SUNWARD FLOW IN JUPITER'S MAGNETOSHEATH

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Abstract. The position of Voyager crossings of Jupiter's bow shock show a dependence on solar wind pressure to the -1/3 power. This dependence is used to calculate typical bow shock speeds of 50 km/s from Voyager solar wind plasma data. Since the bow shock and magnetopause move approximately in unison in response to solar wind pressure changes, the resulting movement of the magnetosheath at a sizeable fraction of the solar wind speed leads to reversed, sunward flow in large portions of the dayside region when the boundaries are expanding. Voyager 1 plasma data show evidence of such reversed flow.

Introduction

Outstanding features in the data from both the Pioneer and Voyager spacecraft pairs are their encounters with Jupiter's bow shock and magnetopause many times over large distances [Intriligator and Wolfe, 1976; Bridge et al., 1979]. Smith et al. [1978] discuss the Pioneer 10 and 11 magnetopause crossings at both 100 R_J and 50 R_J and conclude that Jupiter's magnetosphere is considerably more compressible than Earth's. Further, the scattered boundary crossings over large distances imply large boundary speeds. From Pioneer 11 data, Smith et al. (1975) estimated bow shock speeds on the order of 100 km/s.

In this paper we consider the typical speeds of large scale Jovian magnetosheath motion in response to the continually changing solar wind pressure. We use Voyager solar wind data measured near Jupiter orbit to calculate speeds from the rate of change of pressure. We then show that the effect of the resulting high speeds is to reverse the antisunward component of flow to sunward flow over significant portions of the dayside magnetosheath when the magnetopause and bow shock are expanding. Voyager 1 plasma data consistent with reversed flow are presented.

Boundary Speeds

In the following we use the first order approximation that the bow shock and magnetopause move together and maintain a constant distance ratio relative to Jupiter. Since the positions of these boundaries depend upon solar wind pressure, their speed depends upon the rate of change of pressure. In this section we use pressure data to determine the probability of a spacecraft encountering the bow shock at any given speed.

We assume the radial distance R_s between a planet and the subsolar point on the magnetopause or bow shock varies with solar wind pressure p as

$$R_s = R_o\left(\frac{p}{p_o}\right)^{-\frac{1}{b}} \quad (1)$$

where the subscript zero refers to initial values. We further assume that equation (1) is valid while the solar wind pressure changes in time. For this to be strictly true, the time scale for changes in p should be greater than the propagation time of the wave carrying the information of a pressure change across the system. We consider time scales greater than four hours, which is the time required for the solar wind to fill the dayside magnetosheath. Thus the assumed validity of equation (1) is equivalent to the assumption that the propagation speed of pressure in the magnetosphere is greater than the solar wind speed in the magnetosheath. This certainly is true in Earth's magnetosphere, and it is a reasonable assumption for Jupiter.

For a vacuum magnetosphere the denominator b of the exponent in equation (1) has the value six. This value provides a good fit for Earth's magnetopause [e.g., Holzer and Slavin, 1978]. Pioneer 10 and 11 and Voyager 1 measurements suggest that for Jupiter's magnetopause and bow shock the value of b is about three [Smith et al., 1978; Bridge et al., 1979].

The following analysis leading to the calculation of typical boundary speeds is performed only for the bow shock because of the immediate availability of solar wind parameter measurements outside the shock. The time delay between solar wind measurements and magnetopause crossings makes their relationship considerably less certain.

In Fig. 1 the distances R_s from Jupiter of both Voyager 1 and 2 bow shock crossings are plotted against the solar wind dynamic pressure term nV^2, where n and V are proton number density and speed, respectively. The arrow on each point shows the direction of shock movement for that crossing. The Voyager 1 and 2 data are fit separately with equation (1). The separation between the Jupiter-sun line and spacecraft trajectory by ~20° is ignored here. The fits are quite good; the correlation coefficient is 0.9 in both cases. There are two curves for each data set, one being the regression of nV^2 on R_s and the other the regression of R_s on nV^2. The four resulting values of b are indicated at the right ends of the curves in the figure and also in Table 1 along with the appropriate coefficients. The values of b are consistent with the estimates referenced above. For Voyager 2 they are 3.5 and 4.3, somewhat larger than the values of 2.6 and 3.1 for Voyager 1, suggesting that during the Voyager 2 crossings there was less material inside the magnetosphere than during the Voyager 1

