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OBSERVATIONS OF THE HELIOSHEATH AND SOLAR WIND NEAR THE TERMINATION SHOCK BY *VOYAGER 2*

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ABSTRACT

This paper describes the principal features of 24 hr averages of the magnetic field strength variations $B(t)$ and their relationships to the plasma and energetic particles observed prior to and after the crossing of the termination shock (TS) by *Voyager 2* (*V2*). The solar wind (pre-TS crossing) and heliosheath (post-TS crossing) data extend from day of year (DOY) 1 through 241, 2007 and from 2007 DOY 245 through 2008 DOY 80, respectively. In the solar wind, two merged interaction regions (MIRs) were observed in which the ratio of plasma pressure to magnetic pressure in the solar wind was relatively low. Strong magnetic fields and low values of beta were also observed just prior to its crossing of the TS. The predicted correlation between peaks in the intensity of energetic particles in the solar wind when *V2* crossed the heliospheric current sheet from positive to negative magnetic polarity in the solar wind was not observed. In the heliosheath, *V2* observed a feature characterized by large enhancements of the density N and the proton temperature T, a small increase in speed V, and a depression in B. The distributions of 24 hr averages of B and beta were approximately log-normal in both the solar wind and the heliosheath. A unipolar region was observed for 73 days in the heliosheath, as the heliospheric current sheet moved toward the equatorial plane to latitudes lower than *V2*.

Key words: magnetic fields – MHD – shock waves – solar wind

1. INTRODUCTION

Voyager 2 (*V2*) encountered the termination shock (TS) at least five times from day of year (DOY) 242 to 244, 2007 (Burlaga et al. 2008; Decker et al. 2008; Gurnett & Kurth 2008; Richardson et al. 2008; Stone et al. 2008), and *V2* has been moving through the heliosheath since that time. The purpose of this paper is to describe the principal features of the magnetic field strength profile variations $B(t)$ and their relationships to the plasma and energetic particles observed for several months prior to and after the *V2* crossing of the TS. We consider (1) the interval from 2007 DOY 1 through 241 during which *V2* was in the solar wind and (2) the interval from 2007 DOY 245 through 2008 DOY 75 during which *V2* was in the heliosheath. The words "solar wind" and "heliosheath" in the text below refer to the two intervals just defined. *Voyager 2* moved from 81.6 AU from the Sun and 27°.1 south to 85.4 AU and 27°.8 south during the intervals considered in this paper.

Many stars have supersonic stellar winds that decelerate across a TS to a subsonic heliosheath flow, which makes a transition from the supersonic wind to the interstellar medium. The observations presented here provide some constraints on models of stars with hot coronae whose stellar winds carry magnetic fields and encounter an interstellar medium that contains neutral material. Interaction regions between the solar wind and interstellar medium (astrospheres) are reviewed by Wood (2006). Particular astrospheres have been studied by Wood et al. (2002, 2005a, 2005b), and an analytical theory of astrospheres was published by Nickeler et al. (2006).

The average magnetic field strength produced by the *V2* spacecraft at the location of the outboard magnetometer of the dual magnetometers system (Behannon et al. 1977) on *V2* varies between 0.1 and 0.2 nT, comparable to the most probable magnetic field strength in the inner heliosheath and significantly larger than the most probable magnetic field strength in the distant supersonic solar wind (see below). The spacecraft magnetic field is a complex, time-dependent signal that must be removed from the measured magnetic field signal in order to derive the ambient magnetic fields of the solar wind and heliosheath. Corrections must also be made for spurious magnetic signals and noise associated with the telemetry system, ground-tracking systems, and other factors. A nonperiodic modulation of the spacecraft's magnetic field, with amplitudes comparable to the average ambient magnetic field strength and periods in the range from 1 to 12 hr, has been present approximately half the time in the *V2* data since ≈1990, beginning in ≈1985. These problems were discussed by Burlaga (1994) and Burlaga et al. (2002), and in http://cohoweb.gsfc.nasa.gov/html/cw_data.html#vy_mag. Finally, a spacecraft systems command during late 2006 had the unintended consequence of exposing the sensors to temperatures well beyond their design limits for more than one week. This command also rotated one set of dual triaxial sensors through a large angle and produced additional noise, drifts, and spurious signals as a result of damage to the sensor assembly. Extracting the signal describing the solar wind and heliosheath from many sources of uncertainty is a complex and lengthy process. At this stage of the data reduction, there remain extraneous points in the data that can significantly affect some hour averages and any higher resolution data. However, the daily averages of magnetic field presented here are sufficiently accurate to describe the basic features of the magnetic field, its long-term averages, and variations in the intervals of interest in this paper. We estimate that the 1σ uncertainty in the daily averages in the magnetic field strengths presented below is typically $\approx \pm 0.03$ nT.

