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MAGNETIC FLUX CONSERVATION IN THE HELIOSHEATH

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ABSTRACT

Voyager 1 (*VI*) and *Voyager 2* (*V2*) have observed heliosheath plasma since 2005 December and 2007 August, respectively. The observed speed profiles are very different at the two spacecrafts. Speeds at *VI* decreased to zero in 2010 while the average speed at *V2* is a constant 150 km s⁻¹ with the direction rotating tailward. The magnetic flux is expected to be constant in these heliosheath flows. We show that the flux is constant at *V2* but decreases by an order of magnitude at *VI*, even after accounting for divergence of the flows and changes in the solar field. If reconnection were responsible for this decrease, the magnetic field would lose 70% of its free energy to reconnection and the energy density released would be 0.6 eV cm⁻³.

Key words: magnetic fields – solar wind – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

The heliosheath is the highly variable region of shocked solar wind plasma between the termination shock and heliopause. The *Voyager* spacecrafts have observed this region in situ since 2004 (*VI*) and 2007 (*V2*) when they crossed the termination shock. The magnetic field shows large variations on all timescales but on average is consistent with a Parker spiral field, with the field mainly in the *T* direction (Burlaga & Ness 2009, 2012). (We use the standard RTN coordinate system, where *R* is radially outward, *T* is parallel to the solar equator and positive in the direction of solar rotation, and *N* completes a right-handed system.) *VI* continues to observe heliospheric current sheet (HCS) crossings while *V2* has several times entered unipolar magnetic field regions below the HCS.

The flow velocities observed at *VI* and *V2* are very different. The plasma instrument on *VI* does not work, so speeds at *VI* are determined from higher energy particle data using the Compton–Getting effect (Gleeson & Axford 1968), which states that the particle intensities and energies will vary depending on the flow direction relative to the detector. The *Voyager* Low Energy Charged Particle (LECP) experiments measure ions with energies from tens of keV to tens of MeV. The instrument steps through 8 sectors in roughly the *RT* plane and can determine the plasma speed in the *R* and *T* directions, V_R and V_T . In 2011 a series of spacecraft rolls were initiated which allowed LECP to occasionally determine V_N (Decker et al. 2012). The Cosmic Ray Subsystem (CRS), which measures >0.5 MeV ions, can derive V_N during the rolls that occur every few months to calibrate the magnetometer, also using the Compton–Getting effect (Stone et al. 2012). These measurements show that the radial flow at *VI* was about 80 km s⁻¹ after the termination shock (TS) crossing, then decreased steadily to zero in early 2010 (Krimigis et al. 2011). The radial speed has remained near zero through 2012 August. The *T* component was steady at -40 km s⁻¹ until 2011, when its magnitude decreased to about 20 km s⁻¹. The *N* component was northward and has been roughly equal to the *R* component, also approaching zero in 2010 (Decker et al. 2012; Stone et al. 2012).

The *V2* plasma experiment directly measures the solar wind protons using four Faraday cups, three of which point toward the Sun (Bridge et al. 1977). The data from these cups are fit with convected isotropic Maxwellian distributions to determine the plasma velocity, speed, and density. The speed at *V2* has remained constant at near 150 km s⁻¹ since the TS crossing, but the flow direction has changed and is now about 55° from radial in the *T* direction and 25° in the -*N* direction. The radial flow speed has decreased from 130 to 90 km s⁻¹.

The magnetic flux is a conserved quantity for a steady state flow. For a radial flow, such as the supersonic solar wind upstream of the TS where the magnetic field is in the *T* direction, the magnetic flux $V_R B R$ is constant (Parker 1963) assuming no sources or losses of magnetic flux. The only significant source is the solar dynamo and the only loss is reconnection, which is minimal in the supersonic solar wind (Gosling 2011) but in the heliosheath (Opher et al. 2011). The magnetic flux must remain constant across the TS as well to satisfy the Rankine–Hugoniot relations. This Letter presents observations of the magnetic flux in the outer heliosphere and heliosheath and shows that for *V2* the magnetic flux is constant. At *VI*, the magnetic flux is not constant across the heliosheath. We discuss possible causes of this discrepancy.

