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SOLAR CYCLE DEPENDENCE OF THE LOCATION OF THE VENUS BOW SHOCK

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Abstract. Initial measurements of the Venus bow shock obtained by Pioneer Venus in 1979 near solar maximum indicated that the bow shock was on average 2.44 R_V from the center of the planet in the terminator plane. This is 0.35 R_V further from Venus than observed by Venera 9/10 in 1976. In the past this discrepancy has been attributed to some effect of the solar cycle. Recent measurements by Pioneer Venus support this interpretation. In 1980 the distance to the bow shock reached a maximum of 2.45 R_V and since then has been almost steadily declining toward the distance measured by Venera near solar minimum. The variation in bow shock position is well correlated with the sunspot number and the F 10.7 cm flux over this period. We attribute this behavior to the variation in the neutral atmosphere of Venus with the solar cycle and its subsequent effect on the mass-loading of the solar wind.

Introduction

The nature of the solar wind interaction with Venus is complex. Due to a lack of an intrinsic magnetic field the interaction of the solar wind Venus is quite different from that at the Earth. The observed location of the nose of the bow shock is consistent with an obstacle presented to the solar wind the size of the planet plus its ionosphere (Verigin et al., 1978, Slavin et al., 1979a,b, 1980, Smirnov et al., 1980). The shock at the terminators, however, is significantly more flared than would be expected for such a simple obstacle. It has not been possible to account for the flare using gas dynamic approximation to flow around such an obstacle and this failure has been attributed to other features of the solar wind interaction with Venus related to mass-loading (Tatrallyay et al., 1984).

The first survey of the bow shock location from a Venus orbiter was made near solar minimum in 1975 and 1976 by the Venera 9/10 spacecraft (Smirnov et al., 1980). At this time the bow shock at the terminator was found to lie at a distance of 2.09 R_V. In contrast, near solar maximum when Pioneer Venus entered its Venus orbit the shock at the terminator was found to be at 2.44 R_V. The difference between these two observations was 16% of the mean of the two missions, a difference much larger than expected from statistical sources. This difference has been attributed to solar cycle effects (Slavin et al., 1979a,b).

Since Pioneer Venus has now been in orbit over six years, well over half a solar cycle, we are provided with an excellent opportunity to test the dependence of the bow shock location on the solar cycle. We will show that there is a good correlation between the fall off in solar productivity and the retreat in bow shock position, that indeed the long-term variability in bow shock location is responsive to the EUV output of the sun.

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Observations

In order to determine the location of the terminator bow shock, we examined magnetic field records obtained on orbits that crossed the bow shock near the terminator plane (± 20° in solar zenith angle) while moving nearly perpendicular to the bow shock, as illustrated by a typical orbit in Figure 1. Roughly 100 orbits were used each Venus year. The aberration of the solar wind by the motion of Venus was taken into account in an average sense by rotating 5° about the Venus orbital pole. The shock locations were then extrapolated to the terminator using a model for the bow shock position derived from the first 255 PVO orbits using data obtained near the terminators (Tatrallyay et al., 1983). The equation was of the form

$$R = L/(1 + \varepsilon \cos(\mathrm{SZA}))$$

where R is the observed bow shock planetocentric distance, L is the terminator crossing, ε is the eccentricity (0.755 in our model) and SZA was the

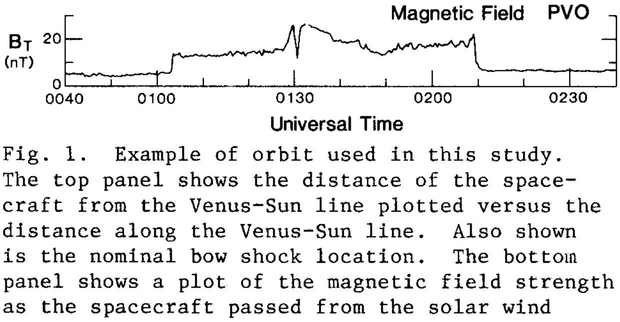

Fig. 1. Example of orbit used in this study. The top panel shows the distance of the spacecraft from the Venus-Sun line plotted versus the distance along the Venus-Sun line. Also shown is the nominal bow shock location. The bottom panel shows a plot of the magnetic field strength as the spacecraft passed from the solar wind through the magnetosheath and back into the solar wind again.

