Observations of the magnetic field and plasma in the heliosheath by Voyager 2 from 2007.7 to 2009.4

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[1] The density and temperature profiles of the plasma measured by Voyager 2 (V2) behind the termination shock changed abruptly near 2008.6 from relatively large average values and large fluctuations during 2007.7 to 2008.6 (interval A) to relatively low average values and very small-amplitude fluctuations during 2008.6 to 2009.4 (interval B). This paper shows that the change in the magnetic field strength B(t) was less abrupt than the plasma changes, and the fluctuations of the magnetic field strength in interval B were of moderate amplitude, with indications of a quasiperiodic structure in part of the interval. The magnetic field was directed away from the sun (positive polarity) ~ 78% ± 5% of the time in both interval A and interval B, changing in an irregular way from positive to negative polarities throughout the interval. The polarity distribution indicates that the minimum latitudinal extent of the heliospheric current sheet (HCS) was near V2 throughout the interval, consistent with the extrapolated minimum latitudes of the HCS computed from solar magnetic field observations. Thus, V2 was observing magnetic fields from the southern polar coronal hole most of the time. The distribution of B was lognormal in interval A and Gaussian interval B.

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1. Introduction

[2] Voyager 2 (V2) crossed the termination shock (TS) at 84 AU in August 2007 [*Richardson et al.*, 2008; *Burlaga et al.*, 2008a; *Decker et al.*, 2008; *Gurnett and Kurth*, 2008; and *Stone et al.*, 2008], and it has been moving in heliosheath toward the heliopause since that time. The bulk speed V in the heliosheath [*Richardson and Wang*, 2010], observed by the plasma instrument on V2 [*Bridge et al.*, 1977], has been twice as high as that observed by Voyager 1 (V1) when it crossed TS in December, 2004 [*Stone et al.*, 2005; *Gurnett and Kurth*, 2005; *Decker et al.*, 2005; *Burlaga et al.*, 2005a]. These high speeds were observed from the last crossing of the TS in September 1, 2007 (2007.7) to 2009.7. *Richardson and Wang* [2010] suggested that the high speeds are related to the entry of V2 into the transition region between the high speed and low speed solar wind, based on the Ulysses observation of a transition from high density low speed solar wind to low-density high speed wind at latitude −28° [*McComas et al.*, 2008]. One of the aims of the present paper is to use measurements of the magnetic polarity observed by the magnetic field experiment on V2 [*Behannon et al.*, 1977] and calculations of the position of the heliospheric current sheet (HCS) based on solar magnetic field observations to show that the minimum latitudinal extent of the HCS was indeed close to V2 from 2007.68 to 2009.4.

[3] *Richardson and Wang* [2010] showed that the density (N) and proton temperature (T) as well as the variations of N and T observed by V2 in the heliosheath were larger from ≈ 2008.6 to 2009.7 than from ≈2007.68 to 2008.6. They suggested that the decreasing density in the heliosheath may be at least partly related to the turning of the flow toward the heliotail, consistent with earlier evidence of this effect by *Decker et al.* [2006]. *Roelof et al.* [2010] suggested that ≈26 day quasi-recurrent pressure pulses moved past V2 from ≈2008.5 to 2008.9, and weaker ≈26 day quasi-recurrent pressure pulses moved past V2 from ≈2008.9 to 2009.3. We examine the relationship between the magnetic field and plasma from 2007.68 to 2009.4 and the change in the character of the plasma and magnetic field near 2008.6.

2. Polarity and Strength of the Magnetic Field

[4] Daily averages of the observations of B, the azimuthal angle λ, and elevation angle δ of the magnetic field **B** in HG coordinates from 2007.68 to 2009.4 (interval AB) are shown Figure 1. The V2 heliosheath observations just behind the TS, from 2007.68 to 2008.3 were discussed by *Burlaga*