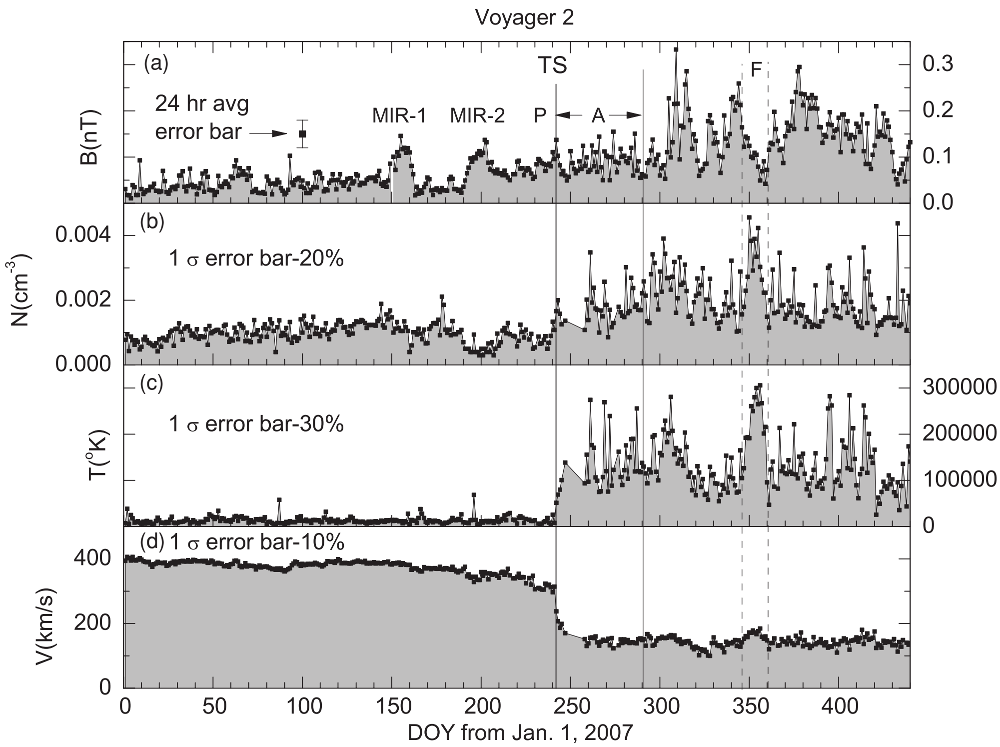

Figure 1. Daily averages of magnetic field strength (a), plasma density (b), proton temperature (c), and bulk speed (d) measured by *V2*.

2. MAGNETIC FIELD AND PLASMA OBSERVATIONS

2.1. Solar Wind Features

The daily averages of the magnetic field strength (B) measured by the magnetic field instrument on *V2* from 2007 DOY 1 to 2008 DOY 75 (DOY 440 relative to 2007 January 1) are shown in Figure 1(a). The 1σ uncertainty in B, $\pm$ 0.03 nT, is indicated by the error bar in Figure 1(a). The time of the TS crossings on DOY 242–244, 2007, is indicated by the line labeled "TS." Daily averages of the density (N), proton temperature (T), and solar wind speed (V) measured by the plasma instrument on *V2* (Bridge et al. 1977) are shown in Figures 1(b), 1(c), and 1(d), respectively. The estimated average uncertainties in V, N, and T are 10%, 20%, and 30%, respectively. The plasma data near the TS were discussed by Richardson et al. (2008).