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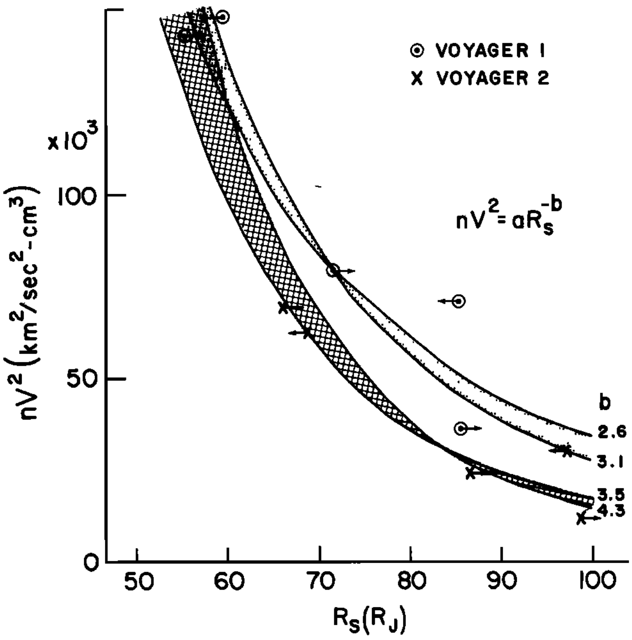

Fig. 1. Plot of radial distances R_s from Jupiter of Voyager 1 and 2 bow shock crossings against the solar wind pressure term nV^2, where n and V are proton number density and speed measured in the solar wind just outside the shock. Arrows show direction of shock movement. Curves are power fits to data points (see Table 1).

crossings. However, it is possible that the difference may be due to a higher alpha particle content in the solar wind during the Voyager 2 crossings (C. Goodrich, private communication).

By differentiating equation (1) with respect to time, the shock speed V_s is obtained as

$$V_s = - \frac{R_s}{bp} \frac{dp}{dt} \qquad (2)$$

In order to determine a typical distribution of Jovian bow shock speeds, equation (2) was applied to Voyager 2 solar wind plasma data measured during December, 1978, and January-February, 1979, when the spacecraft was at radial distances near Jupiter's orbit. Since it takes about four hours for plasma to travel the length of the Jovian dayside magnetosheath, four-hour running averages of the pressure term nV^2 were calculated from hourly averages of n and V, and the term $(1/p)(dp/dt)$ in equation (2) was evaluated at each hour as

$$\frac{\Delta p}{p \Delta t} = \frac{(nV^2)_1 - (nV^2)_2}{\frac{(nV^2)_1 + (nV^2)_2}{2} \; (4\text{ hr})}$$

where subscripts 1 and 2 refer to values separated by four hours. The remaining terms b and R_s in equation (2)were taken to be three and 75 R_J, respectively.

Normalized histograms of the resulting shock speeds are shown in Fig. 2a. Because of the averaging process described above, these speeds are representative of the continual large scale movements in response to gradual changes in solar wind pressure. Pressure changes across discontinuities would add values to the tail of this distribution. A total of 968 hours (~40 days) of data were used. This total is considerably shorter than the 2 1/2 month interval of the data set owing to numerous data gaps. In Fig. 2a the compression and expansion speeds are plotted separately, with 461 and 507 cases in each group, respectively. The two histograms are nearly identical, although the compression events slightly outnumber the expansion events at higher speeds. The mean speeds are about 25 km/s.

The histograms in Fig. 2a give the probability at any time that the bow shock will be moving at any given speed within a 5 km/s interval. However, for a spacecraft moving through the region of the bow shock at a speed slow compared to shock speeds, the probability of encountering the shock at any given speed is different, since a shock with a high speed is more likely to pass over the spacecraft than one with negligible speed. In the limit of zero spacecraft speed, the probability of the spacecraft encountering the shock at any given speed is proportional to that speed, and may be determined by multiplying the number of cases in each 5 km/s bin by the central speed and then normalizing the resulting histogram.

Figure 2b shows such a probability graph calculated from the sum of the expansion and compression cases. The mean speed from Fig. 2b is 55 km/s. Thus the average bow shock speed encountered by a spacecraft is more than twice as large as the average speed of the bow shock itself. The smoothed cumulative curve in Fig. 2b, with its scale to the right, gives the percentage of encountered speeds greater than a certain value. For example, 50% of bow shock encounters