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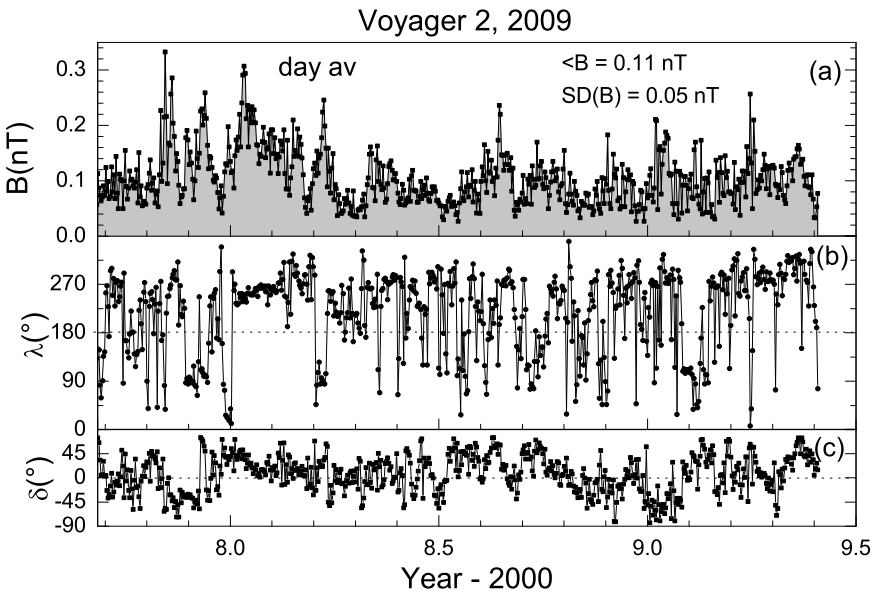

Figure 1. Daily averages of (a) magnetic field strength B, (b) azimuthal angle λ, and (c) elevation angle δ measured by V2.

et al. [2009a]. The remaining observations in Figure 1 from 2008.3 to 2009.4 are presented here for the first time.

[5] The polarity of the magnetic field is determined by the azimuthal angle λ shown in Figure 1b. The 1 σ uncertainty in each component of **B** is ± 0.03 nT. When B is relatively weak, the uncertainties in λ and δ can be very large. Therefore, we consider the distribution of λ for the subset of data with abs(B_T) > 0.05 nT, where B_T is the tangential component of **B** in RTN coordinates, which is plotted in Figure 2b. This distribution is based on 384 daily averages of λ.

[6] There are two peaks in the distribution of λ, at 90° and 270°, which correspond to the orientation of the Parker spiral magnetic field [*Parker*, 1963]. The peaks at 90° and 270° are partly a consequence of our assumption that the average of the radial component of **B** over two solar rotations centered at each roll of the spacecraft at ≈3 month intervals is zero. This is a reasonable assumption in the inner heliosheath, since Parker predicted that the radial component of **B**, B_R, is inversely proportional to the square of the distance from the sun. Thus, at 100 AU < B_R > is of the order of 0.0006 nT, which is well below the limit of detection. When $0° \leq \lambda \leq 180°$ **B** points sunward along the Parker spiral and is said to have "negative polarity." When $180° \leq \lambda \leq 360°$ **B** points "away" from the sun, and is said to have "positive polarity." Figure 2a shows that from 2007.68 to 2009.4 the polarity of **B** was positive 78% of the time and negative 22% of the time. The uncertainty in these polarities is ± 5°, based on distributions of λ computed with various assumptions. Most of the time, V2 was observing a magnetic polarity corresponding to that of the magnetic fields from the southern polar coronal hole. This implies that the minimum latitude of the heliospheric current sheet (HCS) [*Ness and Burlaga*, 2001; *Smith*, 2001] was close to the latitude of V2, (≈−28°S) during the interval AB. Voyager 2 crossed the HCS and sampled conditions on both sides of it many times during interval AB (see Figure 1b).

[7] The polarities of **B** observed by V2 during interval AB are consistent with those predicted by calculations of the maximum and minimum latitudes of the HCS as a function of time, shown at Figure 3. A detailed discussion of the

