusian bow shock. For that reason this paper reports on the position of this shock as observed by the magnetometer experiment during the first 65 orbits of the Pioneer Venus mission and makes a direct comparison with similar data on the terrestrial bow shock.

PVO Shock Crossings

On December 4, 1978 the Pioneer Venus orbiter was inserted into a 24 hour orbit about the planet with an inclination to the equator of 105.6°, an apoapsis of 12 R_V, and a periapsis altitude of 140-200 km with a spin rate near 5 rpm (Colin, 1979). Hence, each day the satellite twice encounters the planetary bow shock, before and after its magnetosheath and ionospheric passage. For the first 65 orbits all distinct bow shock crossings have been identified using 64 second average quicklook data from the UCLA fluxgate magnetometer experiment which has been described elsewhere (Russell et al., 1979a). Out of a total of 130 passes shock positions were found for 86 with the lack of identification in the remaining 44 cases due to data gaps and/or the absence of a clear signature in the 64 second data. Multiple encounters took place on only 11 of 86 passes in which case the average position is used. It should also be noted that the use of the averaged data together with the requirement of an unambig-

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uous signature results in the crossings selected being predominantly of the quasi-perpendicular type. In Figure 1 these shock positions have been plotted in solar wind aberrated Venus centered solar ecliptic coordinates (VSE) using solar wind speeds obtained for each orbit from the PVO solar wind plasma experiment (Wolfe et al., 1979; Intriligator et al., 1979). Hence, the x' axis is oriented opposite the direction of the solar wind flow in the Venus rest frame calculated assuming radial flow from the sun and a constant orbital velocity for the planet, the y' axis lies in the ecliptic plane with positive directed towards dusk, and z' completes the right handed orthogonal system. Previous studies (Holzer et al., 1972) have shown that for the range in sun-planet-satellite angle examined here the shock surface may be well represented by a conic curve with one focus centered on the body. A least square fit to the data in Figure 1 produced an ellipse of eccentricity 0.80 and a semi-latus rectum of $2.44R_V$ as displayed. In order to better assess the scatter in the crossings the best fit obtained was then used to map all of the shock encounters into the x'=0 plane assuming a constant eccentricity of 0.80 as shown in Figure 2. In this plane the inferred shock location is distributed about a mean of $2.44R_V$ with a standard deviation of $0.23R_V$ or 9.4%.

The variance in the distribution of crossings is attributed to day to day changes in the flow about Venus as would occur for a hard obstacle with varying Mach numbers and solar wind induced alterations in the effective size of the obstacle through the pickup and/or loss of particles to the ionosphere as well as the variation in ionopause height with external conditions. However, from the observed distribution of these Mach numbers at 1 AU which will be quite similar to those at 0.72 AU (e.g. Figure 3 from Fairfield, 1971) and the gasdynamic models of the bow shock (e.g. Figure 1 from Spreiter and Rizzi, 1974) it may be expected that the variation in shock location for the region considered due to changing Mach number will be much less than $1R_e$ at the earth and $0.1R_V$ at Venus. This inference is supported by the fact that Fairfield (1971) was able to predict shock position at the earth to within $1R_e$ 80% of the time based on a predicted magnetopause position and a constant stand-off distance. Ionopause altitudes determined on 52 passes with PVO magnetometer data (Elphic et al., 1979) have shown the average height of this boundary for sun-Venus-satellite angles $\leq 40°$ to be ∿310 km with a standard deviation about the mean of ∿80 km implying again that changing ionopause location has less than a 1% effect on total obstacle size in most cases.

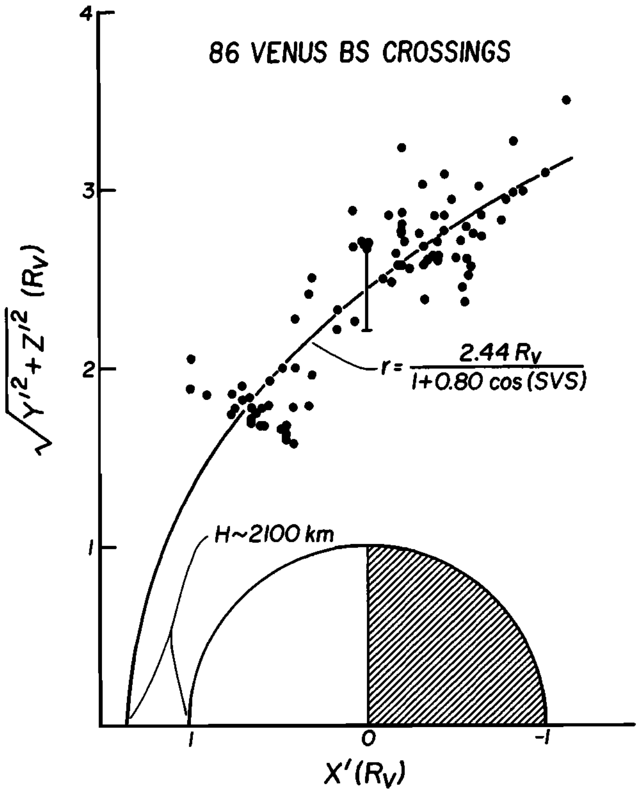

Figure 1. Plotted in solar wind aberrated VSE coordinates are the observed positions of the Venus bow shock on 86 passes by the Pioneer Venus Orbiter. Typical uncertainties in the boundary location correspond to the diameter of the markers. A vertical bar indicates the standard deviation in position in the aberrated terminator plane.