2. THE DATA

We use daily average *VI* magnetic field data and daily average *V2* plasma and magnetic field data from COHOWEB provided by the Space Physics Data Facility (SPDF). The *VI* heliosheath V_R and V_T are 26 day averages from LECP observations (Decker et al. 2012). The magnetic field is predominantly in the *T* direction; the B_R and B_N components typically have magnitudes comparable to the uncertainties in the measurements and average 0 (Burlaga & Ness 2010). Thus the data are consistent with $B = B_T$. The magnetic flux for radial outflow is given by $V_R B R = \text{constant}$. The value of this constant changes with the solar source of magnetic flux, which is variable. The source of magnetic flux is very low in the recent solar minimum (Smith & Balogh 2008) and is larger at solar maxima. The

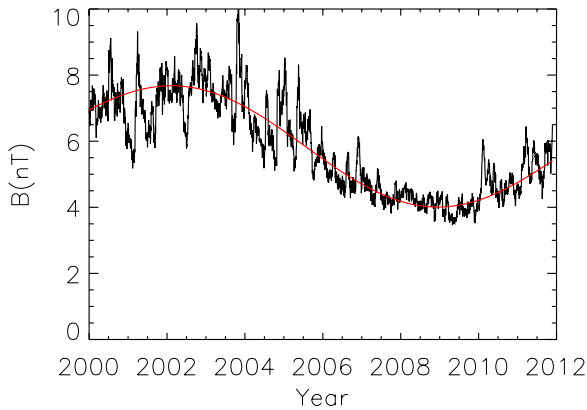


Figure 1. 25 day sunning averages of the magnetic field magnitude observed at 1 AU from the OMNI data set and our fit to the data used to normalize the magnetic field in the outer heliosphere.

(A color version of this figure is available in the online journal.)

OMNI data from 1 AU are used to normalize the magnetic field in the outer heliosphere to remove the time dependence of the source. Figure 1 shows OMNI daily averages and the fit to the data which is used for the normalization. We use a propagation time of 1 year from 1 AU to the *Voyager* spacecraft.

For V2, the flow in the heliosheath is primarily in the R and T directions (Richardson & Wang 2012). Since T is parallel to B , flow in the T direction does not effect the magnetic flux. Figure 2 shows $V_R BR$, V_R , and B for V2. The speed drops by a factor of 2–3 at the shock, the magnetic field increases, but the average magnetic flux $V_R BR$ does not change significantly. Thus the magnetic flux is constant at V2 as expected.

The VI heliosheath plasma velocity is derived from energetic particle data from LECP and CRS using the Compton–Getting effect. Figure 3 shows $V_R BR$, V_R , and B for VI. We assume that the solar wind speed was 400 km s^{-1} until the TS, similar to V2 observations, then used the downstream 26 day average radial speeds from LECP (Decker et al. 2012). The resulting speed profile is shown in the middle panel of Figure 3. The dashed line shows the TS crossing. The speed decreases to near zero for a few months after the TS, which has been attributed to inward motion of the TS (Jokipii 2005). From mid-2005 to 2011 V_R decreases nearly monotonically from about 80 km s^{-1} outward to 10 km s^{-1} inward. The quantity $V_R BR$ decreases by about 40% at the TS then decreases again from 2007 to 2011. After 2007 the speed decreases but the magnetic field does not increase enough to keep $V_R BR$ constant (Burlaga & Ness 2012).

3. DISCUSSION

For V2, $V_R BR$ is constant as expected. For VI, $V_R BR$ decreases across the TS and after 2007 in the heliosheath. Since $V_R BR$ conservation is valid for radial flow, we consider whether the V_N component, which at VI is comparable to V_R in the heliosheath, could produce this decrease. Since the field is predominantly in the T direction, only flow in the R and N directions results in a decrease in B . Flows in the N direction can only be calculated during spacecraft rolls which occur every few months. These roll observations show consistent northward flows with speeds comparable to the radial outflow (Stone et al. 2012), so the flow angle in the RN plane is roughly 45° . Like V_R , V_N decreases from 80 km s^{-1} after the TS in 2005.5 to near-zero in 2011.