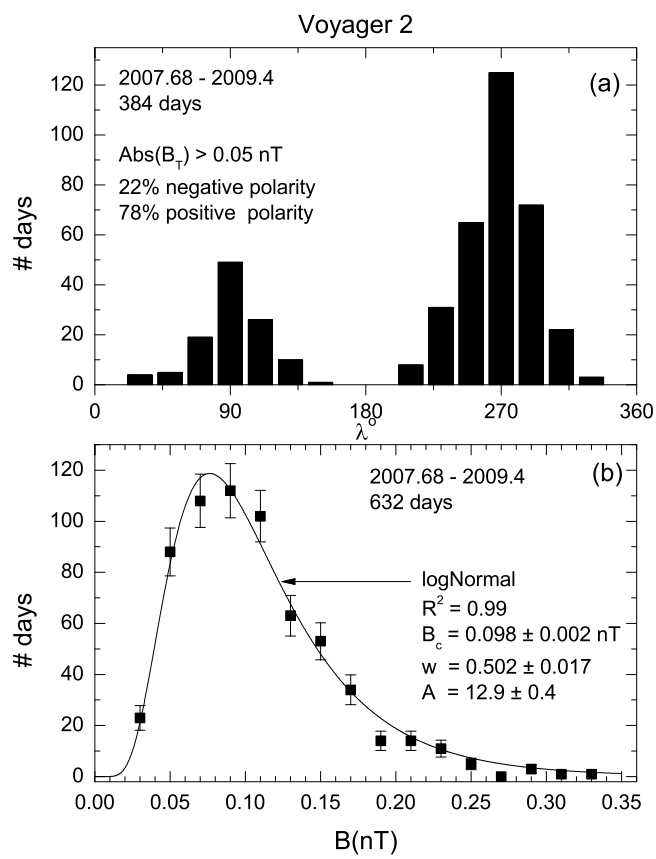

Figure 2. (a) Distribution of the polarity of the magnetic field and (b) distribution of magnetic field strength (squares) together with a lognormal fit (curve).

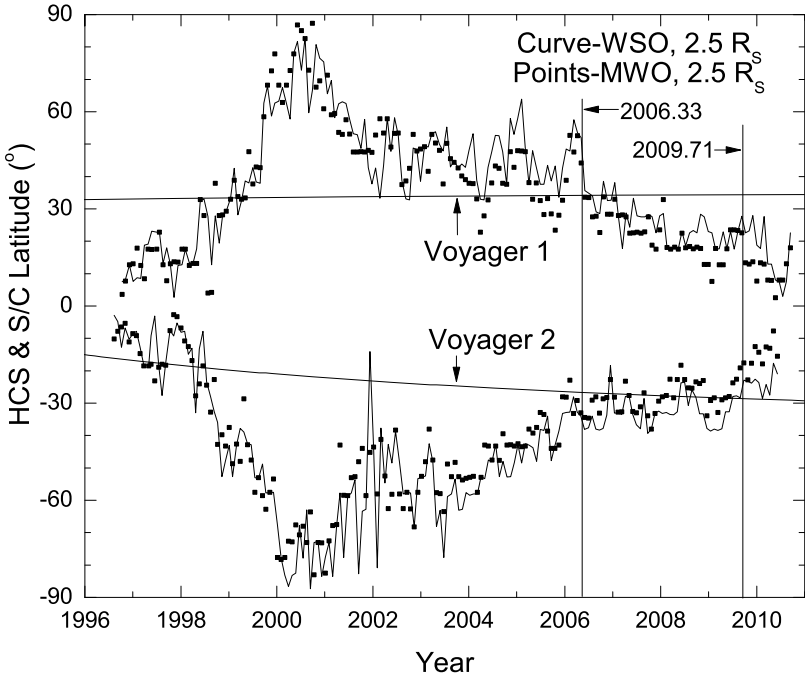

Figure 3. The maximum and minimum of the latitudinal extents of the heliospheric current sheet computed from the "radial model" with a source surface at 2.5 solar radii, with data from the Wilcox Solar observatory (WSO) and the Mount Wilson Observatory (MWO). The latitudes of V1 and V2 are shown by the nearly straight lines.

computation of these curves is presented by *Burlaga et al.* [2009b] and the references in that paper. The HCS is a surface that intersects a hypothetical "source surface" near the sun in a curve called the "neutral line." The neutral line is computed as a function of time using solar magnetic field data from both the Wilcox Solar Observatory (WSO) and the Mount Wilson Observatory (MWO) and "the radial model" of *Wang and Sheeley* [1992]. This potential field model includes the polar magnetic fields self-consistently and puts the source surface at 2.5 solar radii. The neutral line on this source surface determines the maximum and minimum latitudes of the HCS at a given time. Figure 3 shows the maximum and minimum latitudinal extent of the HCS as a function of time computed with this model. The data are plotted with a time delay corresponding to the propagation of the solar wind and frozen-in magnetic fields at a speed of 400 km/s from the sun to the positions of V1 and V2. Previous studies have shown that the latitudinal extent of the HCS changes little, O(10°), with increasing distance from the Sun out to 40 AU and even as far as the TS at ≈90 AU [*Burlaga et al.*, 2007].