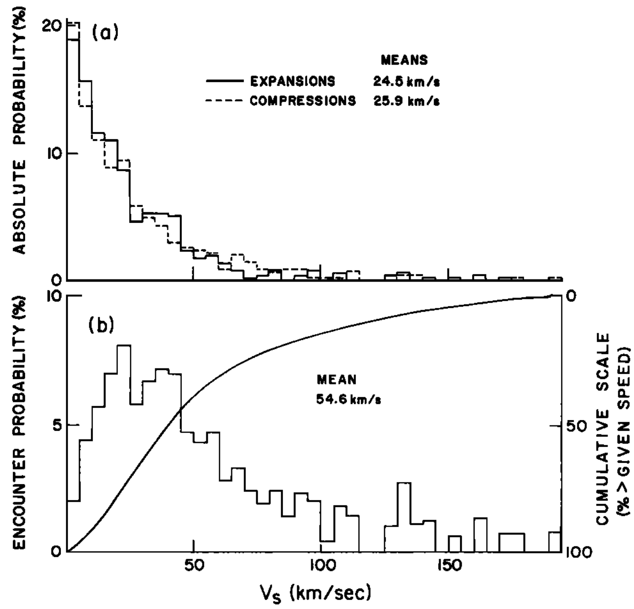

Fig. 2. Histograms of (a) bow shock speeds and (b) shock speeds encountered by a spacecraft moving slowly relative to the shock. The scale on the right side of (b) is for the smoothed cumulative curve constructed from the histogram.

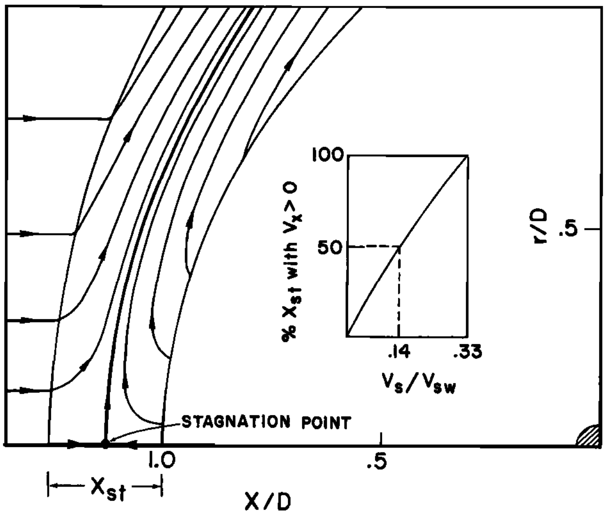

Fig. 3. A sketch of streamlines of solar wind flow in the magnetosheath of Jupiter. The x-axis is the Jupiter-sun line marked in units normalized by the distance D between the center of Jupiter and the subsolar magnetopause point. The ordinate is distance r from the x-axis, also normalized by D. The inset graph gives the distance at which the stagnation point stands off from the magnetopause, in terms of a fraction of the distance X_{st}, as a function of the ratio of the expansion speed, V_s, to the solar wind speed in Jupiter's rest frame, V_{sw}.

with a spacecraft would be at speeds greater than 40 km/s, and 15% at speeds greater than 100 km/sec.

Magnetosheath Flow Pattern

The next question to consider is: How does whole-body movement of the magnetosheath at speeds that are a sizeable fraction of solar wind speeds affect the flow pattern? If the boundaries are contracting, the pattern will be essentially the same as the usual hydrodynamic pattern calculated for Earth's magnetosheath [Spreiter et al., 1966]. The effect of contraction will be similar to a slowing down of the wind speed, since the magnetosheath is moving with the wind. However, if the boundaries are expanding, the pattern will be considerably different. Figure 3 shows a qualitative picture of the expected pattern. As the boundaries expand into the wind, the effect is like that of a snowplow of appropriately Olympian dimensions. What had been the stagnation region near the magnetopause now has a component of flow toward the sun, and a new stagnation point forms away from the magnetopause. The flow field in Fig. 3 is not stationary in time, and, as a result, the magnetopause appears to be a source of solar wind, which would, of course, be impossible for a time stationary, incompressible flow. In order to calculate the distance from the boundary of the new stagnation point, we assume that in the frame of reference of the moving boundaries, where the flow pattern is the usual one, the bow shock reduces the solar wind speed by a factor of four, and the speed along the stagnation streamline decreases linearly to zero at the magnetopause [Lees, 1964]. The new stagnation point in the stationary frame of reference is then located where the speed along the stagnation streamline is equal to the speed of the expanding boundaries. The inset in Fig. 3 shows the results of the calculation. The abscissa is the ratio of boundary speed V_s to solar wind speed V_{sw}, and the ordinate is the function $(4\ V_s/V_{sw})/(1+V_s/V_{sw})$, expressed as percent of the stagnation streamline X_{st} where the flow is sunward. For the case illustrated, with sunward flow along 50% of the stagnation streamline, the plot shows that $V_s = .14\ V_{sw}$, or 57 km/s for $V_{sw} = 400$ km/s. This value of V_s is very nearly the mean value encountered by spacecraft. When $V_s \geq .33\ V_{sw}$, or 133 km/s, reversed flow will occur along the entire length of the stagnation streamline.

