The Solar Wind Interaction With Venus: Pioneer Venus Observations of Bow Shock Location and Structure


Pioneer Venus observations are used in conducting a study of the location and structure of the Venus bow shock. The trace of the shock in the solar wind aberrated terminator plane is nearly circular at an altitude of 1.38 Rv independent of interplanetary magnetic field orientation with an extrapolated sub-solar height of 0.38 Rv. Gas dynamic relations and scaling of the terrestrial analogue are used to determine the effective impenetrable obstacle altitude from the mean shock surface with the conclusion that it lies beneath the observed height of the ionopause. The short-term variability in shock position is similar to that found at the earth, while over the long-term bow shock, altitude varies by up to ~35% in phase with the solar cycle owing to causes other than changing solar wind Mach number. In contrast to ionopause position, which is shown to be well determined by external pressure measurements, bow shock altitude is found to be only weakly dependent upon ionopause height and solar wind dynamic pressure. These results are interpreted in terms of interactions with exospheric neutrals and/or lack of complete deflection of the incident solar wind by currents induced in the ionosphere modifying the flow about Venus from that associated with a tangential discontinuity obstacle of nearly constant radius. The downstream bow shock is smaller in diameter than that of terrestrial case despite the larger Mach cone angle at 0.72 AU most probably due to the smaller relative size of the Venus magnetotail. A brief survey of shock structure with Pioneer Venus instrumentation shows general agreement as to the time and location of the shock crossings with a transition layer thickness of the order of the ion inertial length scale. The observed variation in bow shock structure and the foreshock with upstream parameters was similar to that seen at the earth.

1. INTRODUCTION

Pioneer Venus orbiter (PVO) magnetometer observations at low altitudes in the nightside ionosphere have been used by Russell et al. [this issue] to set an upper limit on the intrinsic near the planet and its wake in which magnetic fields dominate its playing any role in the solar wind interaction with Venus. Hence the magnetosphere of Venus (i.e., those regions low altitudes in the nightside ionosphere have been used by Russell [1979], Breus [1979], and Slavin and Slavin [1979]). In particular, the magnetic moment of the planet that is small enough to pre-
In addition, depletion of energetic electrons (>10^2 eV) in the ionosheath observed by Mariner 10 [Fjeldbo et al., 1975], and Venera 9 and 10 [Ivanov-Kholodny et al., 1979]. Prior to the direct observations of the ionopause the M5 altitude recorded in 1967 has sometimes been regarded as somehow anomalous with the smooth variation with SVS angle in the solar minimum positions from M10, V9, and V10 represented by a solid line in Figure 3 taken from Ivanov-Kholodny et al. being interpreted as support for a simple hard impenetrable model of the solar wind interaction with Venus [Breus, 1979]. However, Pioneer Venus ionopause crossings indicated in Figure 3 with plus signs show large variations relative to the M10, V9, and V10 points predominately in response to changing solar wind dynamic pressure [Elphic et al., 1980] with ionospheric particle measurements implying an energy input from the solar wind of the order of 10^-4 erg/cm^2 s [Knudsen et al., 1979], which corresponds to a 10% absorption of the incident solar wind kinetic energy flux (i.e., \( \frac{1}{2} \rho_n V_w^2 \sim 10^4 \text{ erg/cm}^2 \text{s} \)) by such means as Joule heating with ionospheric currents [Elphic et al., this issue] or the damping of whistler mode waves of bow shock and ionosheath origin after they propagate into the ionosphere [W. W. L. Taylor et al., 1979]. For the purpose of understanding bow shock location it is important to note that while the altitude of the ionopause is quite variable during the current epoch, the spread in shock position due to such variability in the context of an impenetrable obstacle model is only \( \sim 1-2\% \) about the mean because of the large radius of Venus relative to the thickness of the ionosphere and its changes. Ionopause structure is studied in detail by a number of authors such as Brace et al. [this issue], Elphic et al. [this issue], Sprenner et al. [this issue], and H. A. Taylor, Jr., et al. [this issue].

2. Near-Planet Bow Shock

The solar wind is a collisionless anisotropic multicomponent magnetized plasma that expands outward from the sun with a typical ratio of bulk flow speed to the medium's Alfvén and sonic wave group velocities of about 6-7 at 0.72 AU (see Tables 1 and 2) giving rise to a bow shock upstream
of deflecting obstacles such as the planets. Theoretical approaches to modeling the hypermagnetosonic flow of plasma past these bodies have centered on the gas dynamic description to which the dissipationless single fluid MHD problem is thought to reduce for Alfvénic Mach numbers $M_A$ in excess of $\sim 10$ [Spreiter and Rizzi, 1974; Spreiter and Stahara, [this issue]. In the vicinity of the planet, bow shock shape and location are determined by the upstream flow parameters and boundary conditions on the obstacle surface. Examination of characteristic lines produced by gas dynamic calculations of flow about the earth's magnetopause [e.g., Spreiter et al., 1966] shows that only the portion of the shock surface forward of about one stagnation point radius behind the center of the planet possesses direct knowledge of the dayside deflecting boundary. Far downstream the obstacle starts to resemble a point source with the distant shock wave weakening as it asymptotically approaches the 'Mach cone' of half angle

$$\Psi = \sin^{-1}\left[1 - \frac{M^4}{M_A^4 + 1}\right]^{-1/2}$$

oriented symmetrically with respect to the solar wind velocity vector in the planetary rest frame, where $M$ is the free stream sonic mach number [Dryer and Heckman, 1967]. However, the flow about the earth and to a lesser extent Venus differs from that about a simple hard impenetrable sphere in that the magnetotail region effectively excludes inflow and in axial diameter is as large as or larger than the forward deflecting surface in the terminator plane, as is discussed further in section 4.

Accordingly, for the purpose of studying the solar wind interaction with the Cytherean ionosphere this section considers in Figures 4–8 only those bow shock crossings recorded by PVO and other spacecraft with $X' \geq -1 R_V$. Figure 7 displays as line segments the portions of the Venera 9 and 10 orbits over which the transition between shocked and unshocked solar wind plasma occurred in the wide-angle plasma analyzer [Verigin et al., 1978]. As is shown, the near-planet bow shock observed by the two Soviet orbiters in 1975–1976 appeared quite stable in location, as was the dayside ionopause altitude inferred from their radio occultation measurements in Figure 3. Its close proximity to the planet, at least in some cases, was difficult to reconcile with the expectations of gas dynamics [Romanov et al., 1978]. The Mariner 10 shock encounter [Bridge et al., 1974; Russell, 1977] was in good agreement with the mean V9 and V10 boundary position, while the Mariner 5 crossing [Bridge et al., 1967; Russell, 1977] in 1967 was more distant from the planet. For both the M5 and M10 flybys the upstream flow Mach numbers were similar to $M$ and $M_A$ values of $\sim 6$–$7$ [Shefer et al., 1979; Lepping and Behannon, 1978]. Assuming the SVS angle dependence of ionopause altitude from the Venera observations displayed as a solid line in Figure 3, the subsolar heights for M5 and M10 were about 500 km and 280 km, respectively, the difference being attributed to changing solar wind dynamic pressures and the ionospheric effects of solar EUV radiation in each case [Wolff et al., 1979]. As was discussed earlier, ionopause altitude variations should have little effect on obstacle radius and hence shock altitude, such as in the case, where the simple tangential discontinuity obstacle model of the interaction would predict the M5 shock crossing to be more distant by a factor of $(6050 + 500)/(6050 + 280) \approx 1.03$ than that of M10 after the SVS angle dependence of shock shape is taken into account. However, the observed ratio in the terminator plane is $\sim 1.3, as is evident in the figure. A possible explanation that was first suggested in reference to the solar wind interaction with the moon [Sonett and Colburn, 1968] and later invoked by Russell [1977] at Venus is that the exosphere/ionosphere can absorb part of the incident flow and can thereby present an effective obstacle to the solar wind that is smaller than the physical dimensions of the planet. In this connection it is of interest to note that not only upstream solar wind parameters but also solar EUV emissions may exert some control over the ability of the upper ionosphere to shield itself from the solar wind as suggested by Slavin et al. [1979b]. Solar EUV flux, which plays an important role in ionospheric photochemistry [e.g., Chen and Nagy, 1979],