[8] The radial model predicts that the minimum latitudinal extent of the HCS was close to the trajectory of V2 from 2006.3 to 2009.7 (Figure 3). If the effects of heliosheath flows in the HSH near V2 are small, this implies that V2 should have observed predominantly (but not exclusively) positive magnetic polarity throughout this interval, including the interval AB in Figure 1, consistent with the observations in Figure 2a.

[9] Figure 3 predicts that the minimum latitude of the HCS in the solar wind will be below the latitude of V2 after 2009.7, which is a consequence of the declining solar activity. Voyager 2, in the heliosheath, might then be observing exclusively positive polarity magnetic fields and conditions that are associated with the relatively fast flows from the southern polar coronal hole, if meridional flows in the heliosheath are not large. Figure 3 shows that the projected HCS moved past Voyager 1 (V1) after 2006.33 and was below the latitude of the V1 throughout the period discussed here. Voyager 1 observed negative polarity magnetic fields from the northern polar coronal hole throughout the interval from 2006.3 to 2006.9 [*Burlaga et al.*, 2007]. It is surprising that V1 observed a large oscillation of B during this interval. Large fluctuations in B were also observed in unipolar regions by V1 from 2004.98 to 2005.3 [*Burlaga et al.*, 2006] and by V2 from 2008.11 to 2008.56 [*Burlaga et al.*, 2009a]. It will be interesting to determine whether V2 will observe large fluctuations in B when it becomes immersed in the unipolar magnetic fields from the southern polar coronal hole.

3. Relation Between the Magnetic Field Strength and the Plasma Parameters

[10] *Richardson and Wang* [2010] suggested that V2 began to sample fast flows from the south polar hole before crossing the TS in August 2007. Our results are consistent with this hypothesis. The location of V2, near the minimum latitude of the HCS for an extended period of time, is consistent with the sustained high speeds observed in the heliosheath during the period that we are considering, assuming that the speed of flows from the polar coronal hole are relatively high on average on the southern side of the HCS. Daily averages of the radial component of the speed VR in the heliosheath in interval AB are shown in Figure 4d.

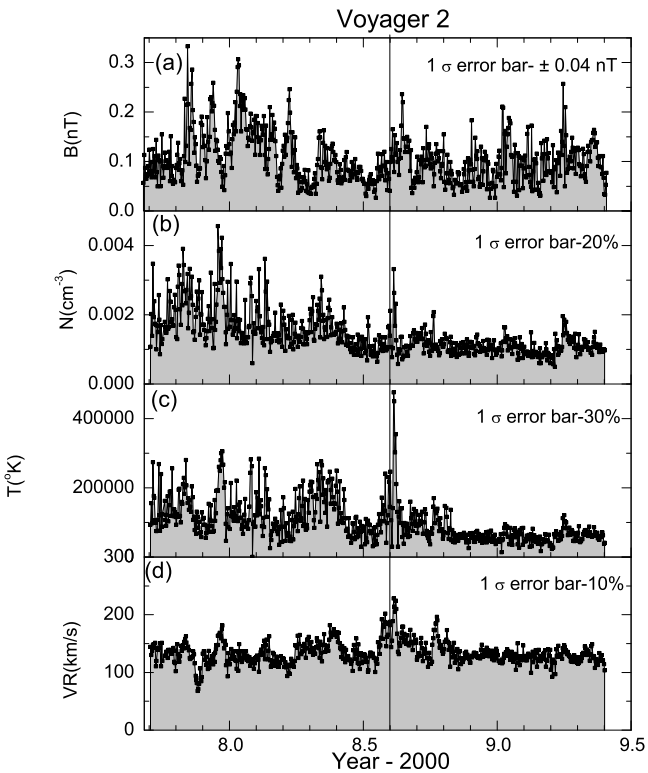

Figure 4. Daily averages of (a) magnetic field strength B, (b) density N, (c) proton temperature T, and (d) radial component to the speed VR measured by the plasma instrument on V2.

[11] Daily averages of B, N, and T are shown in Figures 4a, 4b and 4c. The observations of N and T were published by *Richardson and Wang* [2010], who noted that the N and T were stronger on average and fluctuated more during the first part of the interval AB than during the second part. Figure 4a shows that B was also stronger on average and fluctuated more during the first half of interval AB. In order to be specific, we consider two intervals: Interval A from 2007.68 to 2008.6 and interval B from 2008.6 to 2009.4. The variability of the magnetic field strength in interval B, although moderate compared to that interval A, is significantly larger than the variability of N and T in interval B.