Three major features in the solar wind, characterized by regions with relatively large B, are labeled MIR-1, MIR-2, and P in Figure 1a. We identify MIR-1 and MIR-2 as "merged interaction regions" (MIRs; Burlaga et al. 1985), which are produced by the coalescence of interaction regions as they move away from the Sun. *Voyager 2* measures the thermal pressure of the solar wind ($P_P \equiv NkT$) and the magnetic pressure ($P_B \equiv B^2/8\pi$). "Interaction regions" are defined as regions of enhanced B and pressure $P_{PB} \equiv P_P + P_B$ produced by identifiable features near the sun, such as corotating streams, shocks, and ejecta (Burlaga & Ogilvie 1970). Figures 2(a)–2(c) show that P_B and $P_{\rm PB}$ are relatively high in MIR-1 and MIR-2, confirming that these features in the distant heliosphere are merged interactions. Often, but not always, N and T are high in MIRs, and McDonald et al. (2005) observed that from 2000.5 to 2005.0 V was relatively high in MIRs. The plasma data in Figures 1(b)–1(d) show that N, T, and V were not enhanced in MIR-1 and MIR-2. The plasma pressure was not enhanced in the MIRs (Figure 2b). Low values of $\beta_{\rm PB} \equiv NkT/(B^2/8\pi)$ in MIR-1 and MIR-2, shown in Figure 2(d), suggest that the MIRs might have formed by the coalescence of ejecta carrying strong magnetic fields from the Sun rather than by stream interactions or shocks.

The enhancement of B marked "P" in Figure 1(a) occurred during a month just prior to the TS crossing in association with a decrease in the speed of the solar wind. It is possible that this enhancement of B was produced by processes associated with the TS, such as compression associated with deceleration associated with mass loading by particles from the TS and post-TS region (Richardson et al. 2008; Burlaga et al. 2008; Zank 1999; Pogorelov et al. 2006). Figure 2(d) shows that $\beta_{\rm PB}$ was also low in region "P" (as it was in MIR-1 and MIR-2), primarily because of the strong magnetic fields in this region. Thus, we cannot exclude the possibility that a third MIR was at least contributing to the relatively strong magnetic fields in region "P." Merged interaction regions are expected to significantly affect the position of the TS (Whang et al. 1995; Zank 1999; Zank et al. 1996; Washimi et al. 2007). The possible role of MIRs in controlling and determining the position of the TS at the time of its encounter by *V2* should be investigated further.

2.2. Heliosheath Features

The magnetic field strength observed by *V2* in the heliosheath (Figure 1a) is very complex, nonstationary and inhomogeneous, as also observed by *Voyager 1* (*V1*; Burlaga et al. 2005). The same is true of variations in the density and proton temperature observed by *V2* shown in Figures 1(b) and 1(c), respectively. Thus, one cannot assume that the properties observed in any one interval of the heliosheath are representative of the inner heliosheath as a whole.

The transition from the solar wind to the heliosheath by *V2* was not seen as a significant enhancement of the 24 hr averages of B in the ≈50 day interval centered on the time of the TS crossings (Figure 1a) in contrast to the observations of the TS crossing made by *V1* (Burlaga et al. 2005). However,