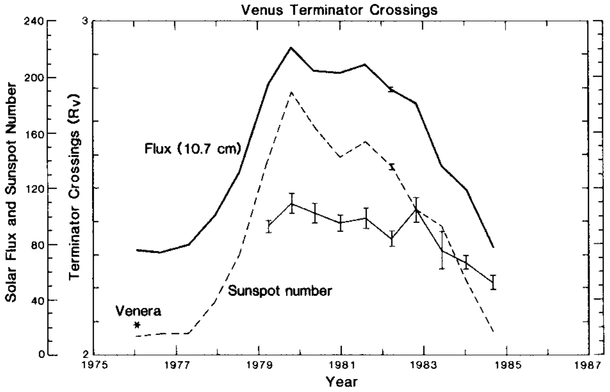

Fig. 2. Mean Venus shock terminator positions for selected orbits plotted vs. time. Also shown are the mean sunspot numbers and F 10.7 cm flux for the same orbits.

solar zenith angle in our aberrated system. This is a simple conic of revolution with a focus at the center of the planet.

Mean values and their standard deviations were calculated for each Venus year and are plotted versus time on Figure 2. Sunspot numbers and the F 10.7 cm flux are plotted for the same period of time averaged over the interval in which the bow shock location was monitored. These values were obtained from the Solar Geophysical Data publications of the National Oceanic and Atmospheric Administration. Also shown is the Venera position obtained in late 1975 and early 1976.

The location of the terminator bow shock as observed by Pioneer Venus not only is much further from Venus than the Venera observations would indicate, it also increases with time until it reaches a peak of about 2.45 R_V 1980. Thereafter, it declines (with the exception of the late 1982 point) until the present. This behavior reflects well the solar cycle as registered in sunspot number and the F 10.7 cm flux. The correlation between the Venus bow shock location and the sunspot number is .89 and between the bow shock location and F 10.7 cm flux is .94.

Discussion

The Pioneer Venus observations clearly show that the bow shock is now returning to the location originally detected at solar minimum by Venera 9 and 10. This change is beyond what could be produced by a change in the Mach number of the solar wind. The sensitivity of the terminator distance of the bow shock was examined by Tatrallyay et al., (1984) who found that at high Mach numbers near the peak of the solar cycle in 1979 the bow shock distance asymptotically approached about 2.30 R_V, well above the 2.09 R_V measured by Venera 9 and 10.

Because the obstacle shape is mainly determined by the ionopause, which is the resultant of a balance between the magnetic pressure of the solar wind and the thermal pressure of the ionosphere, changes that effect the ionospheric number density can change the obstacle size. Features of the solar wind interaction with the ionosphere that are solar cycle dependent include changes in ionopause height due to fluctuations in EUV flux, the expansion and excitation of the neutral atmosphere, and absorption of the solar wind at the subsolar point caused by charge exchange producing fast neutrals that are not deflected by the planetary ionosphere (Gombosi et al., 1981). That the latter effect could produce a variation in subsolar bow shock location has been postulated by Russell (1977), Romanov (1978), and Slavin et al. (1979a). Wolff et al. (1979), calculated the solar cycle modulation of ionopause height and found it to vary by 100 km over the solar cycle, while the absorption as a function of ionopause height was calculated and found to be greatest at solar minimum (16%), less at solar maximum (10%), Gombosi et al.,(1981) implying more solar wind interaction with the neutral atmosphere at solar minimum than at solar maximum. Nagy et al. (1981) however, showed that the Venus exosphere is primarily composed of oxygen and that there exists significant numbers of "hot" oxygen at altitudes of 1400 to 4000 km, produced by the dissociative recombination of ions of molecular oxygen. The existence of this hot oxygen corona leads to a number of modifications of the solar wind interaction with Venus. An increase in the number densities within the corona could lead to significant increases in the amount of mass-loading via photoion pickup at Venus. The oxygen corona plays an important role in the solar wind absorption process, as Gombosi et al. (1981) found, as the maximum amount of absorption found without consideration of the hot oxygen corona was only 7%.