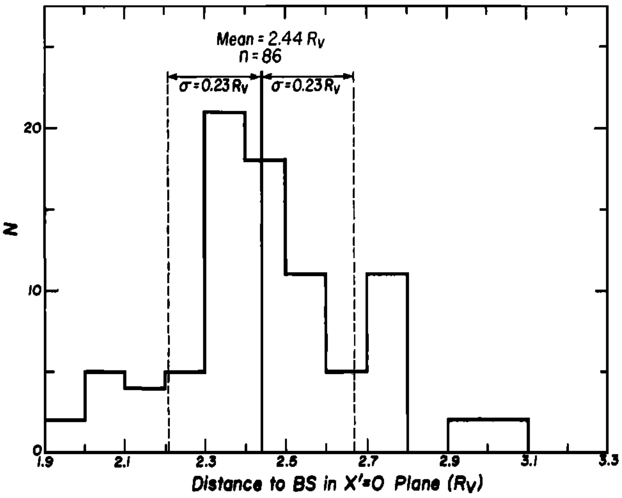

Figure 2. Distance to the shock in the x' = 0 plane during the 86 passes considered in Figure 1 inferred using the observed location and assuming the mean shock shape previously determined is displayed.

Thus, with the observations available at this time at least half of the variation in boundary location evident in Figure 2 is not easily accounted for by the hard obstacle model of the solar wind interaction with Venus. The remaining scatter may be regarded as evidence that the ionosphere/exosphere of this planet is acting as a sink (e.g. Russell, 1977) and/or source (e.g. Cloutier, 1976) for part of the plasma in the magnetosheath. Cloutier (1976) predicted an asymmetry in shock location with respect to IMF orientation with the most distant shock position in the x' = 0 plane exceeding the minimum by $0.36R_V$ due to the efficiency of planetary ion pick-up and compressibility of the magnetosheath depending on magnetic field and flow velocity directions. Using Venera 9 and 10 measurements Romanov et al. (1977) concluded that the bow shock was located farther from the planet in the x' = 0 plane in directions perpendicular to the

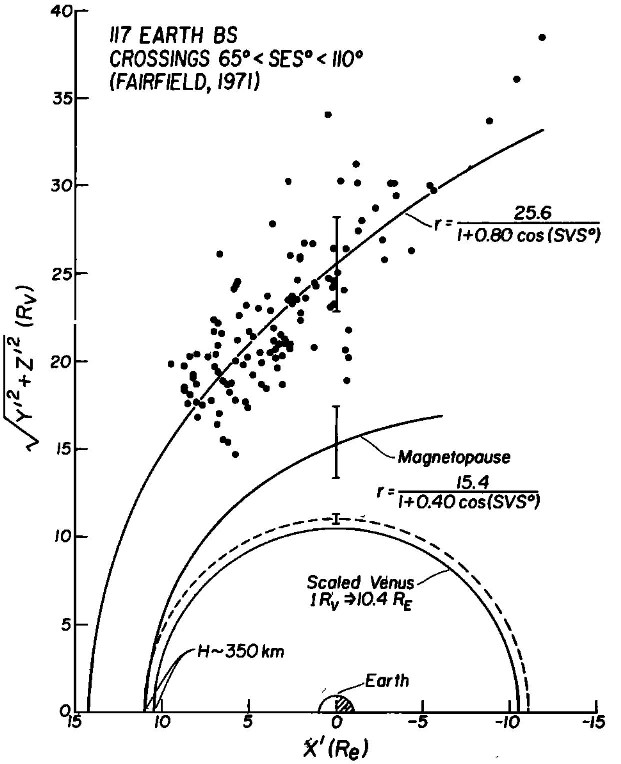

Figure 3. Terrestrial shock crossings taken from Fairfield (1971) for Sun-planet-satellite angles comparable to those in Figure 1. The mean magnetopause position from Holzer and Slavin (1978) is also shown.

transverse IMF by an amount similar to Cloutier's values. Due to its high inclination orbit and the tendancy for the IMF to lie parallel to the ecliptic PVO samples this region "above" and "below" the planet where the shock may be most distant and most variable in position in the photo-ion accretion models (e.g. Cloutier, 1976). By comparison the Venera 9 and 10 missions had much smaller inclinations and found the position of the shock to vary by only half as much as shown in Figures 1 and 2 (Verigin et al., 1978) thus supporting the hypothesis that Venus does not behave simply as a hard obstacle in the solar wind.