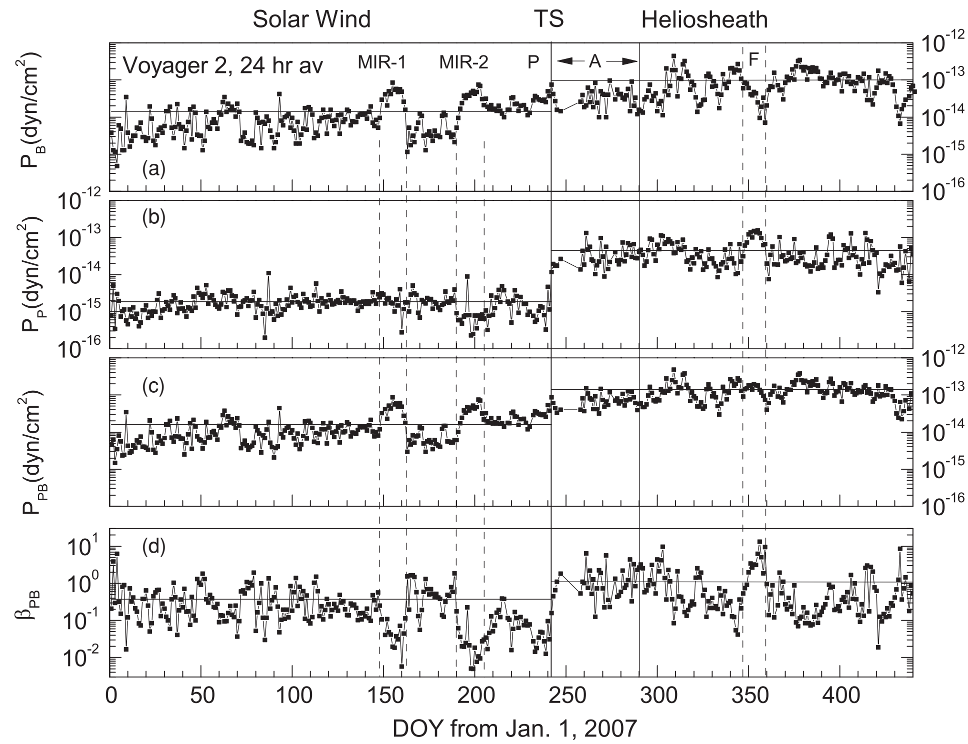

Figure 2. Daily averages of the magnetic pressure (a), the proton thermal pressure (b), the sum of the pressure and proton pressure (c), and the ratio of the proton pressure to the magnetic pressure (d) measured by *V2*.

high-resolution observations of the magnetic field (Burlaga et al. 2008) and plasma (Richardson et al. 2008) identify the TS unambiguously. And the plasma data shown in Figures 1(b)–1(d) clearly identify the shock crossing as an increase in N, an increase in T, and a decrease in V on a larger scale.

In the heliosheath just behind the TS, *V2* observed a region (marked "A" in Figure 1a) in which B appeared to have rapid small amplitude fluctuations about the average B in this region. However, a preliminary examination of the high-resolution data showed that B was actually highly variable on the timescale of tens of minutes in region A; this variability was largely filtered out and aliased by the successive 24 hr averages of B that are plotted in Figure 1(a). At $\approx$ 2007 DOY 290, a transition occurred from region A to a region with large amplitude fluctuations in B on scales of tens of days. Whether this transition is a physical effect related to the postshock flow or coincidence related to solar wind flows that passed through the TS remains to be determined. Figure 1 shows that N and T, but not V, are also highly variable in the heliosheath.

A prominent feature with high values of N and T (hence, high-plasma pressure) was observed in the heliosheath near 2007 DOY 350, which is marked "F" in Figure 1(a). Figure 1(a) shows low values of B associated with the high values of N and T as well as a small but distinct increase of V in region F. Figures 2(a) and 2(b) show an anticorrelation between P_B and P_P; thus, region F is not an MIR. Although the anticorrelation between P_B and P_P suggests a pressure-balanced structure, the unknown pickup ion pressure must be considered in the identification of a pressure-balanced structure (Gloeckler et al. 2005).

