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THE DISTANT BOW SHOCK AND MAGNETOTAIL OF VENUS: MAGNETIC FIELD AND PLASMA WAVE OBSERVATIONS

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Abstract. An examination of the magnetic field and plasma wave data obtained by the Pioneer Venus orbiter in the wake region behind Venus discloses a well developed bow shock whose location is similar to that observed on previous missions in contrast to the dayside bow shock. Venus also has a well developed magnetotail in which the field strength is enhanced over magnetosheath values and in which the magnetic field is aligned approximately with the solar wind direction. The boundary between magnetosheath and magnetotail is also marked by a change in the plasma wave spectrum.

Introduction

The Pioneer Venus orbiter crosses through the wake region behind the planet both at low altitudes near periapsis (~150 Km) and at high altitudes about 7 to 12 Venus radii behind the planet. Because of the near polar orbit (inclination ~105°) the spacecraft does not probe the intervening region. The wake is interesting because its properties are determined by the nature of the interaction of the solar wind with the planet and thus its study gives us information about that interaction. For example, if ionospheric ions are picked up and accelerated by the solar wind, they should be observable in this region; indeed evidence of ion pickup is given by Mihalov et al., (1980). We would also expect to observe a "magnetotail" due to either the "capture" of interplanetary field lines by the ionosphere or the "stretching-out" of any intrinsic planetary magnetic field. The distant bow shock is also an important source of information about the interaction. The Pioneer Venus orbiter can routinely probe the bow shock to distances of 10 obstacle radii, corresponding to over 100 earth radii for the scaled terrestrial interaction. We have very little data on the terrestrial shock at these distances.

This paper reports on our first extensive examination of the distant bow shock and wake using the magnetic field data with some reference to the electric field data from the Pioneer Venus orbiter. Previously, we have examined in detail the position and structure of the bow shock over the forward hemisphere and near terminator regions (Russell et al., 1979a,b; Slavin et al., 1979a,b; 1980; Theis et al., 1980), but only briefly surveyed the behavior of the distant shock (Slavin et al., 1980; Scarf et al., 1980a). These studies showed that a well developed bow shock exists consistent with the deflection of most of the solar wind by the planet. An unexpected feature of these data was that the bow shock was about 30% further from Venus during the initial PVO orbits than it had been during the Venera 9 and 10 observations reported by Verigin et al. (1978). Our initial examination of the low altitude nightside magnetic field data revealed moderately strong, up to 40 nT, magnetic fields, with almost random directions (Russell et al., 1979c, 1980a) but little evidence for an overall planetary moment. In fact, the upper limit to the Venus intrinsic magnetic moment is less than 4 x 10^{-5} of the terrestrial moment (Russell et al., 1980b). Despite this lack of a significant intrinsic planetary magnetic field, we expected to observe a magnetotail. An "induced" magnetotail had been observed in laboratory simulations (Dubinin et al., 1978) and in the near Venus wake by Venera 9 and 10 (Yeroshenko, 1979). A tail-like field was also observed by Mariner 5 (Russell et al., 1976) in the near wake region. The planetary "end" of the field lines in this "induced magnetotail" might thread the dayside ionosphere as in the model of Daniell and Cloutier (1979) and as inferred from the Pioneer Venus observations of occasional large magnetic field strengths in the dayside ionosphere (Luhmann et al., 1980); they might thread the nightside ionosphere as consistent with the observations of radial magnetic fields near midnight (Luhmann et al., 1981); these lines could also simply be field lines passing in front of the planet in the magnetosheath above the ionopause on which the plasma convection has been slowed as a consequence of the solar wind-Venus interaction as predicted by gas dynamics and by the mass loading action of photoionization of the neutral atmosphere. In order to decide which of these possible sources is responsible for the formation of the magnetotail we must determine the magnetic flux content of the tail, but before attempting this we will examine the location of the distant shock.