### Table 1. Typical Interplanetary Parameters Measured at 1 AU and Scaled to 0.72 AU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 AU</th>
<th>0.72 AU</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>7.0</td>
<td>13.5</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$B_p$</td>
<td>4.24</td>
<td>8.2</td>
<td>nT</td>
</tr>
<tr>
<td>$B_p$</td>
<td>5.9</td>
<td>1.01</td>
<td>nT</td>
</tr>
<tr>
<td>$V_{sw}$</td>
<td>430</td>
<td>430</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>$T_e$</td>
<td>$7 \times 10^4$</td>
<td>$9.7 \times 10^4$</td>
<td>°K</td>
</tr>
<tr>
<td>$T_e$</td>
<td>$1.5 \times 10^5$</td>
<td>$2.5 \times 10^5$</td>
<td>°K</td>
</tr>
</tbody>
</table>

### Table 2. Derived Quantities From Table 1 Relevant to the Bow Shocks of Venus and the Earth

<table>
<thead>
<tr>
<th>Derived Quantity</th>
<th>1 AU</th>
<th>0.72 AU</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMF spiral angle</td>
<td>45</td>
<td>36</td>
<td>deg</td>
</tr>
<tr>
<td>$\omega_{ce}$</td>
<td>24</td>
<td>33</td>
<td>kHz</td>
</tr>
<tr>
<td>$\omega_B$</td>
<td>556</td>
<td>772</td>
<td>Hz</td>
</tr>
<tr>
<td>$c/\omega_p$</td>
<td>89</td>
<td>64</td>
<td>km</td>
</tr>
<tr>
<td>$P = n k_B (T_e + T_i)$</td>
<td>$2.1 \times 10^{-10}$</td>
<td>$6.5 \times 10^{-10}$</td>
<td>dynes cm$^{-2}$</td>
</tr>
<tr>
<td>$B^2/8\pi$</td>
<td>$1.4 \times 10^{-10}$</td>
<td>$4.1 \times 10^{-10}$</td>
<td>dynes cm$^{-2}$</td>
</tr>
<tr>
<td>$\beta = 8n_k P/B^2$</td>
<td>1.5</td>
<td>1.6</td>
<td>…</td>
</tr>
<tr>
<td>$V_s/M_A$</td>
<td>55, 7.9</td>
<td>69, 6.2</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>$V_p/M_A$</td>
<td>50, 8.7</td>
<td>60, 7.2</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>$M_{MD}$</td>
<td>5.8</td>
<td>4.7</td>
<td>…</td>
</tr>
</tbody>
</table>
and hence perhaps electrical conductivity, varies with solar cycle [Hinteregger, 1979] and has been estimated to have been ~30% greater for the Mariner 5–Venus encounter in 1967 as solar maximum approached than for Mariner 10 and Venera 9 and 10 near minimum [Wolff et al., 1979]. By comparison, dynamic pressure was twice as high for M10 than for M5 [Lepping and Behannon, 1978; Shefer et al., 1979], while the upstream interplanetary magnetic field was less aligned with the X axis and less steady for M5 [Bridge et al., 1967] than was the situation for M10 [Ness et al., 1974]. In addition, the Mariner 10 Lyman alpha observations indicated a decrease in exospheric neutral hydrogen by at least a factor of 2 from the Mariner 5 levels near solar maximum [Broadfoot et al., 1974]. Thus the larger effective obstacle to the solar wind inferred from the M5 measurements could be associated with higher solar EUV flux, a denser neutral exosphere, a lower external dynamic pressure, and/or the effects of IMF orientation and its variations on the ionosphere. Studies to be performed in the future as well as those discussed in this article are aimed at gaining an understanding of the variation in the Venus interaction with the solar wind associated with these parameters and others.

Figure 4 shows the location of 172 bow shock crossings by PVO during its first Venus year in orbit for which \( X' \geq -1 \) \( R_V \). Multiple encounters were relatively rare for Pioneer Venus dayside boundary crossings, but when present, the average bow shock position per inbound or outbound pass was used. All crossing identifications were made with magnetometer observations as available, crossings at small angles to the shock surface such as occur at smaller and larger SVS angles being excluded to avoid biasing the surface mapping with nonuniform spatial coverage. As was found by Slavin et al. [1979a] in a preliminary study, the Venusian bow shock surface is not only very similar to its terrestrial counterpart in shape but also in variation about its mean position, which at the earth is due to the sixth root dependence of ionopause height on solar wind dynamic pressure [Binsack and Vasyliunas, 1968; Fairfield, 1971]. At Venus the small contribution of ionosphere thickness to obstacle radius and the exponential dependence of ionospheric pressure on altitude limit the effects of varying external pressure on shock altitude to ~1–2% compared with ~10% at the earth [Holzer and Slavin, 1978; Slavin et al., 1979a].

In the earlier study, bow shock crossings recorded during the first 65 orbits of PVO were modeled with a simple polar form conic whose focus was centered on the planet [Holzer et al., 1972],

\[
 r = L/(1 + \epsilon \cos(SVS)) \tag{2}
\]

where \( r = (X'^2 + Y'^2 + Z'^2)^{1/2} \), \( L \) is the semi-latus rectum, and \( \epsilon \) is the eccentricity. Thus aberration due to the orbital motion of Venus is taken into account, but the actual solar wind velocity direction at the time of the crossings is not. However, this latter effect is small owing to the strong tendency of the solar wind velocity to be oriented radially outward from the sun [Wolfe, 1972]. A best least square fit to the near planet crossings from the first year of magnetometer data in Figure 4 produced \( \epsilon = 0.80 \) and \( L = 2.44 \) \( R_V \), [Slavin et al., 1979a]. In order to further enhance the goodness of fit the focus was allowed to range along the \( X' \) axis with the optimum fit found to occur with the focus at \( X_0 = +0.2 \) \( R_V \) for which \( \epsilon = 0.80 \) and \( L = 2.22 \) \( R_V \), with a slightly smaller rms deviation of 0.17 \( R_V \). It was further noted that this fit as shown in Figure 4 appears a little too far from the planet for the smallest SVS angles and too close at the largest angles, suggesting that a better fit (i.e., smaller rms deviation) is possible with a larger eccentricity. Accordingly, the fit in Figure 4 was iterated upon by binning the points by equal intervals in cos (SVS) normal to the curve and fitting the medians as shown in Figure 5, which effectively weights the data to create a uniform sampling with cos (SVS) to be fit. In the coordinates \( 1/r \) and cos (SVS), conic section curves are straight lines, as can be seen by inverting (2):

\[
 1/r = \epsilon \cos(SVS)/L + 1/L \tag{3}
\]

The best least square fit to the points in Figure 5 does give a larger eccentricity of 0.88 with nearly the same \( L = 2.21 \) \( R_V \) to produce a better fit with an rms deviation for 172 crossings of 0.16 \( R_V \). As it is displayed, this curve is slightly higher than

\[
\text{Fig. 4. One hundred and seventy-two Pioneer Venus shock crossings plotted in solar wind aberrated solar ecliptic coordinates along with a mean forward ionopause assumed spherical at an altitude of 300 km.}
\]

\[
\text{Fig. 5. Medians in shock position as described in the text displayed in conic coordinates together with a best fit (see Table 3).}
\]
the medians at both ends but lower in the center, so that no further improvement can be expected with a different eccentricity. These results are summarized in Table 3. Using the best mean surface, all of the crossings in Figure 4 have been mapped into the aberrated terminator plane and plotted as a histogram in Figure 6. As is shown, the mean of the distribution is \(2.39\, R_v\) with a standard deviation about the mean of nearly 10%, which as mentioned earlier is similar to that observed for the terrestrial shock [Fairfield, 1971], where the cause is a nearly impenetrable, but compressible, obstacle.