2.3. Comparison of the Solar Wind and the Heliosheath

Figures 1(a) and 1(b) show that on average B and N are higher in the heliosheath than in the solar wind, as expected. The average of B in the solar wind and heliosheath is (0.05 $\pm$ 0.03 nT) and (0.13 $\pm$ 0.03) nT, respectively. The quantities following the $\pm$ signs here and in the remainder of this paragraph are the standard deviations of daily averages. The ratio of $\langle B \rangle$ in the heliosheath to that of the solar wind is 2.5 $\pm$ 1.7, which is consistent with the value determined by *V1* obtained by averaging over several months before and after the TS (Burlaga et al. 2005). The average of N in the solar wind and heliosheath is (0.0010 $\pm$ 0.0002) cm^{-3} and (0.0020 $\pm$ 0.0004) cm^{-3}, respectively, so that the ratio of $\langle N \rangle$ in the heliosheath to that of the solar wind is 2.0 $\pm$ 0.6. The averages of V in the solar wind and heliosheath are (374 $\pm$ 37) km s^{-1} and (144 $\pm$ 14) km s^{-1}, respectively; hence, the ratio of $\langle V \rangle$ in the solar wind to that in the heliosheath is 2.6 $\pm$ 0.4. These observed ratios of B, N, and V are consistent with the equality of the ratios that is expected for a perpendicular TS, $(B_2/B_1 = N_2/N_1)$, where the subscripts 1 and 2 refer to the solar wind and heliosheath, respectively.

High-resolution observations indicate that (1) across the third crossing of the TS, TS-3, B increased by a factor of 1.8 $\pm$ 0.2 (Burlaga et al. 2008) and N increased by 1.6 $\pm$ 0.7 (Richardson et al. 2008) and (2) across the second crossing of the TS, TS-2, N increased by 2.4 $\pm$ 0.1 (Richardson et al. 2008). Thus, although the strength of the TS is variable (e.g., owing to the changing angle between the magnetic field and the shock normal), the local values of the shock strength are comparable to the average value.

The average values of $\beta_{\rm PB} \equiv NkT/(B^2/8\pi)$ in the solar wind and the heliosheath (see Figure 2d) are 0.4 and 1.1, respectively. This definition of $\beta_{\rm PB}$ does not include the contribution of pickup protons to the thermal pressure, which is dominant in the distant heliosphere (Burlaga et al. 1994) as predicted by Isenberg (1986) and Whang et al. (1995). The distribution of $\beta_{\rm PB}$ is log-normal in the solar wind and the heliosheath (Figures 3b and 3d), but it is very broad owing in large part to the uncertainties in the measurements of B, N, and T. Nevertheless, it is notable that