The Distant Bow Shock

Records of the Pioneer Venus magnetometer (Russell et al., 1980c) and the Pioneer Venus electric field detector (Scarf et al., 1980b) were examined for the entire orbit at 12-second resolution for orbits 180 to 220. These 40 orbits included the entire wake passage. Apoapsis was in the center of the aberrated wake on orbit 187. This interval was chosen to provide shock crossings over a wide range of distances behind the planet. Shocks were identified by the increase in field magnitude and drop in plasma wave emission frequency upon entry into the magnetosheath. There was often an increase in the amplitude of the plasma waves in the 100 Hz channel. The signature is often ambiguous in either the plasma wave or field data. Both were needed for the identification of the bow shock in this region of space. Interplanetary shocks were distinguished from bow shock crossings by the existence of multiple crossings of the distant bow shock on essentially every orbit. The mid-time of these sets of multiple crossings was chosen for an outbound passage and one for an inbound passage, i.e., two each orbit. However, when there were several distinct groupings of multiple crossings, as possibly caused by a change in solar wind conditions, several mid-times were chosen.

Four orbits in this interval never entered the solar wind, or entered only for a brief period. This observation indicates a bias in our analysis which we will discuss below. On the basis of our criteria, 91 bow shock crossings were identified. These are shown in solar cylindrical coordinates in Figure 1. Here, the expected ~5° aberration angle of the solar wind has been removed and the distance of the shock from the planet sun line is plotted versus the distance along the sun line. We also show Venera and Mariner shock crossings. It is evident from the plot that, at distances more than 9 R_V behind the planet, the observed shock location is well inside the position extrapolated from positions observed closer to the planet. These closer points are caused by a sampling bias coupled by the motion of the shock. The sampling bias arises because the satellite does not adequately cover the region further from the tail axis at these distances. In the analysis below we overcome this sampling bias by ignoring the most distant data points.

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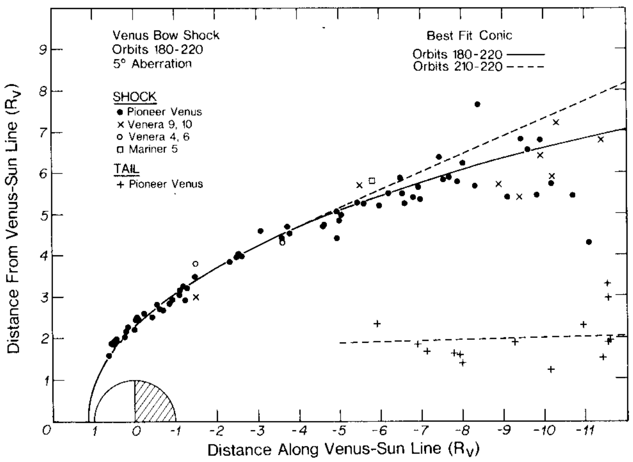

Figure 1. Location of observed distant bow shock crossings and tail encounters in solar-cylindrical coordinates. The expected 5° aberration of the solar wind by planetary motion has been removed from these data. Due to a possible bias in the shock location due to the persistent proximity of the orbit to the expected shock position from orbits 180–209, the shock has been fit separately using only the crossings on orbits 210–220. This fit is shown with the dashed curve and the overall fit to all crossings is shown with a solid line. Entries and exits from the tail are indicated by crosses.

Fitting these shock-crossing data with a conic section whose focus is at the center of Venus and whose eccentricity and size are allowed to vary, we obtain a terminator distance of 2.271 ±.044 R_V and an eccentricity of .969 ±.010. This solution lies in the middle of the range of solutions obtained using Mariner 5 and 10 and Venera 4, 6, and 9 data (Russell, 1977). In this early study, which covered a similar range of solar zenith angles but for which only six crossings were available, the terminator distances ranged from 2.21 to 2.58 and the eccentricity from 0.91 to 1.03 depending on which data were included. The fact that the distant shock location in the PVO data is similar to that seen on earlier missions is illustrated by Figure 1.

