GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 10, PAGES 1207-1210, MAY 15, 1996

Near-simultaneous bow shock crossings by WIND and IMP 8 on December 1, 1994

J. A. Slavin, A. Szabo, M. Peredo, R. P. Lepping, R. J. Fitzenreiter, and K. W. Ogilvie
Laboratory for Extraterrestrial Physics, NASA/GSFC, Greenbelt, Maryland

C. J. Owen
Astronomy Unit, Queen Mary and Westfield College, London, U.K.

J. T. Steinberg
Center for Space Research, Massachusetts Institute of Technology, Cambridge

Abstract. Near-simultaneous dawn-side bow shock crossings by WIND and IMP 8 on December 1, 1994 are analyzed to determine shock location and shape and to examine the changes in shock structure and the foreshock MHD wave properties with increasing downstream distance. The WIND and IMP 8 crossings took place at sun-Earth-spacecraft angles of 64.7° and 115.3°, respectively. The solar wind speed and interplanetary magnetic field magnitude were near their long-term average values. However, the orientation of the IMF was unusual in that it rotated from an angle of ~50-60° to the sun-Earth line at the beginning of the interval of shock crossings to less than 20° just after the final crossings. The ratio of the downstream to upstream components of the magnetic field tangential to the shock decreases from 4.1 at WIND to 3.1 at IMP 8 in general agreement with theory. In addition, the overshoot in the shock magnetic ramp observed at WIND is greatly diminished by the downstream distance of IMP 8. In the foreshock, MHD waves with periods of 10-20 s and amplitudes of 3-6 nT were observed at both spacecraft. However, at WIND they have a strong compressional component which is much weaker farther downstream at IMP 8. Unexpectedly, the radial distance of the shock at both spacecraft is only ~80-85% of that predicted by recent models. Motivated by this event, we have statistically analyzed a larger data set of bow shock crossings which took place under quasi-field-aligned flow conditions. On this basis it is suggested that magnetosheath thickness may decrease by ~10% as the IMF becomes increasingly flow aligned.

Introduction

Much effort has been devoted to the fitting and empirical modeling of the bow shock and magnetopause boundaries [e.g., *Fairfield*, 1971; *Sibeck et al.*, 1991; *Peredo et al.*, 1995]. The primary motivation for this work is to test and refine theoretical models of the solar wind flow about the magnetosphere [e.g., *Spreiter and Stahara*, 1980; *Wu*, 1992; *Cairns and Lyon*, 1995]. These boundaries are unique because, unlike individual solar wind streamlines, they are readily identifiable and their observed position and shape can, therefore, be used to validate theoretical predictions. Secondary rationales are the development of empirical models to meet operational needs and the contribution such models may make to our understanding of the critical plasma processes which take place in these thin interface regions.

Paper number 96GL01351
0094-8534/96/96GL-01351$05.00

In this letter we report upon a serendipitous conjunction between WIND and IMP 8 on December 1, 1994 in which these spacecraft obtained nearly simultaneous observations of the dawnside bow shock at distances of X = 7.6 R_e and -15.3 R_e, respectively. After taking into account solar wind velocity and ram pressure, the locations of these crossings, their surface normals, jump conditions and foreshock waves are examined and used to test empirical and theoretical models.

Magnetic Field Observations

Two hours of 3 sec averaged measurements from IMP 8 and WIND MFI magnetometer investigations [*Lepping et al.*, 1995] taken on December 1, 1994 are displayed in Figure 1. These observations are unique because they depict near-simultaneous traversals from the dawnside magnetosheath into the solar wind at two well separated points. The WIND - IMP 8 separation vector in Geocentric Solar Ecliptic Coordinates (GSE) based upon an average over the multiple crossings at each spacecraft was (–22.7,–16.0, 1.7 R_e). From the measured solar wind component along the sun-Earth line, V_x = -515 km/s, the time lag between the arrival of plasma parcels at the two spacecraft would be 22.7 R_e / 515 km/s = 282 s or 4.7 min.