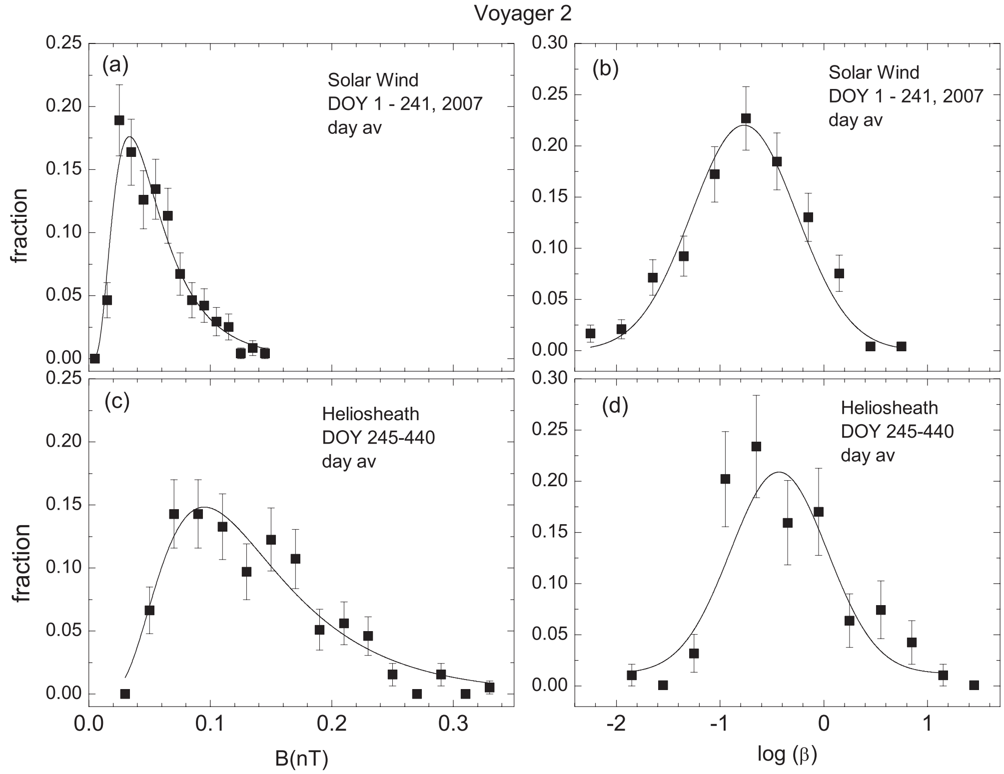

Figure 3. Distribution of 24 hr averages of the magnetic field strength in both the solar wind (a) and in the heliosheath (c). The distribution of B is described by a fit to the lognormal distribution (*curve*). The distribution of log (β) in the solar wind (b) and in the heliosheath (d). The distribution of log (β) is described by a fit to the Gaussian distribution (*curve*), that is, the distribution of β was lognormal in both the solar wind and heliosheath.

$\langle\beta_{PB}\rangle$ ~0.4 in the solar wind near 82 AU, since this implies significant heating of the solar wind in the distant heliosphere (>30 AU), which is presumably due to pickup protons (Smith et al. 2006; Isenberg 1987). Likewise, it is significant that $\langle\beta_{PB}\rangle \approx 1$ in the heliosheath (as it is near 1 AU), which is only ≈3 times the value of $\langle\beta_{PB}\rangle$ in the distant solar wind.

The average pressure $P_{PB} \equiv NkT + B^2/8\pi$ (again, neglecting the pressure of the pickup protons) is 1.6×10^{-14} dyn cm^{-2} in the solar wind and 14.1×10^{-14} dyn cm^{-2} in the heliosheath (Figure 2c). The increase of P_{PB} in the heliosheath relative to the solar wind is due primarily to heating by the shock (Figure 1c). Nevertheless, the substantial increase in T across the TS $(136{,}000 \pm 60{,}000)\,\mathrm{K}/(13000 \pm 8000)\ \mathrm{K} = 10$ is significantly smaller than expected (Richardson et al. 2008).

The probability distribution function of 24 hr averages of B observed by *V2* in the solar wind and in the heliosheath prior to and after crossing the TS is shown in Figures 3(a) and 3(c), respectively. Both distributions are consistent with a lognormal distribution function of B. The distribution of 24 hr averages of B in the solar wind is typically lognormal in a one-year interval from 1 AU (Burlaga & King 1979) throughout the supersonic solar wind (Burlaga 2001) and out to at least 81.6 AU (Burlaga et al. 2007). Figure 3(a) extends this result to 84 AU. However, it is surprising to find that the distribution of 24 hr averages of B observed by *V2* in the heliosheath is lognormal, since Burlaga et al. (2007) found a Gaussian distribution of 24 hr averages of B in the *V1* observations of the heliosheath from 2005.0 to 2006.92. The distribution of B observed by *V2* in the heliosheath (Figure 3b) might differ from that observed by *V1* for the following reasons. (1) It is based on an average over only 238 days rather than the average over 700 days for the *V1* data and (2) the magnetic field variations in the heliosheath are neither stationary nor homogeneous. Further observations and studies of B in the heliosheath by *V2* are needed to determine whether the distribution of 24 hr averages of B in Figure 3(c) is a statistical anomaly or a physical property of the heliosheath at the latitude and temporal epoch of the *V2* observations discussed here.

3. MAGNETIC FIELDS AND ENERGETIC PARTICLE OBSERVATIONS

Previous studies of the solar wind have shown that MIRs are associated with either decreases in the >70 MeV/nucleon ion intensity (Burlaga et al. 1985) or changes from a recovery to a plateau in the >70 MeV/nucleon ion intensity (Burlaga et al. 2003) in the solar wind. Figures 4(a) and 4(e) show that the recovery of the intensity of cosmic rays was interrupted by the passage of MIR-1, MIR-2, and region P. Similar results were obtained by *V1* prior to and after crossing the TS (Burlaga et al. 2005).

The relationship between the enhancements in B and the intensity of >70 MeV cosmic rays and the solar wind near the TS is not the same as the quantitative relationship given by the CR-B relation observed closer to the Sun (Burlaga et al. 1985). Moreover, there were no enhancements in the 10 MeV electron intensity at MIR-1 and MIR-2 similar to those observed at other MIRs closer to the Sun (McDonald et al. 2005). The reason for the different responses of cosmic rays and electrons to MIRs near the TS is not known.