As noted above, 4 orbits spent negligible time in the solar wind during the interval covered in this study. The reason for this is that during the first 30 orbits from 180–209, the spacecraft never was more than one Venus radius outside the expected position of the bow shock. Thus if the shock expanded more than one Venus radius, it could completely encompass the orbit, as it did on these four occasions. This in turn suggests that the present study may have a bias due to the fact that the shock could not be observed much further out than its average position, hence decreasing its average observed radius and perhaps influencing its apparent shape. Since orbits after orbit 209 seemed free of this problem, we analyzed these separately. The results are shown by the dashed line in Figure 1 which corresponds to a shock terminator distance of 2.083 ± .120 R_V and an eccentricity of 1.024 ±.023. Again this is consistent with the earlier work of Russell (1977) but at the extremes of the range. The flaring angle of the distant shock is about 22°, corresponding to a magnetosonic Mach number of 2.7, a number somewhat lower than the 3–4 observed at 1 AU. However, this conclusion should be regarded as tentative until a larger number of distant bow shocks can be analyzed.

The Distant Magnetotail

In the center of the wake region there is a region of generally enhanced field strength whose direction is more aligned with the solar wind direction rather than the expected direction of the magnetosheath field. Thus this region is similar to the terrestrial magnetotail. On the orbits studied here tail-lobe field was on the average 83% stronger than in the adjacent magnetosheath. Figures 2 and 3 show typical examples of the Venus "magnetotail" on orbits 188 and 191. The top panel shows the 5.4 kHz electric field data and the bottom panels the magnetic field components and magnitude. We recall that the center of the aberrated wake is expected to occur on orbit 187. As illustrated here the entry and exit from this region is usually quite distinct in both the magnetic field and plasma waves. The field is usually predominantly parallel or antiparallel to the X-direction, i.e., either towards or away from the planet. There are very frequent reversals of the field within the magnetotail and these reversals typically occur while the total field is depressed well below its "tail-lobe" field strength. A particularly striking depression of the field occurs from 1400 to 1600 UT on orbit 191 between extended regions of sunward and antisunward field. This region of very small field strength is very similar in appearance to the signature of the terrestrial plasma sheet. The energy density of the plasma required to provide pressure balance in these depressions is close to 1 kev cm^{-3}. We note that on orbit 191 the exit from the magnetotail is not as clearly seen in the plasma waves at 5.4 kHz or at other frequencies. This should not be taken to indicate the absence of plasma waves at this time for the filter channels are narrow compared to the spacing between channels and the emission could fall between channels.

The IMF on orbit 191, after returning to the interplanetary medium, is 9 nT and is oriented mainly northward and outward from the sun along the spiral angle. Thus we would expect the magnetic field in the tail to be towards the planet in the southern lobe of the tail and away in the north if it is produced by IMF draped over the planet. At the entry to the tail region the spacecraft is south of the planet and sees a field towards the planet as expected. We note that BY and BZ tend to be small except for occasional positive impulses near current sheet crossings. Depending on the current sheet configuration these transient fields may be due to field-aligned currents perhaps coupling the tail stresses to the night time ionosphere or they could be components normal to the current sheet. If so, with the configuration of the interplanetary field seen on orbit 191, these

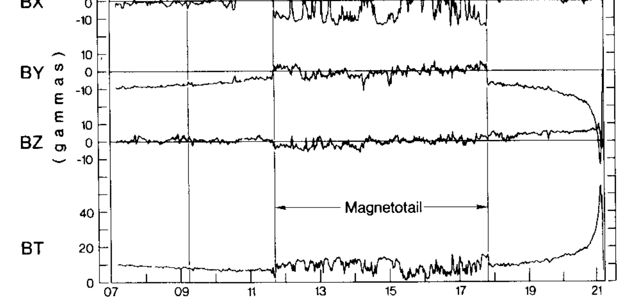

Figure 2. One minute average magnetic field in spacecraft coordinates (approximately solar ecliptic) and plasma wave data for orbit 188 inbound. The top panel shows the peak and the average electric field spectral density in the 5.4 kHz channel. The decrease in plasma wave amplitudes just before 1500 UT is associated with the entry into the optical shadow.

components would indicate the spacecraft was tailward of any neutral point in the tail. This configuration is the same as would be produced if the magnetic lines of force just "slipped around" the planet.