Evidence of reversed flow in the magnetosheath at Voyager 1 encounter is presented in Fig. 4. The two traces are the time variations of measured current proportional to proton flux in the C and D Faraday cup sensors. The C-cup points approximately toward the sun, and the D-cup toward dawn. The spacecraft orbit passed through the magnetosheath on the dawn side of the noon-midnight meridian at an angle of about 20° with the Jupiter-sun line. In the time interval shown, the bow shock and magnetopause were expanding past the spacecraft. The signature of the shock crossing at 1226 UT is clearest in the D-cup, since it looks at right angles to the solar wind flow direction and, thus, senses only the increase in temperature and density behind the shock. In the magnetosheath, beginning just after 1600, there is a

TABLE 1. Power Curve Fits

	$nV^2 = aR_s^{-b}$		$R_s = a(nV^2)^{-1/b}$	
Voyager	1	2	1	2
a*	4.7×10^6	1.4×10^8	2.9×10^2	1.9×10^2
b	2.6	3.5	3.1	4.3

*Units are for n in cm^{-3}, V in km/s, and R_s in R_J.

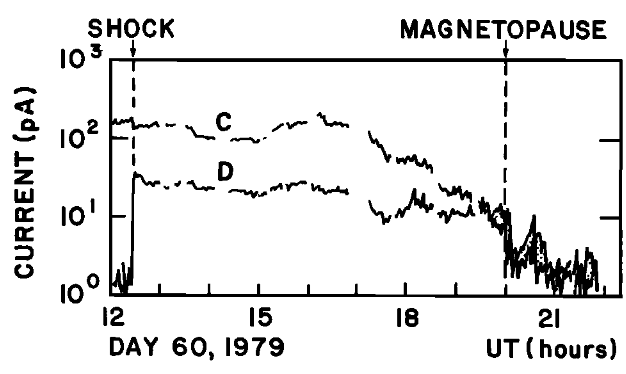

Fig. 4. Time variations of current in picoamperes (10^{-12}A) into the C and D Faraday cup sensors during a Voyager 1 magnetosheath traversal. The C-cup points approximately sunward, and the D-cup approximately dawnward.

dramatic, four-hour decrease in the level of C-cup current by almost a factor of 30. In contrast, the D-cup current decreases only for the first 1 1/2 hours, until about 1730, and then remains steady at a value that exceeds the C-cup current just before the magnetopause, near 1930, as indicated by the shading between the two traces when D > C.

If both currents in Fig. 4 decreased in the same manner, then the decrease might be the signature of a density depletion layer occurring on a larger scale than as observed against Earth's magnetopause [Crooker et al., 1979]. But because the D-cup current changes little, another phenomenon must be responsible for the C-cup decrease. We argue here that it is the phenomenon of reversed flow. The D-cup sensor has an effective geometrical factor that is two to three times smaller than that of the C-cup. Thus an appropriately normalized D-curve in Fig. 4 would intersect the C-curve about an hour sooner, around 1830. At this time then the proton flux was equal in both sensors and the flow must have been at zero velocity or directed at an angle equidistant from both sensors. If we assume that the flow has the expected dawnward component at this position in the magnetosheath, into the back of the D-cup, it follows that the remaining component must have been of equal magnitude and directed sunward into the back of the C-cup. Such flow directions of 45^o from the Jupiter-sun line occur in Fig. 3 near the magnetopause in the vicinity of the bottom two streamlines curving away from the boundary. We propose that Voyager 1 was in a similar flow field around 1830. Afterwards, when proton flux in the D-cup was greater than in the C-cup, the sunward component of flow must have exceeded the dawnward component, consistent with movement toward the magnetopause in a reversed flow field.

Voyager 1 and 2 each crossed the dayside magnetopause three times. The first Voyager 1 crossing is illustrated above. The second was outbound, corresponding to a contraction of the boundary, and the current in the D-cup remained a factor of three or less throughout the magnetosheath, consistent with no sunward flow, as expected. On the final crossing, the currents in the C and D-cups were about equal, again consistent with the sunward flow upon boundary expansion. For the Voyager 2 crossings, the D-cup current was always less than the C-cup current. Thus the two expansions must not have been at high speeds. However, the ratio of C to D currents was considerably greater for the contraction crossing, consistent with a larger antisunward flow at that time.

Conclusion

The large size and compressibility of Jupiter's magnetosphere result in whole-body movement of the magnetosheath at speeds encountered by spacecraft that are commonly a sizeable fraction of solar wind speeds. When the boundaries are expanding at these speeds, large portions of the dayside magnetosheath flow pattern will have a sunward component. Data from the MIT plasma instrument provide evidence for such sunward flow.

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