The average bow shock from the Pioneer Venus observations described above is compared with M5, M10, V9, and V10 in Figure 7. While in good agreement with M5 near solar maximum in 1967, the shock in 1978-1979 probed by PVO is seen to be \(~35\) percent more distant from the center of the planet in the \(X' = 0\) plane than was the case for M10, V9, and V10 in 1974-1976. The possibility of this increase in shock altitude being due to a spatial asymmetry in shock shape such as that proposed by Cloutier [1976] sampled at differing locations by the high-inclination Pioneer Venus orbiter and the lower-inclination Venera satellites was discounted by Slavin et al. [1979b] after an examination of the dependence of shock altitude on the IMF orientation failed to detect any significant asymmetry such as had been reported by Romanov et al. [1978] and set an upper limit of \(~12\)% on the contribution from this source to the total change evident in Figure 7. The study of Slavin et al. is extended here with the 172 shock crossings in Figure 4 as displayed in Figure 8. The angle measured counterclockwise as viewed from the sun between the upstream IMF vector projected into the terminator plane and the shock position vector in that same plane is termed \(\Delta x_p\). Thus an interplanetary field parallel to the +\(Z'\) axis at the time of a shock crossing in the \(Y' = 0\) plane with \(Z' > 0\) corresponds to \(\Delta x_p = 0^\circ\), while if the IMF had been oriented parallel to the +\(Y'\) axis for that same crossing, then \(\Delta x_p = 90^\circ\). The near-polar nature of the PVO orbit and the tendency of the IMF to lie parallel to the plane of the ecliptic thus produce more PVO shock encounters in the regions about \(\Delta x_p = 90^\circ, 270^\circ\) compared to \(\Delta x_p = 0^\circ, 180^\circ\) as is evident in the top portion of Figure 8. In the lower part of the figure, mean shock altitude in \(20^\circ\) bins as a function of upstream IMF orientation is displayed as was done by Slavin et al. [1979b]. The standard deviation of the means is only \(0.06\, R_v\), and hence the most probable upper limit on any asymmetry with respect to IMF direction is \(\sim10^\circ\) km. Accordingly, it does not appear that the different inclinations of PVO and Venera orbiters could contribute as much as \(1\) percent to the \(~35\) percent growth in shock altitude from 1975 to 1979. Further, it is also concluded that at Venus the shock position in the terminator plane is more symmetric than has been reported for the earth by some studies [e.g., Formisano, 1979], possibly owing to the intrinsic nature of an ionospheric obstacle as opposed to a dipole with variable, but approximately perpendicular, orientation with respect to the solar wind. It should also be noted that this growth in shock height cannot be attributed solely to the higher ionopause altitude in 1978-1979, which may be due to depressed solar wind dynamic pressure as occurred at last solar maximum [e.g., Fairfield, 1979], over 1974-1976 shown in Figure 3. The \(\sim270\)-km subsolar ionopause height suggested by the Venera and M10 radio occultation data would require a subsolar altitude during the current epoch of \([1.35(6050 + 270) - 6050] \sim2480\) km to explain the growth in shock altitude in terms of a simple tangential ionospheric obstacle model of the interaction without any 'cometary' processes in-
volving the neutral atmosphere as have already been men-
tioned. The actual growth in the ionopause height with the
approach of solar maximum is closer to ~50 km with part of it
probably also due to the previously cited solar cycle variation
in solar EUV flux. The contention of Slavin et al. [1979b]
based upon terrestrial solar wind and shock studies that there
was no large change in solar wind Mach numbers between
1974 and 1979 is further strengthened in section 4, where the
downstream PVO shock crossings are shown to lie no farther
from the X' axis than were those of Venera implying similar
Mach cone angles, and hence Mach numbers via equation (1),
at the time of solar minimum and maximum. Further, the
Mach numbers to be displayed in later portions of this article
computed from PVO measurements do not seem inconsistent
with the expectations based upon average values at 1 AU
scaled to the orbit of Venus as shown in Tables 1 and 2. Thus
the cause of the increase in shock altitude evident in Figure 7
appears to lie with a solar cycle modulation in the solar wind
interaction with the planet possibly associated with the effects
of changing EUV flux on the upper ionosphere and exo-
sphere. In the former case, any variation in ionospheric elec-
trical conductivity would influence its ability to deflect the so-
lar wind as well as the rate of solar wind energy deposition
through joule heating, while in the latter case, altering the
neutral particle profile at ionopause and higher altitudes will
affect the rates of charge exchange and photo-ion pickup and
possibly modify the ionosheath flow field. In addition, the
large orbit to orbit variability in shock height already dis-
cussed is preliminary evidence for shorter-term modulations
of these types.

In the gas dynamic approximation a theoretical relationship
has been established by Spriter et al. [1966] between the nose
distance of the obstacle, D, and the shock standoff distance, d,
such that

\[ d/D = (1.1/M_s^2)((\gamma - 1)M_s^2 + 2)/(\gamma + 1) \]

(4)

where \( \gamma \) is the ratio of the specific heats of the gas at constant
pressure and volume. At the earth the observationally deter-
mained value of \( d/D \) is 0.33 [Fairfield, 1971] for a measured \( M_s \),
~ 7 implying \( \gamma \approx 1.9 \), which is between 2 and 5/3, correspon-
ding to an ideal monotonic gas with 2 degrees and 3 degrees of
freedom, respectively. In the absence of theoretical or empiri-
cal means of obtaining values of \( \gamma \) from basic plasma parame-
ters (see, for example, Chao and Wiskerchen [1974]) it is not
possible to scale \( \gamma \) with distance from the sun as was done for
other relevant quantities in Tables 1 and 2. However, in the
high \( M_s \) limit the jump conditions across a shock go as \((\gamma +
1)/(\gamma - 1)\) [e.g., Spriter et al., 1966], and thus the preliminary
study by Russell et al. [1979d], indicating that the bow shock
of Venus may be weaker than that of the earth, as well as the
study of plasma jump conditions by Mihalov et al. [this issue]
may imply that a slightly larger than terrestrial value of \( \gamma \)
should be used at Venus, as was suggested by Slavin et al.
[1979a]. Using \( \gamma = 2 \) and \( M_s = 6 \) from Table 2 in (4) yields
\( d/D = 0.39 \), which is ~20 percent larger than that found for the
earth. The best fit to the PVO shock crossings from Table 3
extrapolated to the subsolar point gives an altitude of ~2270
km for the nose of the bow shock which for \( d/D = 0.39 \) re-
quires an effective obstacle of ~60 km below the surface of the
planet.

An estimate of the uncertainty in the determination of the
subsolar shock height can be made directly from (2),

\[ \Delta r(SVS = 0\circ)/r(SVS = 0\circ) = |\Delta L/L| + |\Delta e/(1 + e)| L \]

(5)

where \( \Delta r, \Delta L, \) and \( \Delta e \) signify the uncertainties associated with
the shock distance, semi-latus rectum, and eccentricity. The uncertainty in \( L \) is quite small owing to the large number of

case. Hence for \( d/D = 0.39 \) the best determination of effective
subsolar obstacle height is ~60 ± 150 km, or more con-
servatively, using \( d/D = 0.33 \), it is ~210 ± 160 km, both of
which lie below the typical ionopause altitudes.