On orbit 188 the IMF outbound from periapsis is 10 nT and mainly in the ecliptic plane, pointing towards the sun, roughly along the spiral angle, slightly northward. Orbit 188 passes close to the expected center of the wake and the trajectory through the tail was nearly parallel to the expected current sheet position. Depending on the direction of the solar wind and its speed, the spacecraft could have been on either side of the current sheet. From the predominant orientation of the field away from the planet, it appears that PVO was on the -Y side, or the side of the tail in the direction of planetary motion, during most of this tail crossing. We note that on all the tail crossings observed to date, the observed tail field directions are consistent with an interplanetary source.

Figure 4 shows the location of these tail crossings in the Venus Solar Orbital Y-Z plane and Figure 1 in solar cylindrical coordinates. The Venus solar orbital system is analogous to the terrestrial solar ecliptic coordinates but uses the Venus orbital plane for the X-Y plane. The direction of planetary motion is in the -Y direction at 35 km/sec. No data are available for the passages on orbits 184–186 at the interesting times because of spacecraft power conservation measures necessary during solar occulation. Also indicated on the figure are the X-coordinate at tail entry to the nearest R_V and the X-coordinate upon exit from the tail. The heavy part of the orbit trace indicates the satellite was judged to be within the tail based on the direction of the field and the magnitude of the field. There was no evidence for tail-like fields on orbits prior to 180 nor after 194.

The inner 1 R_V radius circle centered on (0,0) represents the optical shadow of Venus. The 2 R_V radius circle centered on (0.7,0) represents an aberrated tail of 2 R_V in radius. The aberration chosen is appropriate only at 8 R_V behind the planet for a 400 km/sec solar wind. The observed tail encounters are roughly consistent with the expected aberrated tail. However, there is much variability from this average picture. This could be due to the intrinsic variability of solar wind speed and direction or could be due to some instability of the magnetotail such as flapping induced by the Kelvin-Helmholtz instability. A better definition of the average tail radius awaits better statistics based on additional wake passages. However, if we take a 2 R_V tail radius and a 10 nT average field we obtain a little over 2.3

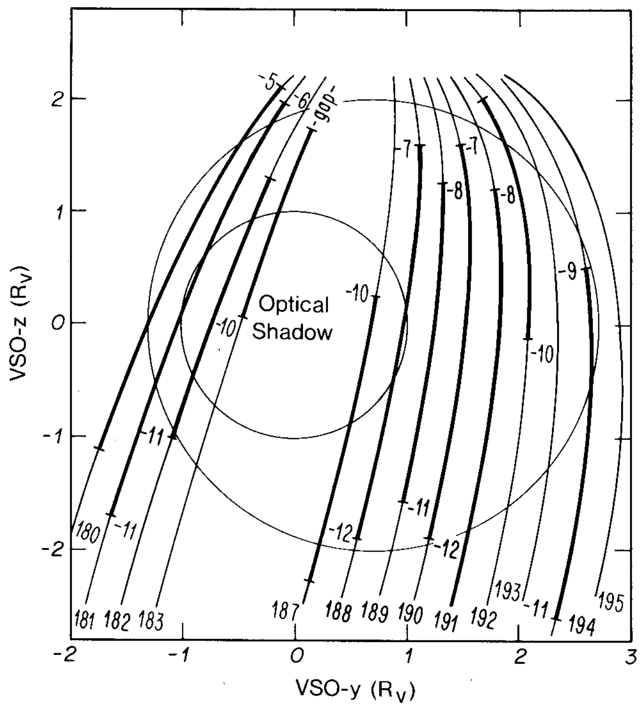

Figure 4. Spacecraft trajectory on orbits 180–195 in plane perpendicular to Venus-sun line. Coordinate system is Venus solar orbital which is analogous to solar ecliptic for the earth in that on average the direction of aberration will be in the Y-direction. The heavy portion on the trajectories indicate when the spacecraft was judged to be in the magnetotail. The numbers near the beginning and end of each trajectory indicate the distance behind Venus in Venus radii at which the entry and exits from the tail occurred. The inner circle is the optical shadow; the outer circle represents the average region of tail encounters.