[12] The averages of B, N, and T are larger in interval A than in interval B. Moreover, $\langle N \rangle$ and $\langle T \rangle$ decrease more than $\langle B \rangle$ from interval A to interval B. In particular, $\langle N_A \rangle / \langle N_B \rangle = 1.55$ and $\langle T_A \rangle / \langle T_B \rangle = 1.75$, whereas the ratio $\langle B_A \rangle / \langle B_B \rangle = 1.15$. Likewise, Table 1 shows that the fluctuations of B, N, and T, measured by the respective standard deviations, are greater in interval A than in interval B. The simple statistics shown in Table 1 do not capture some of the qualitative differences of the observations of B and plasma parameters in intervals A and B that can be seen by eye.

[13] *Richardson and Wang* [2010] attributed the difference in the character of the plasma parameters observed by V2 in region A and region B to the deflection of the flow toward a heliotail as it moved deeper into the heliosheath. It is possible that the difference might also be related to (1) temporal changes associated with the declining solar activity, (2) ejecta related to solar activity in interval A, (3) fast flows from a lobe of the southern polar coronal hole, and (4) a changing minimum latitudinal extent of the HCS. The weaker magnetic fields in interval B than in interval A could be a consequence of declining solar activity, as observed by V1 [*Burlaga et al.*, 2009b]. But this does not explain the abrupt change in T and N from interval A to interval B, which was associated with large spikes in N, T, and V and a smaller enhancement in B. Since interval A corresponds to a period of exceptionally weak solar activity, it is unlikely that the disturbed and relatively strong values of B, N, and T could be associated with ejecta. Since the variations of V published by *Richardson and Wang* [2010] and the variations in VR shown in Figure 4d are small, variations of **V** owing to fast flows from a lobe of the polar coronal hole are not apparent. A changing latitudinal extent of the HCS would be manifested by a change in the distribution of the polarity of the magnetic field from interval A to interval B, which we now consider.

[14] The distributions of λ for the subset of data with abs $(B_T) > 0.05$ nT in interval A and interval B are shown in Figures 5a and b, respectively. There are two peaks in the distributions, at 90° and 270°. The polarity distributions in Figure 5a and 5b are essentially the same within the 5% uncertainty. The dominant polarity is positive for 76% of the 222 days in interval A and 80% of the 162 days in interval B. The observations show that the HCS was not below the latitude of V2 throughout interval B (which would imply a positive polarity of nearly 100% during interval B).

[15] Now let us consider the suggestion of *Roelof et al.* [2010] that ~26 day quasi-recurrent pressure pulses moved past V2 from approximately 2008.5 to 2008.9 and weaker ~26 day quasi-recurrent pressure pulses moved past V2 from ~2008.9 to 2009.3. Inspection of Figure 1a shows that there were three "recurrent" enhancements of B between approximately 2008.5 and 2008.9 and two additional broad irregular enhancements of B between 2008.9 and 2009.3. These enhancements are not strictly periodic, and they do not recur with a period close to 26 days. There are no quasiperiodic fluctuations in V or VR during this interval [see *Richardson and Wang*, 2010] (Figure 4d). Finally, there is no relationship between the enhancements of B and changes in magnetic polarity, such as might be expected if the enhancements were related to a fast stream from an extension of the south polar coronal hole.

[16] Nevertheless, it might be significant the two intervals singled out by *Roelof et al.* [2010] (based on energetic particle observations) correspond to an interval that was identified as unique in the plasma data and which contains moderate variations in B that are "quasi-periodic" for at least a few cycles. Models of the radial variation of V and B

Table 1. Average (Av), Standard Deviation (SD), and the Ratio Av-A/Av-B for B, N, T, and in Interval A and Interval B

	Av-A	Av-B	Av-A/Av-B	SD-A	SD-B
B(nT)	0.112	0.097	1.15	0.056	0.040
N(cm^{-3})	0.0017	0.0011	1.55	0.0007	0.0003
T(°K)	131,000	74,000	1.75	61,000	50,000
VR(km/s)	134	135	0.99	21	20