Starting on the left-hand side of Figure 1, the direction and intensity of the magnetic field is remarkably constant early in the magnetosheath interval. The first change comes at about 11:20 UT when the field direction shifts slightly and a 12 min long burst of large amplitude, ±10 nT, compressive fluctuations are observed at WIND. Approximately 2-3 min later a small change in field variance and direction is detected at IMP 8, but with a reduced wave amplitude and duration. While the exact cause of this interval of enhanced field fluctuations cannot be uniquely inferred, the fact that it occurs 2-3 min later at IMP 8 indicates that it is associated with a feature (e.g., a small change in the IMF or solar wind parameters) convected anti-sunward at the solar wind speed.

The initial IMP 8 shock crossing occurs at 11:51 UT which is about 5 min before the first crossing at WIND. At IMP 8 a total of 7 bow shock crossings take place over the next 38 min, while at WIND 3 crossings are seen over 12 min. Between the initial and final shock encounters WIND and IMP 8 each traveled a total distance of only about 1600 km and 2800 km, respectively. The fact that the first crossing takes place at the downstream spacecraft and the smaller number of the crossings over a narrower

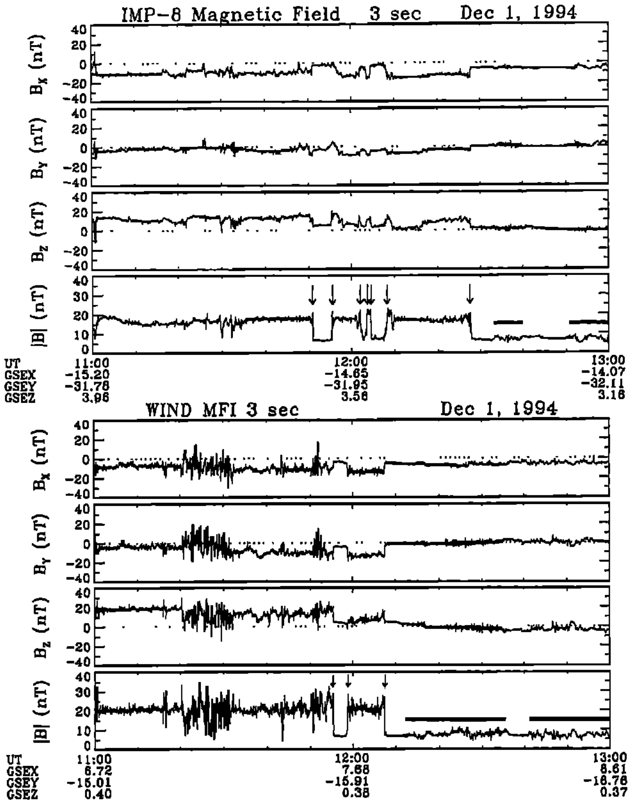

Figure 1. IMP 8 and WIND magnetic field observations for December 1, 1994 show near-simultaneous bow shock crossings. Horizontal bars mark intervals of strong foreshock wave activity.

spatial interval at WIND indicates that amplitude of the shock surface motions are greater at the downstream spacecraft, IMP 8.

Finally, the right-hand side of Figure 1 shows that the IMF just upstream of the shock was very similar in intensity at WIND and IMP 8 at 6.5 and 6.4 nT, respectively. This is very close to the long term average IMF magnitude of about 6 nT. However, the orientation of the IMF was unusual in that it deviated greatly from the average Parker spiral. Upstream of the initial bow shock encounters just prior to 12:00 UT the IMF made an angle of ~50-60° to the sun-Earth line with B_z exceeding B_y and B_x. The direction then changed to the point where B_y and B_z became much less than B_x upstream of the final shock crossings and the field made an angle of less than 20° to the X axis.