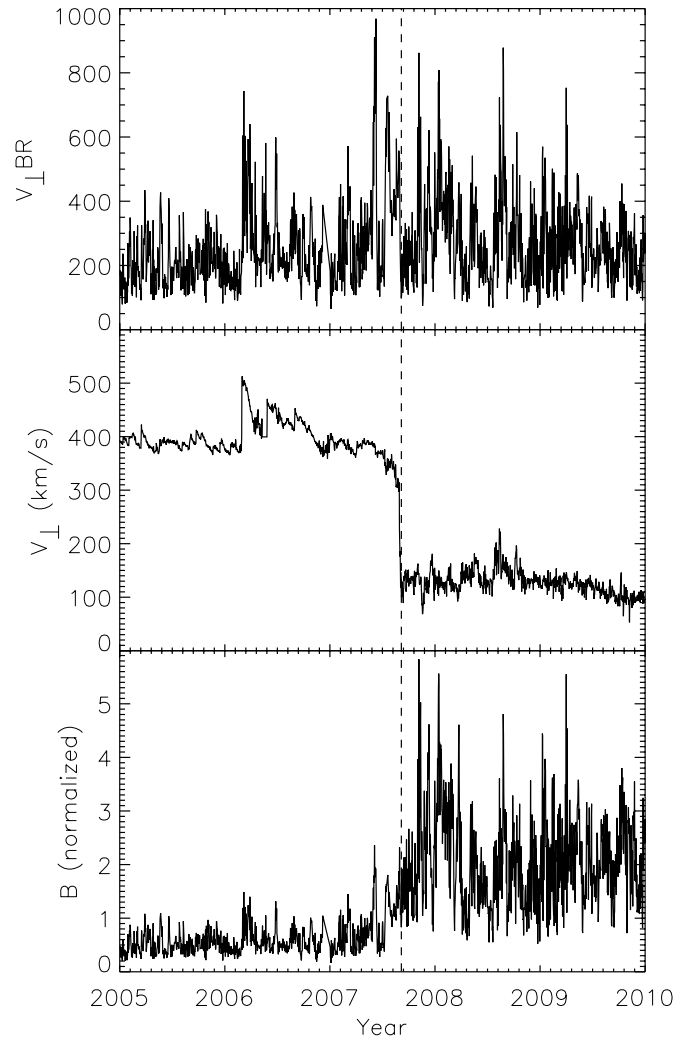


Figure 2. Daily averages of $V_R BR$, V_R , and B observed at *Voyager 2*. The dashed line shows the termination shock location.

For $V_N \sim V_R$ the magnetic flux relation must be modified to account for non-radial flow perpendicular to B . We assume V_N is symmetric about the equator. The magnetic field is frozen into the flow. The effect of V_N is to cause the field lines to diverge faster than if the flow were radial, so the magnetic field strength should decrease more rapidly with distance than for a radial flow. The magnetic field strength is inversely proportional to the separation of the stream lines, L , so the magnetic flux $V_\perp BL = \text{constant}$ where $V_\perp = \sqrt{(v_R^2 + v_N^2)}$.

To calculate the magnetic flux we need to know how L varies with distance. VI is at a heliolatitude of about 35° N. For a flow expanding away from the equator at a 45° angle from radial beyond the TS, the magnetic field should decrease as the increase in distance from the equator to the spacecraft. This increase in distance has two terms, one resulting from the radial expansion throughout the heliosphere and the other from V_N outside the TS. Thus $V_\perp BL = V_\perp B(\sin(\text{heliolatitude}) * R + (R - R_{\text{TS}}) \tan(\text{RN angle})) = V_\perp B(0.57R + R - R_{\text{TS}})$ should be constant where $\text{RN angle} = 45^\circ$ is the observed flow angle in the RN plane.