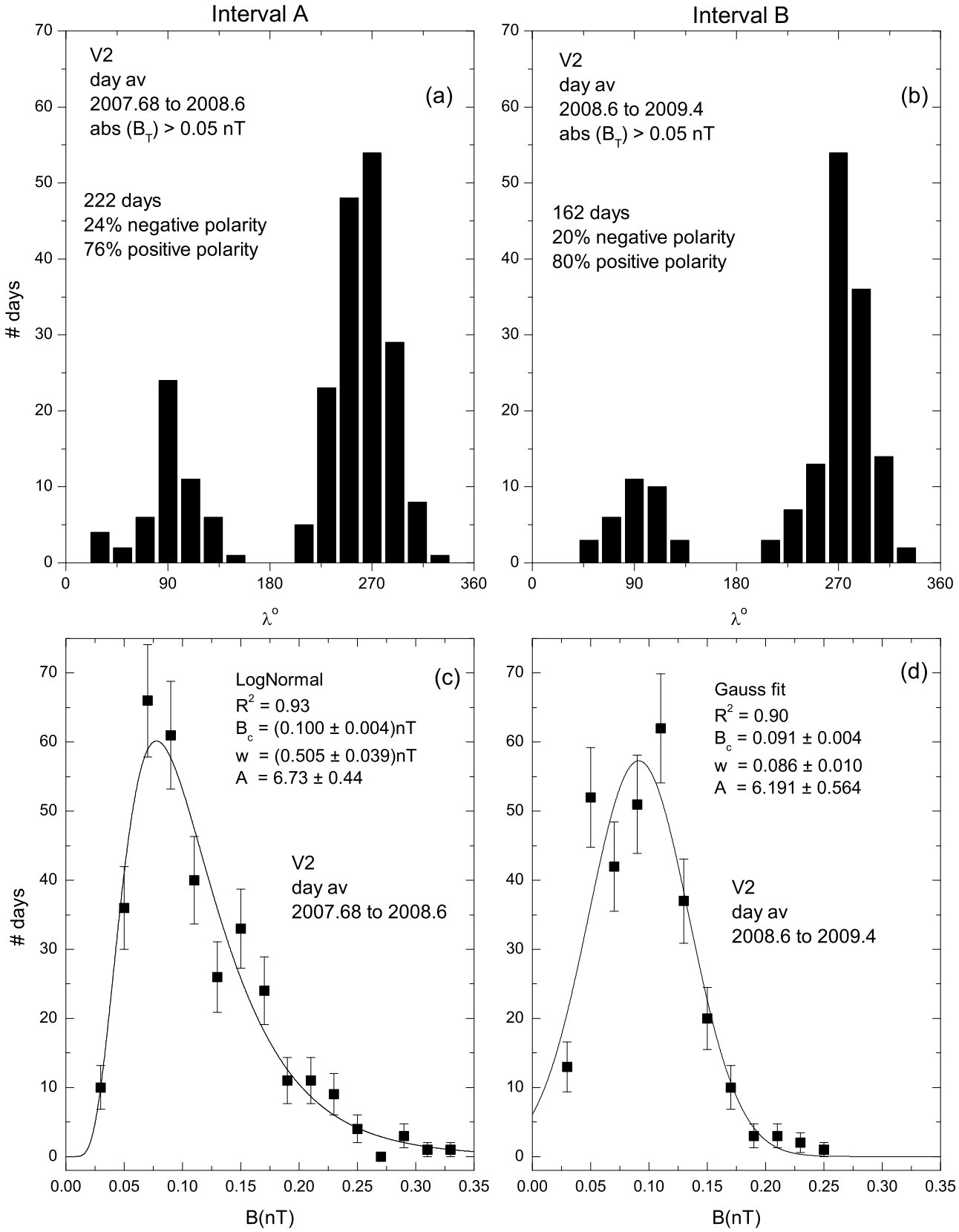

Figure 5. Distribution of the magnetic field polarity (a) interval A and (b) interval B. (c) Distribution of B (squares) and a lognormal fit (curve) in interval A, and (d) distribution of B (squares) and a Gaussian fit (curve) in interval B.