Solar Wind Parameters

The upstream magnetic field and plasma parameters determined by the MFI and SWE [*Ogilvie et al.*, 1995] instruments on WIND have been used to calculate ram pressure, P_{SW}, Alfven Mach number, M_A, and sonic Mach number, M_S. In calculating these quantities averages of the proton, alpha particle and electron densities and temperatures, the proton velocity and the magnetic field magnitude over the interval 12:15 to 12:30 UT have been used. This corresponds to the interval just upstream of the final WIND bow shock crossing. Comparison with the IMP 8 plasma measurements indicated that any inhomgeneities on the scale of the spacecraft separation were small. The resulting values were $P_{SW} = 2.0$ nPa, $M_A = 7.1$, and $M_S = 7.7$. These values are similar to the long term average values in the *Peredo et al.* [1995] study of 1,392 bow shock crossings covering the interval 1963 - 1979, i.e. $P_{SW} = 3.1$ nPa, $M_A = 9.1$ and $M_S = 7.5$. Hence, the IMP 8 and WIND bow shock crossings on December 1, 1994 took place under fairly typical solar wind conditions in terms of their upstream ram pressures and Mach numbers. Finally, the vector solar wind flow angles from SWE were used to rotate the IMP 8 and WIND average bow shock crossings into the aberrated GSE coordinate system in which the solar wind flow direction is anti-parallel to the X'-axis (see Figure 3).

Bow Shock Structure and Upstream Waves

One of the important factors controlling bow shock structure is the angle the upstream IMF makes to the shock normal. Based upon coplanarity determined shock normals, the angles between the upstream magnetic field and the shock normal, Θ_{BN}, for the outermost shock crossing at WIND and IMP 8 were 45.1° and 58.5°, respectively. Given the Mach numbers described earlier and these Θ_{BN} angles, the structure of the shock can be classified at both spacecraft as quasi-perpendicular and super-critical [e.g., *Greenstadt et al.*, 1984]. This conclusion is supported by the clean, sharp jumps in the magnetic field in Figure 1.

Due to the IMF orientation for this event, there was no opportunity to bracket the transition region where the change from parallel to perpendicular behavior takes place. However, the decrease in the strength of the bow shock with increasing downstream distance as the shock normal makes ever larger angles to the incident solar wind flow vector can be readily observed with WIND and IMP 8. Thus, we do have a unique opportunity to simultaneously measure this quantity at two points. In addition, the effect of this weakening on the reflection of solar wind ions is readily visible in the magnetic field overshoot and downstream oscillations visible in the WIND shock crossings at a SES=64.7°. The overshoot and subsequent damped oscillations in the downstream magnetosheath for quasi-perpendicular shocks are understood as being due to the reflection of some solar wind ions in the shock ramp and the time scale for their thermalization when they are convected back into the magnetosheath [e.g., see *Gosling and Robson*, 1985]. At IMP 8, i.e. SES = 115.3°, the overshoot in the magnetic field is much less pronounced indicating less ion reflection presumably due to the weakening of the shock with increasing downstream distance.

Calculation of the ratio of the downstream to the upstream magnetic fields tangential to the shock surface evaluated using magnetic coplanarity normals yields jumps of 4.1 and 3.1 at WIND and IMP 8, respectively. This decrease in the shock intensity is in general agreement with theoretical models of shock jump conditions as a function of SES angle [e.g., *Spreiter and Stahara*, 1980; *Tatrallyay et al.*, 1984; *Winterhalter et al.*, 1985].

The December 1st traversals of the dawnside bow shock also offer a unique view of low frequency MHD waves in the foreshock. In Figure 1 we have marked with a solid horizontal bar intervals of upstream wave activity. Although the durations do not match exactly, there is a great deal of similarity in the spatial distributions of the waves at IMP 8 and WIND. In both cases there is a gap of 5-8 min between the outermost shock crossing and the entry into the region of wave activity. Later on there is a calm interval of greatly diminished wave activity which lasts 7 – 15 min at both spacecraft. These transitions from regions with and without wave activity are most likely associated with small changes in IMF direction and/or shock motion.