Accordingly, the bow shock encounters presented in Fig-
ures 4–8 are often too close to the planet to be compatible
with the gas dynamic models assuming no upstream sources
or sinks and a nonabsorbing obstacle at the observed iono-
pause altitudes. This finding together with the variabili-
y in shock location and its apparent solar cycle dependence are in-
dicative of a dynamic interaction between Venus and the solar
wind possibly as has been proposed by Cloutier et al. [1969],
Bauer and Hartle [1974], and Russell [1977]. More recently,
Gombosi et al. [this issue] have suggested from theoretical modeling that up to 10% of the incident solar plasma may be absorbed near the ionopause (i.e., charge exchange with neutrals), thus influencing shock location. In this event the electric potential imposed by the solar wind across the planet could be of the order of 10 percent the total available, or ~4 kV, as opposed to the small 40 V implied by the near tangential discontinuity model of the ionopause [Daniell and Cloutier, 1977]. Just as dayside magnetic reconnection is thought to control the potential across the terrestrial magnetosphere, the amount of ionospheric absorption determined by solar wind conditions and possibly solar radiation sets the electric potential drop which powers the magnetosphere of Venus. The larger potential suggested here on the basis of bow shock-inferred knowledge of the ionosheath flow field could provide the ultimate source of energy for the 1- to 3-keV ions observed in the magnetotail plasma sheet by Verigin et al. [1978] as well as during periods of changing tail magnetic configuration referred to as 'substorms' by Romanov et al. [1978] when inductive mechanisms should also produce charged particle acceleration.

3. INFLUENCE OF IONPAUSE ALTITUDE AND SOLAR WIND CONDITIONS

To further investigate the large variation observed by PVO in bow shock position, the ionopause crossings in Figure 3 with SVS ≤ 50°, for which a shock crossing recorded on the same inbound or outbound pass is available in Figure 4, were identified. Crossings of these two boundaries on the same leg of the orbit were required to minimize the effects of temporal variability and provide the closest approximation to a 'snapshot' possible with Pioneer Venus. Ionopause encounters with SVS ≤ 50° were chosen both because it is the forward obstacle surface that is expected to influence the bow shock in the region considered in Figure 4 and because for those sunward crossings the ionopause appears approximately spherical, so that the observed boundary distance can be assumed to approximately equal the subsolar distance for the purposes of making comparisons among crossings at various SVS angles. Of the 23 events meeting those two criteria, solar wind ion number density and flow speed were available for 18 which are considered in Figures 9 through 13.

In the upper portion of Figure 9 the distance from the center of the planet to the bow shock, $R_{BS}$, in the aberrated terminator plane is plotted as a function of ionopause distance from the center of Venus, $R_{ip}$. Shown as a dashed line in both panels, with the bottom one to be discussed later, is the expected mean terrestrial dependence already considered

$$R_{BS}(X' = 0) = 1.33(\text{subsolar obstacle radius}) \times (\text{terrestrial value of } R_{BS}(SVS = 90^\circ)/R_{BS}(SVS = 0^\circ)) = 2.4R_{ip}$$

In agreement with the conclusion reached in the previous section that the shock is generally closer to the planet than is found by scaling the earth observations despite the slightly smaller Mach numbers anticipated at 0.72, 13 of the 18 cases in the top panel are at lower altitudes than the terrestrial analogue. Further, the correlation coefficient between $R_{BS}$ and $R_{ip}$ is not great, suggesting the presence of more important controlling factors to be identified. A trend toward increasing $R_{BS}$ with larger $R_{ip}$ is evident, but as the shock altitude increases with decreasing Mach number and ionopause distance grows with smaller dynamic pressure, both of which follow solar wind speed, the effects of these two parameters must be examined separately before a causal relationship between $R_{BS}$ and $R_{ip}$ is drawn.

To this end, Figure 10 investigates the dependence of $R_{BS}$ on the upstream Alfvén Mach number. A significant correlation is present with decreasing Mach number resulting in more distant shock position in the terminator plane, as has

$$R_{BS}(M_A) = -0.115M_A + 3.15, \text{ Corr} = 0.7$$

Fig. 10. Distance to the bow shock in the aberrated terminator plane as a function of Alfvénic Mach number.

$$R_{BS}(X' = 0) = -18nmnV^2 + 2.5$$

Correlation Coefficient = 0.2

Fig. 11. Distance to the bow shock in the aberrated terminator plane as a function of solar wind dynamic pressure.

$$R_{BS}^2(\frac{X'}{X} = 0) = 0.88nmnV^2 \cos^2 SZA + 7.3 \times 10^{-9}$$

Correlation Coefficient = 0.8

Fig. 12. Comparison of external pressure on the ionopause at given locations determined by magnetic pressure in the barrier and upstream dynamic pressure with simple model assumptions.
been found to be the case at the earth [Formisano, 1979]. Similar results are obtained when electron temperature, which in general is not measured, is assumed and the magnetostronic Mach number used in place of $M_a$. The only complete MHD solution for the flow of magnetized plasma about a blunt body is that of Spreiter and Rizzi [1974] for the special case of parallel IMF and solar wind velocity vectors, in which event methods exist to reduce the governing equations to those of gas dynamics as also occurs in the high $M_a$ limit [Spreiter and Stahara, this issue]. While in general $V$ and $B$ are not parallel, the location of the bow shock in the terminator plane for $M_a = 10$ and $y = 5/3$ as a function of $M_a$ from the model of Spreiter and Rizzi is shown with triangles in Figure 10 in the absence of any theoretical model allowing arbitrary $V$ and $B$. The absolute values of $R_{s0}$ have been scaled by the ratio of subsolar obstacle radii at earth and Venus for the purposes of comparison. For larger $M_a$, the aligned flow predictions approach that of the gas dynamic models which neglect $B$ and for which $M_a = 10$ produces shock surfaces too close to the planet at earth [e.g., Fairfield, 1971] where $M_a = 8$ is more typical as well as at Venus where $M_a = 6$ should be close to the mean. However, the slope of the linear fit displayed over the range in $M_a$ of 4 to 8 does not appear inconsistent with the model predictions of Spreiter and Rizzi.

In the bottom panel of Figure 9, $R_{s0}$ is the shock distance scaled by the linear relationship in Figure 10 to the mean value of $M_a$ for the 18 crossings of 6.4. While the correlation is still not strong, the slope of the linear regression to the $M_a$ corrected points is lower than in the upper panel as expected owing to the additive effects of Mach number and dynamic pressure as solar wind speed changes. Hence while the spread is large and the Cytherean shock is at smaller relative heights than the terrestrial model, the relationship between $R_{s0}$ and $R_{s0}$ does tend to parallel that of the earth’s bow shock/magnetopause on the average.

Figure 11 further contrasts the differences between the earth and Venus in the bow shock observations by plotting the $M_a$-corrected shock distance in the aberrated terminator plane against solar wind dynamic pressure. In doing so, it is assumed in the absence of any information on the helium abundance in the solar wind plasma that the ions are all protons. The actual helium contribution to the solar wind plasma that the ions are all protons. The actual helium contribution to the solar wind plasma that the ions are all protons.