The mass-loading process at Venus is the most significant feature of its interaction with the solar wind, however, As the solar wind flow impinges on the ionosphere it interacts with the neutrals via charge exchange, photoionization and impact ionization. These processes add mass to the flow and slow it down. The terrestrial neutra atmosphere is hotter and denser at high altitudes during solar maximum. The increased solar EUV flux should effect the Venus neutral atmosphere in much the same way. Thus the hot oxygen corona should be very responsive to solar cycle changes and expansion of the neutral atmosphere available for direct solar wind interaction should exceed the shielding effect of an enlarged ionosphere. The slowed flux lines cause expansion of the magnetosheath to accomodate the excess flux and this gives the additional measured flare at the terminator. In general therefore, Venus appears to exhibit more comet-like behavior at solar maximum and more of the superconducting ball appearance at solar minimum.

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References

Gombosi, T. I., M. Horanyi, T. E. Cravens, A.F. Nagy,and C. T. Russell, The role of charge exchange in the solar wind absorption by Venus, Geophys. Res. Lett., 8, 1265-1268, 1981.

Nagy, A. F., T. E. Cravens, J. H. Yee, and A. I. F Stewart, Hot oxygen atoms in the upper atmosphere of Venus, Geophys. Res. Lett., 8, 629-632, 1981.

Russell, C. T., The Venus bow shock: Detached or attached?, J. Geophys. Res., 82, 625-628, 1977.

Slavin, J. A., R. C. Elphic, C. T. Russell, J. H. Wolfe, and D. S. Intriligator, Position and shape of the Venus bow shock: Pioneer Venus orbiter observations, Geophys. Res. Lett., 6 901-904, 1979a.

Slavin, J. A., R. C. Elphic, and C. T. Russell, A comparison of Pioneer Venus and Venera bow shock observations: Evidence for a solar cycle variation, Geophys. Res. Lett., 6, 905-908, 1979b.

Slavin, J. A., R. C. Elphic, C. T. Russell, F. L. Scarf, J. H. Wolfe, J. D. Mihalov, D. S. Intriligator, L. H. Brace, H. A. Taylor, and R. E. Daniell, Jr., The solar wind interaction with Venus: Pioneer Venus observations of bow shock location and structure, J. Geophys. Res., 85, 7625-7641, 1980.

Smirnov, V. N., O. L. Vaisberg, and D. S. Intriligator, An empirical model of the Venusian outer environment, 2. The shape and location of the bow shock, J. Geophys. Res., 85, 7651-7654, 1980.

Tatrallyay, M., C. T. Russell, J. G. Luhmann, A. Barnes, and J. D. Mihalov, On the proper mach number and ratio of specific heats for modeling the Venus bow shock, J. Geophys. Res., 89, 7381-7392, 1984.

Tatrallyay, M., C. T. Russell, J. D. Mihalov, and A. Barnes, Factors controlling the location of the Venus bow shock, J. Geophys. Res., 88, 5613-5621, 1983.

Verigin, M. I., K. I. Gringauz, T. Gombosi, T. K. Breus, V. V. Bezrukikh, A. P. Remizov, and G. I. Volkov, Plasma near Venus from the Venera 9 and 10 wide-angle analyzer data, J. Geophys. Res., 83, 3721-3728, 1978.

Wolff, R. S., B. E. Goldstein, and S. Kumar, A model of the variability of the Venus ionopause altitude, Geophys. Res. Lett., 6, 353-356, 1979.

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