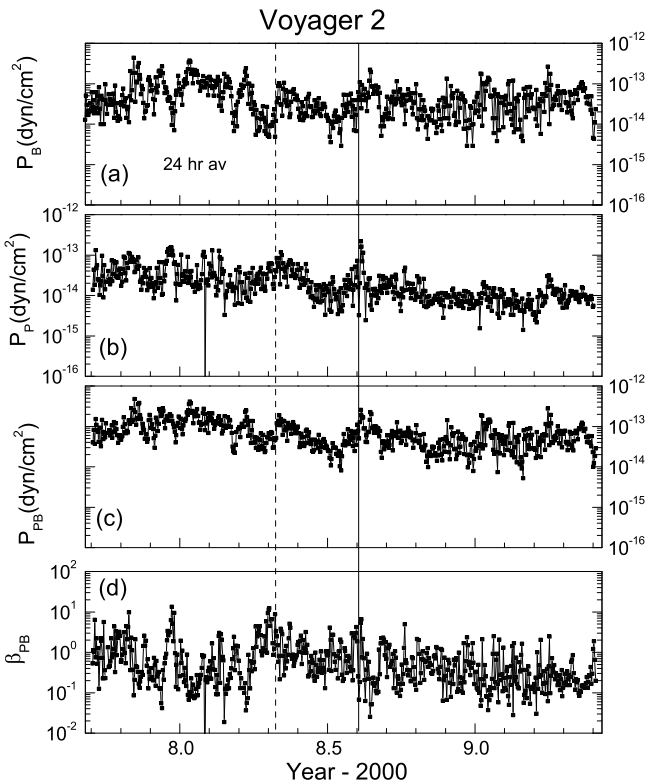

Figure 6. Voyager 2 observations of (a) the magnetic pressure $P_B = (B^2/8\pi)$, (b) solar wind pressure $P_P = NkT$, (c) total pressure $P_{BP} = (P_B + P_T)$, and (d) $\beta = P_P/P_B$.

associated with corotating streams by *Burlaga et al.* [2003a, 2003b] show that the characteristic period increases with distance from the sun out to 30 AU as result of period-doubling associated with merging interaction regions, and that the fluctuations in B are weak and aperiodic between 30 and 90 AU. It is conceivable that the fluctuations of B observed in interval B are related to a corotating stream associated with an equatorial extension of a lobe of the southern polar coronal hole, as suggested by *Roelof et al.* [2010]. But such a relationship is not expected, owing to the complex, nonlinear interactions between 1 and 90 AU [*Burlaga et al.*, 2003a, 2003b]. It would be worthwhile to model the evolution of the fast flow from a single lobe of the southern polar coronal hole, and the expected variation of B, N, and T as a function of time at the latitude and distance of V2, perhaps using the boundary conditions obtained in the manner suggested by *Burlaga et al.* [2008b]. One should consider the possibility that the HCS moved past V2 at ~2009.975 and the steepening of fast flows behind it produced the strong magnetic fields in interval A by the process described by *Burlaga et al.* [2005b].

4. Strength of the Magnetic Field

[17] The observations of B made by V2 from 2007.68 to 2009.4 are shown Figure 1a. The distribution of B is plotted as the points in Figure 2b. A lognormal distribution

$$y = A/[\sqrt{(2 \times \pi)}w \times B] \times \exp\left[-(\ln(B/B_c))^2/(2w^2)\right]$$

shown by the solid curve in Figure 2b, provides an excellent fit to the observations ($R^2 = 0.99$). The parameters of the fit are $B_c = 0.098 \pm 0.002$ nT, $w = 0.502 \pm 0.017$ nT, and $A = 12.9 \pm 0.4$. This lognormal distribution of the V2 observations of daily averages of B from 2007.68 to 2008.3 is in contrast to the Gaussian distribution of the V1 observations of daily averages of B from 2005.0 to 2008.82 [*Burlaga et al.*, 2009b].

[18] Figure 5c shows that the distribution of the magnetic field strength in interval A was approximately lognormal ($R^2 = 0.93$). A fit to the observed magnetic field strength distribution in interval B in (Figure 5d) with a lognormal distribution is less satisfactory ($R^2 = 0.85$). A somewhat better fit to the distribution in Figure 5d ($R^2 = 0.90$) is obtained with a Gaussian distribution, $B = (A/[w \times \sqrt{(\pi/2)}]) \times \exp\{-2[(B-B_c)/w]^2$, where $B_c = 0.091 \pm 0.004$ nT, $w = 0.086 \pm 0.010$ nT, and $A = 6.191 \pm 0.564$, which is plotted as the curve in Figure 5d. The Gaussian fit to the data in interval B could be an indication that the fluctuations observed by V2 are becoming more like the Gaussian distributions observed by V1 as V2 moves farther into the heliosheath and into the polar coronal hole flows [*Richardson and Wang*, 2010]. However, it could be related to a particular type of flow that passed V2 during interval B. The lognormal distribution in interval A expresses the presence of magnetic fields much stronger than the mean field; such strong magnetic fields are absent in interval B, which is more symmetric about the mean. We must wait for further observations to before concluding that the Gaussian distribution observed by V2 in interval B is characteristic of a polar coronal hole flow.