Figure 4 shows $V_R BR$ and $V_\perp BL$ for VI. The additional transport of magnetic flux from the inclusion of V_N results in $V_\perp BL$ being constant across the TS as expected. The larger R dependence of L in the heliosheath decreases the expected B ; this

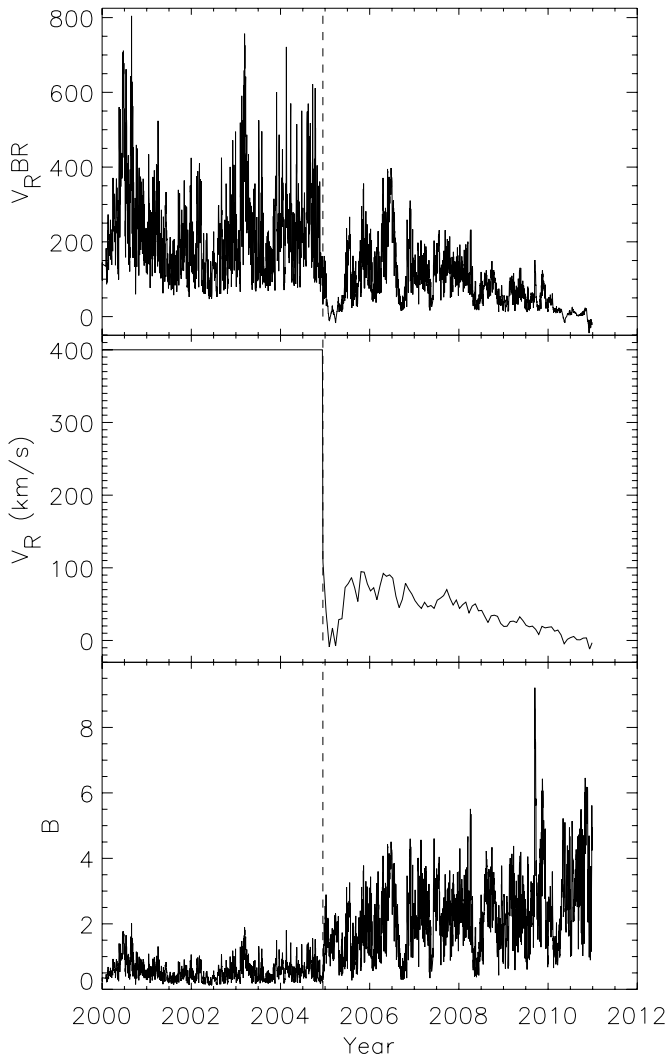


Figure 3. Daily averages of $V_R BR$, V_R , and B observed at *Voyager 1*. The dashed vertical line shows the termination shock location.

decrease is evident in Figure 4 which shows a smaller decrease in $V_{\perp} BL$ than $V_R BR$. However, this difference is small compared to the overall decrease in the magnetic flux. The magnetic flux still shows a significant decrease, a factor of 10, from 2007 to 2011 despite the inclusion of V_N . Note that we assume no flow across the equator. Some models show northward flow across the equator due to the heliospheric asymmetry, which would reduce the divergence in the flow and make the magnetic flux deficit worse.

We test the assumption that the magnetic flux $V_{\perp} BL$ should be conserved by comparing to model results. The bottom panel of Figure 4 shows the values of L , VB , and VBL taken from a three-dimensional MHD model with no reconnection (Opher et al. 2009). The model shows VB decreasing across the heliosheath, L increasing, and the magnetic flux VBL remaining constant, in agreement with expectations.

We consider mechanisms for producing the observed magnetic flux decrease. Time dependence can result in temporary changes in the magnetic flux. In early 2005 soon after the *VI* TS crossing, V_R decreases to near zero for a few months, probably as a result of inward TS motion (Jokipii 2005). Since the Sun still produces magnetic flux, the average value of B inside *VI* must increase slightly or more flux is carried northward (we do not know V_N in this time period). Figure 3 shows that