In Figure 1 the conic fit to the average shock has been extended to the subsolar point at an altitude of ∿2100 km. Gasdynamic theory (e.g. Spreiter et al., 1966) relates the nose distance, d, to the stagnation point on the obstacle at distance, D, by

$$d/D=(1.1/M^2)((\gamma-1)M^2+2)/(\gamma+1) \qquad (1)$$

where M is the sonic Mach number (i.e. solar wind speed divided by sound speed) and γ is $(n+2)/n$ with n being the number of degrees of freedom of the medium. Due to the recent observations that suggest the shock at Venus is 20-30% weaker, in the sense of smaller jump conditions, than at the earth (Russell et al., 1979b) the use of $n=2$ may be more appropriate than $n=3$. For an average value of $M=7$ at 1 AU (Fairfield, 1971) d/D equals 0.38, implying a mean effective obstacle altitude 60 km below the surface of Venus and possibly suggesting partial absorption of the magnetosheath flow by the ionosphere at least during the intervals of some of the closer crossings.

Terrestrial Bow Shock

For comparative purposes 117 crossings of the Earth's bow shock with sun-planet-satellite angles similar to those considered at Venus (Fairfield, 1971) have been plotted in aberrated geocentric solar ecliptic coordinates in Figure 3. Fitting these points in the same manner as before produces as eccentricity of 0.80, as was the case at Venus, and a semi-latus rectum of $25.6R_e$. This curve is in close correspondence with the non-planet centered conic used by Fairfied (1971) to model the complete set of crossings at all sun-Earth-satellite angles. The magnetopause has been plotted using the 0.40 eccentricity mean surface of Holzer and Slavin (1978) with the nose distance set equal to the average determined for this period by Fairfield (1971) with the IMP observations. A bar representing the 13.3% total standard deviation in the distribution of magnetopause positions determined by Holzer and Slavin (1978) is also displayed. As both bow shocks have been found to have the same shape in this region Venus has been drawn to scale where its shock overlays that of the Earth. The dashed circle with its forward edge coincident with the magnetopause shows the scaled obstacle height with an error bar representing a 100 km variation in subsolar ionopause height. In Figure 4 the terrestrial shock encounters have been mapped into the x' = 0 plane where the resulting distribution is about a mean of $25.6R_e$ with a standard deviation of $2.7R_e$ or 10.5% which is nearly the same as was found for Venus crossings in Figure 2. The finding of a similar shape for both shocks is unexpected because the obstacle geometries shown in Figure 3 are different and would be expected to be reflected in the shock surfaces near the terminator region. This finding may suggest that the effective obstacle follows the shape of a magnetopause more closely than the near circular ionopause as might be consistent with the development of a thin boundary layer adjacent to the ionopause (e.g. Perez-de-Tejada, 1976).

Conclusions

In this preliminary analysis of the PVO shock crossings it has been found that the shape and variation in the position of the Cytherean and terrestrial bow shocks are very similar. However, whereas the range in distance over which the shock is observed to occur at the Earth is due predominantly to the variations in magnetopause position,

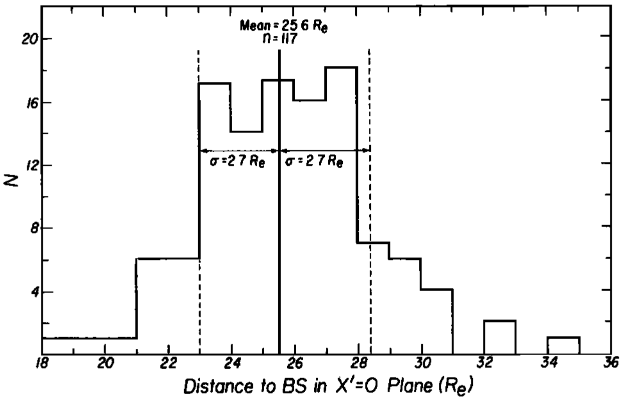

Figure 4. The shock encounters from Figure 3 are shown mapped into the x' = 0 plane as was done in Figure 2.

mechanisms other than simple ionopause height variation with changing solar wind dynamic pressure appear necessary to produce the observed spread in shock locations at Venus. Based on observations near the terminator it also appears that the bow shock of Venus can be significantly closer to or farther from the planet than expected from gasdynamic modeling with an ionopause obstacle considered a tangential discontinuity. Hence, these findings may indicate the presence of processes by which sufficient mass, momentum, and energy may be exchanged between the solar wind and the exosphere/ionosphere of Venus to cause some alteration of the magnetosheath flow as suggested on theoretical grounds by Wallis (1973), Perez-de-Tejada (1976), and Cloutier (1976).

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