In the heliosheath, no correlation between large enhancements in B and the intensity of >70 MeV cosmic rays was observed by either *V1* (Burlaga et al. 2005) or *V2*. It is not known why large enhancements of B have no effect on the cos-

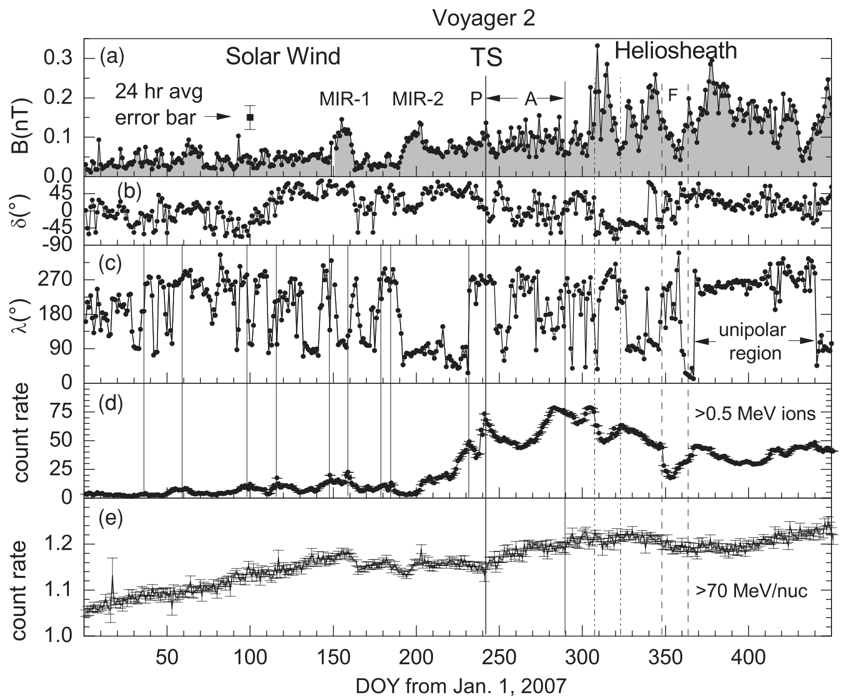

Figure 4. Daily averages of the magnetic field strength (a), elevation angle of magnetic field (b), azimuthal angle of the magnetic field (c), the counting rate of the energetic particles >0.5 MeV (d), and the counting rate of the cosmic rays >70 MeV (e) measured by *V2*.

mic rays in the heliosheath, whereas the enhancements of B do have significant effects on cosmic rays in the solar wind.

In the heliosheath, *V1* observed a depression in the counting rate of energetic particles (>0.5 MeV ions) related to an *enhancement* of B, ≈20 days following the TS crossing. A similar effect was observed by *V2* ≈65 days following the TS crossing (Figures 4c and 4d). On the other hand, a depression in the energetic particle density observed by *V2* on ≈2007 DOY 350 was associated with a *depression* of B related to feature "F." Figure 4 shows that no general correlation between B and the intensity of energetic particles in the heliosheath was observed by *V2*.

Richardson et al. (2006) noted in the *V1* data an apparent correlation between peaks in the intensity of energetic particles and crossings of the heliospheric current sheet (HCS) when *V1* crossed the HCS from negative to positive polarity magnetic sectors. They suggested that a similar correlation would be observed by *V2* except that the peaks should occur at crossings from positive to negative magnetic polarity. Figure 4(d) shows energetic particles (ions > 0.5 MeV), which have been discussed in detail by Stone et al. (2008) and Decker et al. (2008), upstream of the TS crossing by *V2*. The predicted correlation between energetic particle enhancements and crossings of the HCS from positive to negative magnetic polarity was not observed by *V2* (Figures 4b and 4c). Nevertheless, several of the energetic particle enhancements were associated with crossings of the HCS.