As is noted in the introduction, the relationship between ionopause altitude and external pressure has been examined by Elphic et al. [1980]. It is pointed out in their equation (4) that for a homogeneous isothermal ionosphere in equilibrium with its exterior environment without significant intermixing a linear relationship exists between $R_{s0}$ and the logarithm of external pressure with the slope and intercept related to the ionospheric scale height and reference level pressure. Elphic et al. also determined that to a high degree the maximum magnetic energy density just outside the ionopause was approximately balanced by the ionospheric pressure inside the ionopause, suggesting the presence of very little plasma within the magnetic barrier. As is discussed by Siscoe et al. [1968] and Spreiter and Stahara [this issue], the pressure distribution along the forward portion of a blunt obstacle in a high Mach gas flow should be near that predicted by the Newtonian approximation, in which the pressure away from the stagnation point varies with the square of the cosine of the angle between the upstream flow direction and the normal vector from the obstacle surface. For the ionopause crossings considered here, this boundary surface is nearly spherical so that the external pressure will be assumed given by $0.88nmV^2$ where the factor of 0.88 relates dynamic pressure to stagnation pressure on the obstacle and $SZA$ is the solar zenith angle which is equivalent to SVS. Figure 12 plots the maximum magnetic pressure in the magnetic barrier as used by Elphic et al. against the predicted external pressure from the PVO upstream measurements. The agreement is good especially considering the neglect of helium ions in the solar wind, which would probably increase the factor 0.88 coefficient to a value near 1 and make the linear regression intercept closer to the origin and the variable time lag between the period of solar wind observations and the ionopause crossings, which for the 18 events here is the order of half an hour. Ionopause structure and the transmission of solar wind pressure through the ionosphere to the ionosphere are further examined by Elphic et al. [this issue] and Brace et al. [this issue].

In Figure 13 the dependence of $R_{s0}$ on both the external pressure inferred from upstream measurements and magnetic field observations near the ionopause is investigated by regressing boundary crossing distance on the logarithm of pressure as suggested by Elphic et al. [1980]. While the number of events considered in this study is not great, the superior ordering of $R_{s0}$ by log $(B_{n0}^2/8n)$ as compared with log$(0.88nmV^2$ cos$^2$ SZA) strongly suggests that the temporal variations in the solar wind during the time required for PVO to transverse the ionopause are significant in many cases. The slopes and intercepts in both panels are generally similar to those obtained by Elphic et al. despite the limited number of events used in this analysis and hence correspond to physically reasonable ionospheric pressures and scale heights as discussed in that paper. As solar wind pressure increases the percentage decrease in ionopause distance is similar to that found for the bow shock in overall magnitude. However, in contrast to the shock observations in Figure 11 a lower limit on ionopause height near 200 km is evident as has also been noted by Wolff et al. [1979], Vaisberg et al. [1980], and Brace et al. [this issue] and is similarly apparent in Figure 3. These studies have suggested the cause of this lower bound to be simply the exponential depen-
dence of pressure on altitude within the ionosphere, enhanced ionospheric heating from the solar wind for lower ionopause altitudes, and possibly the effects of increased ion-neutral collisions just beneath the ionopause on the transport processes such as diffusion, convection, and electrical conductivity. The study by Gombosi et al. [this issue] suggests an additional factor limiting the minimum ionopause height in the form of the neutral atmosphere supporting the solar wind pressure through increased charge exchange at low altitudes removing hot H+ from the ionosheath and replacing it by cool ions, the difference in energy and momentum being carried away by hot neutral hydrogen as is thought to occur extensively in the solar wind interactions with comets.

4. DISTANT BOW SHOCK

At the earth the solar wind interaction with the geomagnetic field pulls back magnetic field lines anchored in the planet to form a magnetotail [Ness, 1965]. It is composed of two lobes containing oppositely directed magnetic fields separated by a current layer embedded in a thicker plasma sheet of average density of \( \sim 10^{-4} \text{ cm}^{-3} \) and mean particle energies of \( \sim 10^5 \text{ eV} \). In addition, the tail region is subject to large spatial and temporal variations including bulk plasma flows during periods of enhanced dawn-dusk electric fields and energy input from the solar wind termed geomagnetic storms and substorms [e.g., Caan et al., 1979]. While the magnetotail has not been well studied either experimentally or in theory past the orbit of the moon, \( \sim 60 R_E \) it has been reported to be as far as 3100 \( R_E \) downstream from the earth by Pioneer 7 [Intriligator et al., 1979a]. In Figure 14 the earth's distant bow shock and magnetotail from Fairfield [1971] have been plotted in relation to Venus with the scaling of 10.8 \( R_E = 1 R_V \) which corresponds to making the near-planet shock observed by PVO approximately coincide with that of the earth and is roughly equivalent to scaling by the subsolar radii at each planet. Past \( \sim 6 R_V \) (i.e., \( \sim 65 R_E \)) no magnetopause and a dashed bow shock curve is shown owing to the poor sampling available farther downstream only by Explorer 33 [Howe and Binsack, 1972; Mihalov, 1974] and Pioneers 7 and 8 [Scarf, 1979, and references therein] as mentioned above. Near \( \sim 6 R_V \) in the figure the maximum spread in magnetopause location \( (Y^2 + Z^2)^{1/2} \) scales to about \( \pm 1.4 R_V \) [Howe and Binsack, 1972] and \( \pm 1.1 R_V \) for the earth's shock [Mihalov, 1974].

Venera 9 and 10 have reported evidence that Venus also possesses a magnetotail with two lobes similar enough to that of the earth to have these fields at one time partially attributed to the existence of a significant planetary magnetic moment whose magnitude was then estimated from the tail magnetic flux density [Dolginov et al., 1978]. However, as was correctly concluded by Dubinin et al. [1978] on the basis of laboratory experiments and confirmed by Pioneer Venus magnetometer measurements [Russell et al., this issue] the presence of a magnetotail is not a sufficient condition upon which to conclude that the central body has a net magnetic moment. The diameter of the Cytherean tail as determined by V9 and V10 magnetometer observations varies from \( -1.3 R_V \) at \( X' = -1.3 R_V \) to \( -2.3 R_V \) at \( X' = -5.6 R_V \) [Dolginov et al., 1978] and thus tends to lie just within the optical shadow of the planet at lower altitudes and outside the shadow for distances of more than 6 \( R_V \) downstream. In additional, Venera observations [Dolginov et al., 1978, and references therein] have also indicated that inside the tail lobes the plasma sheet is confined \( \beta \ll 1 \), and the magnetic flux density is 15–20 nT, as would be required for pressure balance with the solar wind for a magnetotail that flares out into the flow less than that of the earth and experiences less aerodynamic stress normal to its outer boundary [e.g., Mihalov et al., 1970]. Eroshenko [1979] has used Venera orbiter magnetic field data at 1500- to 2000-km altitudes on the nightside to show that as expected for an induced magnetosphere, the orientation of the current sheet separating the two lobes of the tail is perpendicular to the vector component of the interplanetary magnetic field transverse to the upstream solar wind velocity vector with a time lag of up to ~30 min for changing IMF direction. By utilizing the same type of arguments as have been applied to the terrestrial magnetotail [Dungey, 1965] a magnetotail length at Venus up to \( \tau V_{sw} \sim 130 R_V \) is implied by the findings of Eroshenko assuming the tail field lines to be connected to the IMF as opposed to 'closed.' The occasionally large ionospheric magnetic fields reported by Elphic et al. [this issue] also suggest the possibility of a highly variable magnetotail with its length and magnetic flux content controlled by the dayside interaction as has long been envisioned for comets [e.g., Alfvén, 1957]. In fact, Mariner 10 observed plasma electron and magnetic field perturbations believed to be associated with the Venusian wake region up to \( \sim 10^2 R_V \) downstream, although the magnetotail proper is not thought to have been penetrated [Yeates et al., 1978; Lepping and Behannon, 1978]. It is also of interest to note that the delay time of ~30 min in the response of the Venus magnetotail to the interplanetary electric field variations would suggest a significant electric potential on the order of 1 kV by scaling the terrestrial value using the tail flux convection cycle time of Siscoe et al. [1975] for intrinsic field magnetospheres which may have applicability at Venus if the feet of the tail field lines observed by Eroshenko [1979] were in fact actually convecting through the ionosphere as for example is shown by Brace et al. [this issue, Figure 13].