A close-up view of these upstream waves in the simultaneous IMP 8 and WIND measurements from 12:30 to 12:40 UT is presented in Figure 2. Again, the portions of the same horizontal bars as in the previous figure mark the intervals of strong wave activity. This period was chosen to capture the end of the first interval of wave activity at WIND and the start of the first

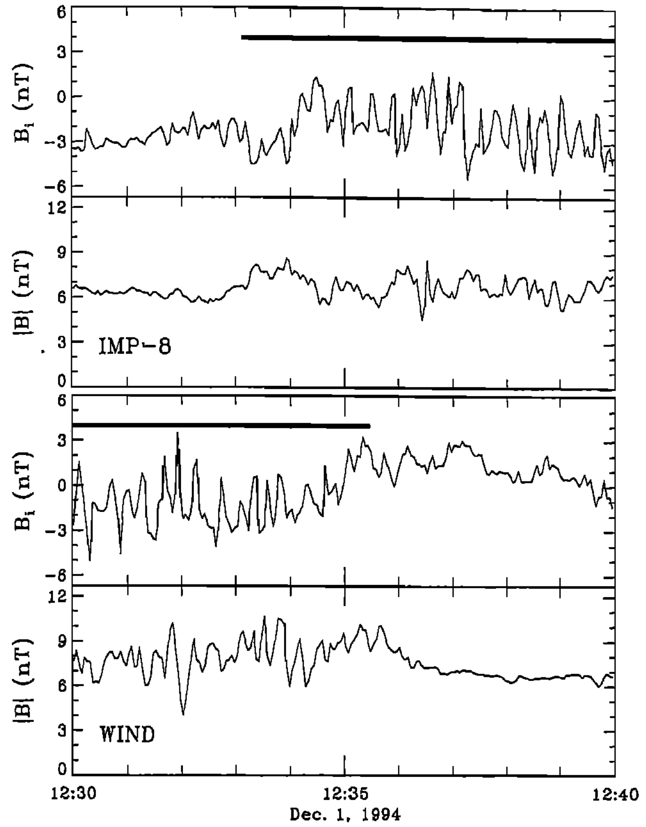

Figure 2. Simultaneous IMP 8 and WIND magnetic field measurements in the foreshock are displayed. The first and third panels display the field component in the maximum variance direction while the second and fourth panels show the field strength.

interval of wave activity IMP 8. Minimum variance analysis has been used to determine propagation directions for these transversely polarized waves; (0.92, -0.38, -0.07) and (0.92, -0.39, 0.00) in GSE coordinates for IMP 8 and WIND, respectively. In Figure 2 the magnetic field component in the maximum variance direction, B_l, has been plotted above the total field magnitude measured at each spacecraft. The periods of these waves are 10-20 sec and they clearly possess a compressive (i.e., magnetosonic) component as indicated by the variations in field magnitude. Such MHD waves are a well documented, but still not well understood aspect of the foreshock of the Earth's super-critical bow shock, albeit, they are well correlated with backstreaming diffuse ions [*e.g., Hoppe et al.*, 1981]. What is new here is the opportunity to observe the foreshock with two spacecraft located just upstream of the bow shock, but separated by 50° in solar zenith angle. The most salient difference between the waves at these two locations is that the magnetosonic component appears to be greatly diminished at the downstream spacecraft, IMP 8. In contrast, the amplitude of the transverse field component is very similar at both spacecraft. This decrease in the magnetosonic component of the upstream MHD waves is an interesting result which could be important for global modeling of the foreshock.

Bow Shock Position and Shape

Existing empirical models of bow shock position are based upon large numbers of shock crossings often collected from years of spacecraft observations. When available, correlative information on the IMF and solar wind plasma is also collected and used to infer statistically the position and shape of the shock surface under a variety of conditions. However, in applying these models it must always be assumed that the instantaneous shock surface does not differ greatly from the average surface as discussed earlier.