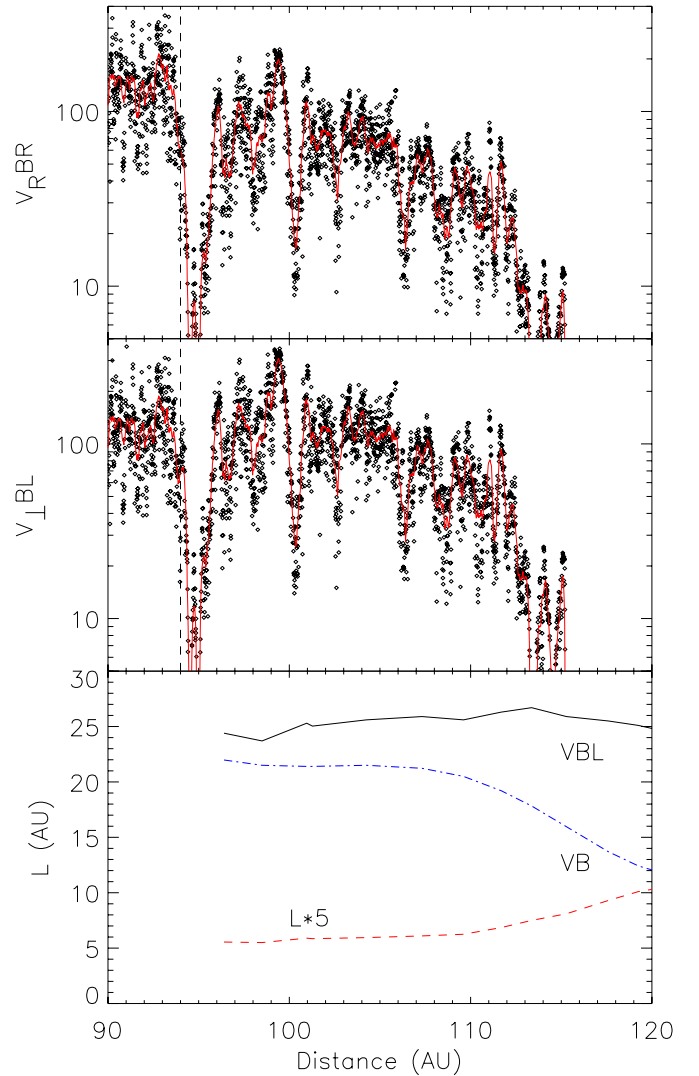


Figure 4. Top: daily averages of $V_R BR$ at *VI* plotted on a log scale. Middle: daily averages of $V_{\perp} BL$. The dashed vertical line shows the termination shock location. Bottom: results along a heliosheath model streamline showing L , VB , and VBL .

(A color version of this figure is available in the online journal.)

the decrease in $V_R BR$ persists from about 2005 to 2011, with shorter scale increases and decreases superposed. This decrease in magnetic flux (normalized to the solar source) persists for several times the transport time through the heliosphere, about two years. Since the plasma and field residence times are shorter than the time over which the magnetic flux deficit is observed, this deficit is probably not a time-dependent effect.

Reconnection may be ubiquitous in the heliosheath since the HCS is compressed, bringing together oppositely directed magnetic fields (Opher et al. 2011). However, direct evidence of reconnection in the heliosheath has only been reported for one HCS crossing (Burlaga et al. 2006). If reconnection were prevalent it would remove magnetic flux. To maintain a constant value of the magnetic flux, the magnetic field would have had to increase by about a factor of 7 to 0.7 nT from 2007 to mid-2010. The actual field increased from 0.1 to 0.2 nT as *VI* entered the stagnation layer. Thus about 0.5 nT of magnetic field strength is missing, so the energy density is reduced by 10^{-12} erg cm^{-3} or 0.6 eV cm^{-3} . This amount of energy is available to heat particles. Drake et al. (2010) estimate that 72% of the magnetic

free energy is released via reconnection and heats particles; this estimate is comparable to the percentage of magnetic energy loss implied by these data. Another puzzle in the heliosheath is the source of the anomalous cosmic rays. One suggestion has been acceleration by reconnection; this amount of energy would be sufficient to accelerate the anomalous cosmic rays (Drake et al. 2010).

The difference between *VI* and *V2* may result from different amounts of time spent within the sector zone. *VI* has remained mostly within this zone where the HCS is important whereas *V2* has been in unipolar zones above the HCS for substantial amounts of its heliosheath traversal (Burlaga & Ness 2011). Thus reconnection could be more important at *VI* than *V2*.

4. SUMMARY

The *Voyager* spacecraft have observed very different plasma conditions in different parts of the heliosheath. We show that the magnetic flux is constant at *V2* but not at *VI*. At *VI*, the magnetic flux decreases by almost an order of magnitude as *VI* approaches the stagnation region. This decrease cannot be explained either by changes at the solar source or by non-radial transport. Reconnection is a candidate for the flux removal since *VI* is in the sector zone.

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