Plasma instruments on Venera 9 and 10 have in addition to detecting the plasma sheet also identified a broad boundary layer analogous to the plasma mantle of the terrestrial magnetotail [e.g., Vaisberg et al., 1976; Gringauz et al., 1976; Romanov et al., 1978]. These observations include evidence for mixing of plasmas of ionospheric and solar wind origin [Vaisberg et al., 1976] and hence some direct flow of solar wind behind the planet, as has been suggested would be the consequence in fluid mechanics of a 'viscous' interaction between the solar wind and the ionosphere [Peres-de-Tejada, 1979]. Pioneer Venus orbiter plasma analyzer measurements [Wolfe et al., 1979] have also found evidence of ionosheath flow with a component in toward the \( X' \) axis behind the planet [Intriligator et al., 1979b].

An additional source of information on the ionosheath flow field in the neighborhood of the wake is the location of the distant downstream bow shock surface. For the purposes of conducting a preliminary survey of the high-altitude nightside shock crossings with PVO the magnetic field data from orbits 165 to 180 (see Figure 1) were examined as available. Pioneer Venus bow shock crossings are shown as plus signs in Figure 14 with the initial and final encounters on a given pass displayed and connected with a solid line segment in the event of multiple encounters. Shock locations from the M5 flyby [Bridge et al., 1967; Russell, 1977], the Venera 4 and 6 probes [Gringauz et al., 1970], and the Venera 9 and 10 satellites [Smirnov et al., this issue] are also shown for comparison as indicated in the figure. In the region \( -6 R_V < X' < -1.5 R_V \) the Venus shock crossings from all sources straddle the
scaled terrestrial shock as is expected owing to the previously discussed similarity in shape between the Cytherean and terrestrial near-planet shock surfaces and the scaling used in constructing Figure 14. However, at greater distances downstream the Venus shock as sampled by both PVO and Soviet orbiters lies closer to the $X'$ axis than does the shock at the earth. From equation (1) and Table 2 the asymptotic Mach cone angles at 1 AU and 0.72 AU are expected to be $-10^\circ$ and $-12^\circ$, respectively, on the average. Thus with the two shock waves lying close together for $X' > -4 R_v$ it would be expected that the shock surface at 0.72 AU would move outward from the axis of symmetry more rapidly with decreasing $X'$ than the shock at 1 AU, owing to its larger Mach cone angle. However, the opposite effect is seen in Figure 14 with the Venus shock of $-1.5 R_v$ closer to the $X'$ axis for $-11 R_v < X' < -7 R_v$ than the scaled terrestrial shock surface. The probable cause is the small volume occupied by the Cytherean magnetotail relative to that of the earth from which ionosheath flow is believed to be largely excluded. At the distances downstream shown the shock wave has a slope twice as great as the eventual Mach cone angle so that it is still being influenced by the flow field adjacent to the obstacle which at Venus and the earth is of different shape downstream of the terminator plane. In addition, if there is enough charge exchange and

Fig. 13. Ionopause distance as a function of external pressure determined by two different sets of measurements.

Fig. 14. Distant bow shock of Venus and Earth ($10.8 R_e = 1.0 R_v$)

Fig. 15. Pioneer Venus ion mass spectrometer, electron temperature probe, electric field detector, and magnetometer measurements across the bow shock on orbit 17 (note that the lack of OIMS data before 1604 and OETP data after 1607 is due to plotter limitations and not the instruments.)
photo-ion pickup near the planet, the ionosheath flow could be altered at Venus relative to the earth as would also be the case if a different value of \( \gamma \) were more appropriate as has already been discussed. Studies to be conducted will map the entire Venus ionosheath region for \( x' > -12 R_e \) using Pioneer Venus measurements and examine the far field flow about Venus and its wake in a more definitive manner than has been possible in this very preliminary survey of shock position. As such, it will be equivalent by the scaling described to studying the terrestrial magnetosheath up to 130 Re behind the planet, which has only rarely been possible, and perhaps yield knowledge that will be of use in the coming decade when the first comet mission are conducted.

5. SHOCK STRUCTURE

In the preceding sections the Venus bow shock has been examined in the context of MHD and gas dynamic continuum models for the purpose of studying the flow of solar wind plasma about the planet. Owing to the dissipationless nature of these fluid approaches the shock is treated as a discontinuity surface of vanishing thickness across which the flow parameters jump in accordance with the MHD Rankine-Hugoniot relations [de Hoffman and Teller, 1950]. Observations made at the terrestrial bow shock have shown the shock transition layer to accomplish these changes in the plasma parameters through a host of dissipative mechanisms including electrical resistivity, various plasma instabilities, and wave-particle interactions, upstream solar wind conditions determining the dominant process at a given time and location [e.g., Greenstadt and Fredricks, 1979]. In addition, there exist ahead of the bow shock regions of upstream waves and backstreaming particles collectively termed the 'foreshock' which are also of great interest [e.g., Greenstadt et al., 1979].

Table 1 scales some relevant interplanetary parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Earth</th>
<th>Venus</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n ) (particles/cm(^3))</td>
<td>10(^3)</td>
<td>10(^4)</td>
</tr>
<tr>
<td>( V_w ) (km/s)</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>( T_i ) (eV)</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>( T_e ) (eV)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( B ) (nT)</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2 contains derived quantities that have been useful in ordering the wide variety of shock structure observed at the earth [e.g., Dobrowolny and Formisano, 1973]. The slightly more radial IMF at 0.72 AU will result in some shift of the regions of the shock surface for which the angle between the upstream IMF and the shock normal \( \theta_{sw} \) is greater or less than 50°. In the latter case a thick transition region up to several \( R_e \) in width results at the earth, and the shock is termed quasi-parallel in structure [Greenstadt et al., 1970]. For \( \theta_{sw} \approx 50° \) the jump in the flow variables is generally well defined, a transition layer scale length of the order of the speed of light divided by the ion plasma frequency \( \omega_p \) leading to the expectation of increasing shock thickness with increasing radial distance from the sun, an expectation which has been con-
Fig. 18. Pioneer Venus electric and magnetic field observations across the bow shock on orbit 3 outbound.

confirmed at Jupiter [Scarf et al., 1979]. At any given time, different portions of the shock wave are either quasi-perpendicular or quasi-parallel, the large physical dimensions of the terrestrial shock and the rarity of simultaneous multiple-satellite boundary crossings generally precluding concurrent observations of both regions. As was noted by Greenstadt [1970], shock measurements at the spatially smaller bow shocks of Mercury, Venus, and Mars by relatively fast moving spacecraft at shock altitudes, such as PVO, will be able to examine the global condition of the shock at two widely separated points over intervals of time sufficiently short that the upstream variables will have remained constant in some cases. The other quantities in Table 2 such as \( \beta \) and sonic, Alfvenic, and magnetosonic Mach numbers all show some changes from the earth to Venus, but according to present theory should not result in greatly different shock structure than has already been observed at 1 AU [Greenstadt and Fredricks, 1979] unless caused by the nature of the solar wind interaction with Venus. In particular, the ionosheath of Venus has a non-negligible neutral particle population which may participate in charge exchange and photo-ion pickup as mentioned earlier [see Gombosi et al., this issue], thereby modifying the sheath flow field and hence perhaps the shock [Wallis, 1973].