Figure 3 plots the mean locations of the WIND and IMP 8 shocks as solid circles in aberrated GSE coordinates (i.e., the solar wind velocity is in the -X' direction). Also displayed in the top panel are 175 shock crossings from the data base assembled by *Peredo et al.* [1995] for which both M_A and M_S are between 7 and 9. All of these crossings have been scaled to the ram pressure of 2.0 nPa appropriate to the December 1, 1994 events. The solid curve is a second order fit to the 175 bow shock crossings; it is very close to the Mach number parameterized surfaces determined

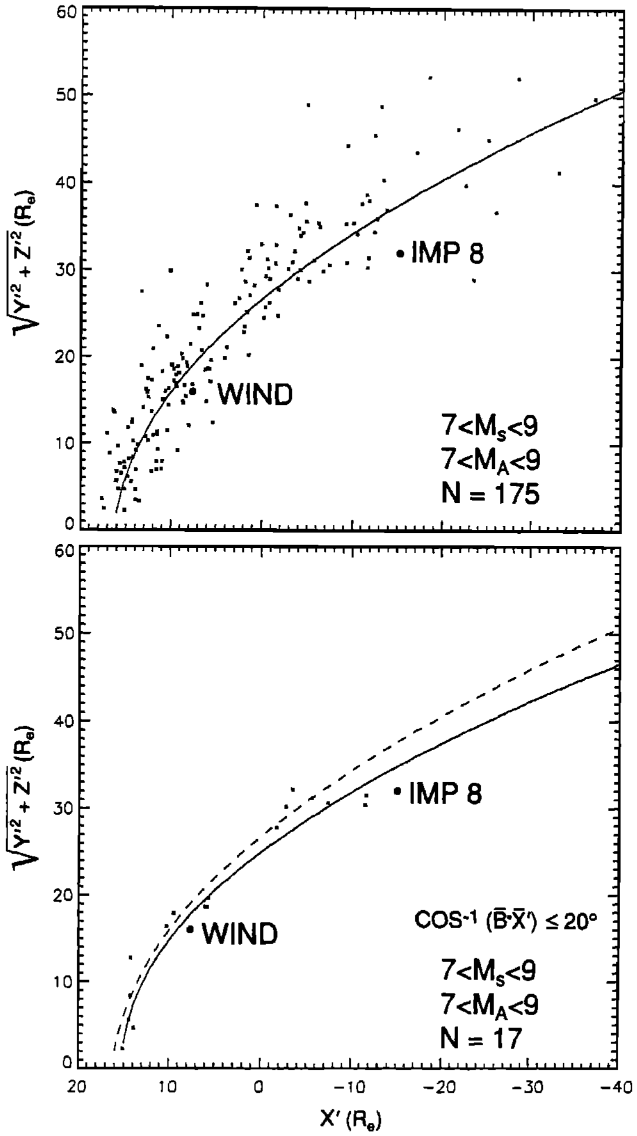

Figure 3. The average locations of the IMP 8 and WIND bow shock crossings (solid dots) are plotted in cylindrical coordinates in the top panel along with 175 shock crossing for which $7 < M_S < 9$ and $7 < M_A < 9$. A second order fit to the points is displayed as a solid line. The bottom panel displays the subset of crossings for which the IMF was within 20° of the X' axis. A second order fit to these points is displayed as a solid line and for comparison the model from the top panel is shown as a dashed line. All of the crossings in both panels have been scaled to common ram pressure of 2 nPa.

by *Peredo et al.* Although still located within the scatter of the larger data set, the WIND and IMP 8 crossings occurred at radial distances of only ~85% and 80%, respectively, of those predicted by our average model. In addition, these two simultaneous crossings suggest a slightly less flared shock surface than that of the model in Figure 3. Since the B_z component of the IMF was northward throughout these evens and all points have been scaled to a common solar wind ram pressure, it is assumed that the less than expected distances to the bow shock observed by WIND and IMP 8 are due to a thinner magnetosheath as opposed to some reduction in the radius of the magnetopause.