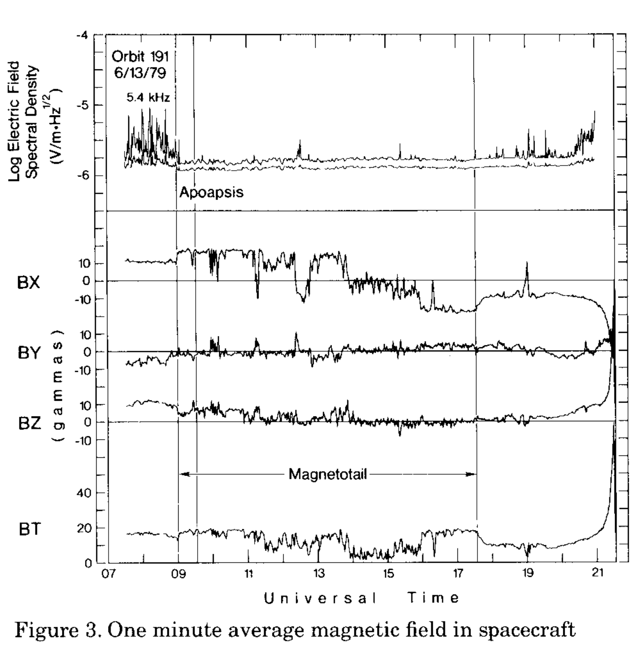

Figure 3. One minute average magnetic field in spacecraft coordinates and plasma wave data for orbit 191 inbound.

Megawebers in each lobe of the tail. This is clearly much more than is present in the horizontal field in the dayside ionosphere or in the radial field in the night time ionosphere. In a 30° wide band of 100 nT field 100 km thick there is only about 3 x 10^4 webers. The radial magnetic flux out of the night time ionosphere amounts to only about 10^5 webers (Luhmann et al., 1981). Part of the flux must certainly close above the dayside ionosphere where the field is presumably being mass-loaded by photoionization of and charge exchange with the neutral atmosphere. However, there can also be much closure across the center of the tail. If the average field normal to the current sheet across its 4 R_V width from the planet to 10 R_V were 1.5 nT all the tail flux could close in the tail. Such a component normal to the current sheet is possible from an examination of Figures 2 and 3. The direction of the Y and Z components in the tail for both orbits is as expected for field lines slipping around the planet and closing across the tail current sheet giving the orientation of the IMF on these orbits.

Summary and Conclusions

Venus has a well developed distant bow shock and magnetotail. The location of the bow shock as observed by PVO is similar to the location observed on earlier missions. Care must be exercised in interpreting these data since there is possible bias due to the location of the orbit relative to the expected position of the shock. More data especially those for which the orientation of the orbit relative to the shock is different will be necessary before a more exact position of the shock is obtained and before analyses of more subtle effects such as dependence on the IMF direction, solar wind Mach number or dynamic pressure are attempted.

The magnetotail of Venus appears in the magnetic data to be similar to the terrestrial magnetotail. The major difference is that the direction of the tail field depends on the orientation of the interplanetary magnetic field. There are several megawebers of magnetic flux in this magnetotail which is much more flux than that found in the nightside ionosphere or in the dayside ionosphere. Much of the flux in the tail must close in the boundary layer or across the center of the tail. These observations suggest the following mechanism for the formation of the tail. The shocked and compressed interplanetary field is pressed against the ionosphere. On days of normal solar wind dynamic pressure some magnetic flux perhaps enters the ionosphere as flux ropes but the majority of the flux remains external to the ionosphere. Here it is mass-loaded due to photoion pickup from the neutral atmosphere via charge exchange and photoionization. This new cold plasma impedes convection and the magnetosheath field lines stretch out to form a tail while the new cold plasma is pulled into the nightside. The flux which does enter the ionosphere is also convected to the nightside and also contributes to the tail flux. On days of high dynamic pressure when the entire dayside ionosphere appears to become magnetized this contribution is of course bigger. Detached plasma clouds above the ionopause may be a signature of this ion pickup process (Brace et al., 1981). The Venus magnetotail is, of course, very analogous to that of comets, and draping models have been proposed for the formation of cometary tails which much resemble the mechanism discussed herein (cf. Alfven, 1957). However, we leave it to future publications to discuss in depth the richness of this analogy.

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