Figures 15–20 display high-resolution Pioneer Venus observations across six bow shock crossings from the first 20 orbits chosen both on the basis of data availability and to show some of the variations in structure encountered in this very preliminary survey. Table 4 lists three basic parameters describing the interplanetary conditions for each of the shock crossings. The normals to the shock surfaces, \( \alpha \), needed in computing all save one of those quantities, were obtained directly from the best fit conic surface found earlier as shown by Holzer et al. [1972]

\[
\alpha = \tan^{-1} \left[ \frac{\sin (\text{SVS})}{(1 + \cos (\text{SVS}))} \right]
\]

\[
\delta = \tan^{-1} \left( \frac{Z'}{Y'} \right)
\]

\[
\hat{n}_x = \cos (\text{SVS} - \alpha)
\]

\[
\hat{n}_y = \cos (\delta) \sin (\text{SVS} - \alpha)
\]

\[
\hat{n}_z = \sin (\delta) \sin (\text{SVS} - \alpha)
\]

Coplanarity determined normals obtained where the magnetic field was steady gave generally similar results as expected from past experience at the earth [Russell and Greenstadt, 1979]. As displayed in the table, \( \theta_{\text{hn}} \), is the angle between the upstream IMF and the normal to the shock surface at the location of the crossing, \( \beta \), is the ratio of solar wind ion pressure \( nkT_1 \) to the magnetic pressure \( B_0^2/8\pi \), and \( M_{\text{ms}*} \) is the magnetosonic Mach number, the asterisk indicating that it is based upon the solar wind velocity component perpendicular to the shock surface, as opposed to the free stream value, calculated with an assumed electron temperature of \( 2.5 \times 10^5 \) K from Table 1. Thus the shocks shown here span a range in \( \theta_{\text{hn}} \) of 35° to 89°, 0.3 to 1.2 for \( \beta \), and 1.9 to \( \geq 4.4 \) in \( M_{\text{ms}*} \).

Fig. 19. Pioneer Venus electric and magnetic field observations across the bow shock on orbit 6 inbound.
For the two shocks shown in Figures 15 and 16 it was possible to compare the shock signatures of four PVO experiments: the UCLA (University of California at Los Angeles) magnetometer [see Russell et al., this issue] the TRW electric field detector [see Scarf et al., this issue] the GSFC (Goddard Space Flight Center) electron temperature probe [see Brace et al., this issue], and the GSFC ion mass spectrometer [see H. A. Taylor et al., this issue]. Such a comparison of shock data is highly desirable not only for the purpose of studying structure, but also in determining the position of this boundary as evidenced by the discrepancies among the Mars 2 and 3 satellite particles and fields instruments as to the location of the Martian bow shock [e.g., Vaisberg, 1976]. While only the total magnitude of the magnetic field is shown for orbit 17 inbound in Figure 15, the IMF orientation was highly variable, $\theta_{BN}$ ranging from $-35^\circ$ to $-65^\circ$. Consistent with the variable and at least occasionally quasi-parallel $\theta_{BN}$, the magnetic field is highly irregular after first encountering the shock at $\sim 1602:48$ UT, 1544 (i.e., 103 km in all three panels). Coincident with the first increase in $B$, the 100-Hz channel of the electric field detector shows an enhanced value for the spectral density which being between the ion and electron gyrofrequencies corresponds to whistler mode waves as are typically observed in planetary bow shock waves [Scarfi et al., this issue]. In addition, while not displayed the increase in $B$ and the 100-Hz channel of OEFD (orbiter electric field detector) is also accompanied by a reduction in the 30-kHz channel which detects electron plasma oscillations (see Table 2) ahead of the shock associated with suprathermal electrons reflected back from the shock. The other two OEFD channels at 730 Hz and 5.4 kHz in the ion acoustic frequency ranges showed smaller changes at the shock for this particular shock crossing. Owing to the limited number of channels and their finite bandwidths the frequency at which the electric field detector produces the strongest shock signature is very much a function of the plasma parameters at the time of a given shock crossing which determine the natural frequencies of the plasma waves associated with the foreshock and transition layer. The Goddard electron temperature probe experiment uses axially (vertical dash marks in the figure) and radially (horizontal dash marks in the figure) mounted Langmuir probes to measure electron temperature and density as discussed in Brace et al. [this issue]. While the absolute calibration used here to convert probe current to density does not take into account the higher temperature of the ionosphere relative to that of the ionosheath plasma and thus overestimates $N_e$ by a factor of 10 or more, OETP detects an electron density increase very near the first increases in $B$ and wave activity. This is in good agreement with the terrestrial observations, which indicate electron heating beginning at the foot of the gradient in the magnetic field whereas ion thermalization continues at a slower rate through the entire transition layer and into the sheath [e.g., Greenstadt and Fredricks, 1979]. Further, the electron density envelope appears to follow that of the magnetic field into the ionosheath as expected where the field is frozen into the plasma. Finally, the uppermost panel shows the Goddard ion mass spectrometer shock signature, which is in the form of ion currents which result from the influx of particles with sufficient energy that thermal ion analysis techniques [H. A. Taylor et al., this issue] are not applicable, and at this point, no unique determination of particle mass or energy has been made. Examination of the detailed behavior of the currents for several orbits indicates that the sensor response is rather impulsive, which would be consistent with the entry of particles with energies of the order of 100 eV or higher. The plot symbols are coded for the measurement sequence and are not indicative of any variation in mass. As is displayed, the main peak in OIMS (orbiter ion mass spectrometer) current comes $\sim 4$ min (i.e., $\sim 10^4$ km in altitude) later than the first clear shock signature in the other instruments. However, while not shown, owing to plotting limitations, the earliest significant ion currents which are much lower in magnitude than the $\sim 1607$ level did occur near 1603. A more comprehensive comparison of shock crossing times with all four experiments for the early orbits shows agreement to better than a minute in general for OMAG (orbiter magnetometer) OEFD, and OETP (orbiter electron temperature probe), those of OIMS tending to lie closer to the planet by up to several minutes, suggesting that the ion mass spectrometer

**TABLE 4. Upstream Parameters for the Shock Crossings in Figures 15-20**

<table>
<thead>
<tr>
<th>Shock</th>
<th>$\theta_{BN}$</th>
<th>$\beta_i$</th>
<th>$M_{MS}$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 out</td>
<td>$51^\circ$</td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>3 out</td>
<td>$65^\circ$</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>6 in</td>
<td>$82^\circ$</td>
<td>0.3</td>
<td>2.7</td>
</tr>
<tr>
<td>6 out</td>
<td>$53^\circ$</td>
<td>0.4</td>
<td>1.9</td>
</tr>
<tr>
<td>17 in</td>
<td>$35^\circ-65^\circ$</td>
<td>1.0</td>
<td>3.9</td>
</tr>
<tr>
<td>18 in</td>
<td>$89^\circ$</td>
<td>0.5</td>
<td>$\geq 4.4$</td>
</tr>
</tbody>
</table>

Fig. 20. Pioneer Venus electric and magnetic field observations across the bow shock on orbit 6 outbound.
jump in plasma ion number density found by Mihalov et al. with the double amplitude of the ionosheath fluctuations in jump in the transverse $B$ is a factor of 4, which is near the Formisano and Hedgecock, 1972. Similar effects are seen here than the former. At the earth, increasing Mach number has amplitude magnetic fluctuations in the magnetosheath [e.g., Dobrowolny and Formisano, 1973]. This shock encounter is also well defined in the OEFD and OETP measurements at nearly the same time as observed with the magnetometer, but the main rise in OIMS ion currents is about a minute later than for the other experiments, as was the case for the previous orbit. The periodic variation in $N_e$ is a spin modulation of the particle flux entering the detector associated with the langmuir probes passing through the spacecraft wake. In addition, the strength of this high Mach shock may be examined by comparing the change in the magnetic field component tangential to the boundary surface and the electron density in passing through the shock transition. The jump in the transverse $B$ is a factor of $-4$, which is near the gas dynamic upper limit of $(\gamma + 1)/(\gamma - 1)$ for $\gamma = 5/3$, whereas the ratio of downstream to upstream electron density is larger near a factor of $\sim 7$, which is also bigger than the jump in plasma ion number density found by Mihalov et al. [this issue]. However, the greatness of the change in $N_e$ as measured by OETP may be due to the constant calibration factor used in Figure 16 which should vary with the increase in plasma temperature across the shock. Thus the PVO observations in Figures 15 and 16 of two very different shock crossings have shown general agreement as to the location of the boundary. In addition, further work quantifying the high-altitude measurements of OETP and OIMS may enable them to support the plasma analyzer ion observations with thermal electron and perhaps also some additional ion measurements.