The deviations of the December 1, 1994 shock crossings taken individually are not surprising and correspond to inward displacements which are comparable to the 5.2 R_e standard deviation of the 175 crossings to the average model. However, the existence of simultaneous crossings observed during an interval when the IMF was rotating toward a more solar wind aligned orientation suggesting a thinner magnetosheath than average merits some further investigation. For this reason we identified the 19 shock crossings in the top panel of Figure 3, including the IMP 8 and WIND crossings, for which $\cos^{-1}(\mathbf{B}\cdot\mathbf{X}') \leq 20°$ and modeled them with a second order fit in the bottom panel. For the purposes of comparison the fit to the larger data base from the top panel is also displayed as a dashed line. As shown, 14 of the 19 crossings in the bottom panel are, indeed, located at smaller distances from the Earth than the mean shock surface (dashed line) from the top panel. A fit to just these quasi-field aligned solar wind flow shock crossings (solid line) is located ~1 R_e and ~5 R_e closer to the Earth than the mean model for all IMF orientations at the solar zenith angles of WIND and IMP 8, respectively.

The determination of how bow shock shape and location is influenced by IMF direction is a long-standing problem. It is, for example, well known that the shock surface deviates from axial symmetry about the aberrated GSE X axis with the dusk-side magnetosheath being ~5-10% wider than the dawn-side presumably due to the asymmetry in the draping of the IMF about the magnetosphere [*Fairfield*, 1971]. Finally, the shape and location of the bow shock as a function of upstream Mach number when the IMF is parallel (or anti-parallel) to the solar wind flow direction has been modeled theoretically by *Spreiter and Rizzi* [1974]. Their modeling results predicted that for a constant sonic Mach number there would be a tendency for the shock surface to become more flared and move in slightly in the subsolar region as the Alfven Mach number decreases below 10. While it is not possible on the basis of the WIND/IMP 8 event presented in this paper or our statistical analysis of shock crossings to perform an adequate test of the *Spreiter and Rizzi* model, the results do suggest that under radial IMF conditions the magnetosheath may be thinner than under more typical IMF orientations.

Summary

Near-simultaneous dawn-side bow shock crossings by WIND and IMP 8 on December 1, 1994 are analyzed. They took place at SES angles of 64.7° and 115.3°, respectively. These two-spacecraft observations were used to examine the instantaneous variation in shock structure with increasing downstream distance, the change in MHD wave properties in the foreshock with increasing SES angle, and the shape and location of the shock surface. The jump in the magnetic field component tangential to the shock decreases from 4.1 to 3.1 from WIND to IMP 8 in good agreement with theory and the overshoot in the shock magnetic ramp was observed to be greatly diminished by the downstream distance of IMP 8. MHD waves with periods of 10-20 s and amplitudes of 3-6 nT are observed at both WIND and IMP 8. However, the compressional component of the upstream waves was much weaker by the downstream distance of IMP 8 where the bow shock is weaker. Unexpectedly, the radial distances to the shock at both WIND and IMP 8 were only 80-85% of that predicted by recent empirical models of the shock. The reason for these inward displacements is not clear. However, these observations have motivated a statistical analysis of a larger bow shock crossing data set which suggests that the magnetosheath becomes thinner by ~10% when the angle between the IMF and the sun-Earth line becomes less than ~20°.

Acknowledgments. We wish to thank all of the individuals who contributed to the success of WIND. We also wish to thank A.J. Lazarus, K.I. Paularena, and D. Huterer for valuable assistance with the IMP 8 and WIND SWE plasma measurements used in this study. The work at M.I.T. was supported in part by NASA Grants NAG5-584 and NAG5-2839. Useful discussions with J. Clemmons and D. Fairfield are also gratefully acknowledged.

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J. A. Slavin, A. Szabo, M. Peredo, R. P. Lepping, R. Fitzenreiter, and K. W. Ogilvie, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: slavin@lepjas.gsfc.nasa.gov)

C. J. Owen, Astronomy Unit, Queen Mary and Westfield College, London, U.K.

J. T. Steinberg, Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.

(Received: November 6, 1995; revised: March 7, 1996; accepted: April 1, 1996.)