5. Pressures and Beta

[19] Magnetic pressure $P_B = (B^2/8\pi)$, solar wind thermal pressure $P_P = NkT$, total pressure $P_{BP} = (P_B + P_P)$, and $\beta = P_P/P_B$ in the solar wind ahead of the termination shock (TS) and in heliosheath behind the TS (from DOY 245, 2007 to DOY 75, 2008 are discussed by *Burlaga et al.* [2009a]. In the heliosheath from DOY 1 − 75, 2008 they reported that $P_{BP} = 14.1 \times 10^{-14}$ dyn cm^{-2}, and $\beta = 1.1$. The corresponding quantities observed in the heliosheath 2007.68 2009.4 are shown in Figure 6. The pressures and β are larger in interval A than in interval B, as expected. There is a positive correlation between P_B, P_P, and P_{PB} from 2008.32 to 2008.6 at which time β is close to unity. Prior to this, there are large fluctuations in β about unity, partly related to an anti-correlation between P_B and P_P. In interval B, β is significantly less than unity, and the fluctuations are smaller.

[20] In general, the large-scale fluctuations in B, N, T, and the corresponding pressures in heliosheath are not understood, in contrast to the merged interaction regions in the supersonic solar wind. Thus, it is not surprising that we do not understand the values and fluctuations of the pressures and β in Figure 6. Nevertheless, there are patterns in these data, such as those described in the previous paragraph. It remains a challenge to understand the variability of the plasma and magnetic field para-

meters on the scale of tens of days to one year in heliosheath.

6. Summary

[21] We analyzed the magnetic field observed by V2 in the heliosheath beyond the termination shock from 2007.68 to 2009.4 (interval AB). During this interval, the magnetic field was directed away from the sun 78% of the time and it was directed toward the sun 22% of the time. This result is consistent with the extrapolation of the latitude of the HCS to the position of V2. Most of the time, V2 was observing a magnetic polarity corresponding to that of the south polar hole. This implies that the minimum latitudinal extent of the heliospheric current sheet (HCS) was close to the latitude of V2 (≈ 28°S) during interval AB. Thus, the high speeds observed in the heliosheath by V2 might be related to the relatively high speeds of the solar wind from the southern polar coronal hole. However, the observation of negative polarity 22% of the time indicates that V2 was crossing the HCS frequently during the interval.

[22] The properties of the magnetic field and plasma in heliosheath differed in the interval from 2007.7 to ~2008.6 (interval A) behind the termination shock and the interval from 2008.6 to 2009.4 (interval B). During interval A, large fluctuations in B were observed in association with the large fluctuations in N and T that were discussed by *Richardson and Wang* [2010]. However, the fluctuations of the magnetic field strength in interval B were significantly larger than the fluctuations of N, T, and VR in interval B.

[23] The polarity of the magnetic field was positive (directed away from the sun) ~78% of the time in both intervals, and there was no significant difference in the polarity distribution in regions A and B. Throughout the interval AB, the minimum latitude of the (HCS) was near that V2, and V2 crossed the HCS a number of times. It is conceivable that the moderate amplitude "quasi-periodic" fluctuations in B observed by V2 in interval B were related to fast flows from an extension of a lobe of limited longitudinal extent from the southern polar coronal hole. However, the lobe was not manifested directly in temporal variations of N, T, and VR.

[24] The distribution of daily averages of B observed by V2 from 2007.68 to 2009.4 was lognormal, in contrast to the Gaussian distribution of daily averages of B observed by V1 in the heliosheath from 2005.0 to 2008.82 [*Burlaga et al.*, 2009b]. However, the distribution of B observed in interval B from 2008.62 to 2009.4 is consistent with a Gaussian distribution. Perhaps the more moderate and symmetric fluctuations of the magnetic field strength in interval B are related to the more uniform flows and magnetic fields in the flow from the south polar coronal hole and the transition region between fast and slow flows; more extensive data are needed to evaluate this hypothesis.

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