Figures 17-20 display magnetometer and electric field observations across four additional shocks for the purpose of briefly considering the effects associated with varying $\theta_{BN}$, $M_n^*$, and $\beta_t$. As is shown in Table 4, two of the crossings, 6 inbound and 18, have $\theta_{BN}$ values in excess of $80^\circ$. In both cases there is an absence of upstream activity and the presence of a well-defined magnetic ramp up to the ionosheath $B$ level. By comparison, orbits 1, 3, and 6 outbound with $51^\circ \leq \theta_{BN} \leq 65^\circ$ do show evidence of upstream activity in both the OMAG and OEFD data, indicative of a well-developed foreshock as mentioned earlier. Finally, for orbit 17, where $\theta_{BN}$ was smaller and more variable, a much thicker and irregular transition region from solar wind to ionosheath conditions was found. Orbits 6 inbound and 18 have similar $\theta_{BN}$ and $\beta_t$ but different Mach numbers, with that of the latter at least 60% greater than the former. At the earth, increasing Mach number has been found to result in a more turbulent shock with larger-amplitude magnetic fluctuations in the magnetosheath [e.g., Formisano and Hedgecock, 1972]. Similar effects are seen here with the double amplitude of the ionosheath fluctuations in orbit 18 about 25% the mean field magnitude compared with only about 5% on orbit 6 inbound. Finally, orbits 1, 3, and 6 outbound exhibit comparable values of $\theta_{BN}$ and $M_n^*$, but with $\beta_t$ equal to 0.3 for 6 outbound and 1.0 and 1.2 for orbits 1 and 3, respectively. For orbit 6 outbound with the lower ratio of ion pressure to magnetic pressure the ionosheath fluctuation amplitude is small in comparison with either of the other two crossings with larger $\beta_t$. Again, this response is similar to that found at the terrestrial shock by more comprehensive studies [Formisano and Hedgecock, 1972].

With only one spacecraft at Venus it is not in general possible to separate spatial and temporal variations in the data and measure the thickness of the shock directly, as is done, for example, by the ISEE mission with its twin satellites [Russell and Greenstadt, 1979]. Observations made at the earth have shown the shock surface to be constantly in motion [e.g., Holzer et al., 1966] with velocities of the order of $10^5$--$10^6$ km/s relative to the planet [Greenstadt et al., 1972]. As the velocity of PVO at shock altitudes, 3--4 km/s, is not large in comparison with the expected speed of shock motions, it is necessary to rely on the terrestrial estimates of mean radial shock speed which are of the order of 10 km/s. Examination of the highest-resolution magnetic field data shows that the mean time spent by PVO in the shock transition layer for the quasi-perpendicular shocks examined here is of the order of ~5 s, which for a mean relative speed of 10 km/s implies a shock thickness of about ~50 km, which is similar to the accepted scaling of $c/\omega_p$, shown in Table 2 and in agreement with the similar conclusion reached by Verigin et al. [1978] using Venus 9 and 10 measurements. By comparison, at Jupiter Scarf et al. [1979] using Voyager 1 observations have estimated shock thickness to also be of the order of the ion inertial length, which for those observations was nearly 400 km.

Hence in this very preliminary survey of Pioneer Venus shock structure, no overt deviations from expectations based on terrestrial experience have been uncovered. In other studies, Scarf et al. [this issue] have compared the OEFD observations with those taken in the vicinity of the earth's bow shock and found evidence of higher relative spectral amplitudes at 30 kHz and 100 Hz, more diffuse crossings in general with electron oscillations being generated within the shock transition layer, and extension of upstream wave activity out to apoapsis possibly associated with solar wind interactions with exospheric neutrals as discussed earlier. In addition, Russell et al. [1979a] have found that the average magnetic field jump across the Venus shock is smaller than has been observed at the earth. The study of the variation in plasma ion density through the Venus shock wave by Mihalov et al. [this issue] produces similar results. If confirmed, these findings indicate the need to carefully evaluate conservation of mass, momentum, and energy with Pioneer Venus observations along streamlines beginning well upstream of Venus at apoapsis on the dayside and extending downstream into the wake region for the purpose of identifying the effects of neutrals on the flow field in general and on the bow shock in particular.

6. SUMMARY

In this paper an attempt has been made using Pioneer Venus observations to conduct a comprehensive, albeit in many ways cursory, examination of the Venus bow shock problem in its entirety drawing heavily on past work at both Venus and earth. The shape and location of the forward portion of the shock is determined in section 1. Its mean altitude in the aberrated terminator plane is found to be highly symmetric about the $X$ axis and independent of upstream IMF orientation. The extrapolated subsolar shock height is shown
through gas dynamic relations and scaling of the terrestrial analogue to imply an effective obstacle altitude below the height of the dayside ionopause. Short-term variability in position about the mean shock surface is similar in magnitude to that at the earth despite the relatively small changes observed to occur in total ionopause radius. Comparison with Venus bow shock observations by other spacecraft during earlier epochs reaffirms the conclusion of Slavin et al. [1979b] that currently available evidence suggests a large, ~35%, variation in distance to the shock with solar cycle that is due to changing solar wind Mach numbers. Section 3 furthers this work by investigating the relationship of shock location to ionopause position and solar wind conditions with a smaller group of events for which this information is now available. The dependence of shock position on that of the ionopause is found to be weak even after solar wind Mach number is taken into account. In addition, whereas ionopause altitude is shown to be well determined by the external pressure, the dependence of shock height on solar wind dynamic pressure is not great with a large spread as in the previous case. All of these findings are interpreted as evidence for a time variable solar wind interaction in which the ionosheath flow field, inferred here from shock observations, is influenced over both short and long time scales by the effects of charge exchange and photo-ion pick up involving the neutral exosphere and/or a lack of complete deflection of the incident solar plasma by the currents induced in the ionospheric plasma. A preliminary study of the location of the downstream bow shock at Venus is conducted in section 4. In contrast to the difference in shock position between PVO and Venera 9 and 10 near the planet, farther behind the terminator plane they converge into approximate agreement. In addition, it is found that at least up to 16 R v downstream the Venus bow shock does not flare away from the X’ axis as much as does the terrestrial example despite the larger Mach cone angle at 0.72 AU. The cause is believed to lie with the much smaller magnetotail of Venus relative to the intrinsic field magnetosphere of the earth. Accordingly, Pioneer Venus observations can be expected to give the first extensive look at the flow about a large obstacle in the solar wind of a shape different from that at the earth.

Finally, section 5 performs a brief survey of shock structure at Venus, examining six shock crossings from the early orbits for which data were available from a number of instruments. The shock signature in the magnetometer, electric field detector, and electron temperature probe are all found to be in good agreement, while that of the ion mass spectrometer and ratio of thermal ion pressure to magnetic field pressure appear consistent with theory and observation at the earth. However, more extensive studies conducted elsewhere, but cited here, suggest that some quantitative differences in shock structure at Venus relative to the earth due to the nature of the Cytherean solar wind interaction may exist.

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