4. A UNIPOLAR REGION

A unipolar region was observed by *V2* in a 73-day interval from DOY 368 to DOY 441 (measured from 2007 January 1), as shown in Figure 4(b). The magnetic field data for the last 10 days in Figure 4 are preliminary results, but they are sufficiently accurate to identify a unipolar region. A similar long-lasting unipolar region was observed by *V1* shortly after its crossing of the TS (Burlaga et al. 2005); this region was identified as a sector that was moving through the heliosheath at nearly the same speed as *V1* (Jokipii 2005; E. Stone 2005, private communication). The unipolar region in Figure 4 is not the result of a sector moving at nearly the spacecraft speed; the plasma data in Figure 1 show that the heliosheath flow was carrying the region past *V2* at ≈150 km s^{-1}, an order of magnitude larger than the spacecraft speed. It is likely that this unipolar region is caused by a motion of the HCS moved toward equatorial plane to latitudes lower than *V2*, as suggested by Figure 14 of Burlaga et al. (2007). A similar effect was observed by *V1* during 2007, as the HCS moved to latitudes lower than *V1*. The decrease in the latitudinal extent of the HCS toward the solar equatorial plane is a characteristic of solar minimum. Thus, it is likely that *V1* and *V2* are observing conditions approaching those of solar minimum.

5. SUMMARY

We discussed 24 hr averages of the magnetic field intensity $B(t)$ of the solar wind and heliosheath made by *V2* and the relationships of B with the plasma and energetic particles, both prior to and after the TS crossings by *V2*. The principal results of the study are as follows.

1. We identified two MIRs (enhancements of the magnetic field strength (B) and the magnetic plus thermal solar wind pressure (P_{PB}), called "MIRs") in the solar wind prior to the crossing of the TS by *V2*. The density (N), proton temperature (T), and bulk speed (V) were not enhanced in these MIRs. Low values of the solar wind proton $\beta_{PB} \equiv NkT/(B^2/8\pi)$ in the MIRs suggest that they were formed from ejecta carrying strong magnetic fields away from the Sun.

2. Strong magnetic fields and low values of β_{PB} were also observed by *V2* in a limited region of the solar wind just prior to *V2*'s crossing of the TS. This feature may have been produced by processes associated with the TS, but one should not exclude the possibility that it was related to a transient MIR.
3. The predicted correlation between peaks in the intensity of energetic particles in the solar wind when *V2* crossed the HCS from positive to negative magnetic polarity in the solar wind was not observed. But there was a correlation between peaks in the energetic particle density and crossings of the HCS.
4. Approximately 40 days after *V2*'s TS crossing, a transition from small amplitude fluctuations in 24 hr averages of B on a scale of days to large amplitude fluctuations of B in the on a scale of the order of ten days was observed.
5. A notable enhancement of both N and T as well as a smaller enhancement in V during an interval of $\approx$10 days was observed by the plasma instrument on *V2* in the heliosheath. This feature was associated with a depression in B, indicating an anticorrelation between the magnetic pressure and thermal pressure. This feature was not an MIR. It is not known how such a structure is formed in the heliosheath.
6. No significant correlation between B and either the intensity of energetic particles ($>$0.5 MeV) or the intensity of cosmic rays ($>$70 MeV/n) was observed in the heliosheath by *V2*, consistent with *V1* observations of the heliosheath.
7. The ratios of the average values of B and N in the heliosheath and solar wind observed by *V2* are approximately 2.5 and 2.0, respectively, consistent with a perpendicular TS on average and similar to the local *TS* observations of B by *V1*.
8. The distributions of B and β_{PB} were approximately lognormal in both the solar wind and the heliosheath. The average of β_{PB} increased from $\approx$0.4 in the solar wind to $\approx$1.1 in the heliosheath. The average of P_{PB} increased by a much larger amount from 1.6×10^{-14} dyn cm^{-3} in the solar wind to 14.1×10^{-14} dyn cm^{-3} in the heliosheath.
9. The observation of a unipolar region for 73 days at the latitude of *V2* suggests that *V2* was beginning to observe the conditions of solar minimum near the end of 2007 and beginning of 2008.

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