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Studies of the Termination Shock and Heliosheath at > 92 AU: Voyager 1 Magnetic Field Measurements

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The Heliospheric Magnetic Field (HMF) has been measured since 1977 by Voyager 1 (V1) from 1 to 96 AU. The HMF generally had the expected properties at these distances and epochs through several solar activity cycles until late in 2004 when V1 was at 94 AU and heliographic latitude of 35˚ N. On December 16, 2004, V1 crossed or was crossed by the Termination Shock and entered the Heliosheath as determined from magnetic field data. The magnitude increased by a factor of ~3-4 and fluctuations were enhanced significantly. We report on these interesting new results and provide preliminary interpretations of the data in 2004 and 2005. Observations of the HMF in 2002–2003 did not provide evidence for any crossings of the termination shock near 85 AU as earlier proposed [1, 2, 3].

1. Introduction

Twin Voyager spacecraft, V2 and V1, were launched in 1977. After encounters with the 4 giant outer planets, they have more or less continuously measured the Heliospheric Magnetic Field (HMF) from 1 to ~96 AU up to the present time (June 2005). Thus, magnetic field observations now cover well over a full 22 years long solar magnetic cycle. The temporal and spatial variations of the magnitude of the HMF have been found to be well described by Parker's Archimedean spiral structure when due account is made for time variations of the source field strength and solar wind velocity [4]. This ICRC 2005 paper summarizes recent HMF observations which demonstrate clearly that the theorized and long-sought Termination Shock (TS) associated with the interaction of the solar wind (SW) with the local interstellar medium (LISM) was detected in mid-December 2004 by Voyager 1(V1) at 94.0 AU while at 35º N heliographic latitude. Since then V1 has been observing in-situ a new astrophysical plasma regime referred to as the Heliosheath (HS).

2. Discussion

The observed annual averages of the magnitude of the HMF measured by V1 since 1977 are shown in Figure 1, left panel. Solar activity related relative minima were seen in ~1987 and ~1997 and maxima in ~1990 and ~2000. The observed data agree well with the expected magnetic field predicted by Parker's model using in-situ HMF observations near 1 AU by the Advanced Composition Explorer (ACE) and the projected SW estimated speed [5, 6]. The plasma probe on V1 has not been operational since 1982, hence the need for a proxy measurement of SW speed in order to predict the HMF magnitude. The dashed lines represent the limits of the predicted HMF assuming a constant lower SW speed of 400 km/sec or a constant higher SW speed of 800 km/sec.

On day 352, 2004 when V1 was at 94.0 AU and 35º N, the HMF magnitude suddenly increased by a factor of ~3 to reach average sustained values ranging up to 0.26 nT. These are larger than had been seen in any such sustained periods since 1990 when V1 was at ~45 AU.

The sudden change and these large values are interpreted as evidence of V1 having crossed the Termination Shock (TS) and entered the Heliosheath. The average magnitude of the HMF measured thus far in 2005 was 0.14 +/- 0.02 nT. Since 1994 but prior to the TS crossing, the annual average HMF was between 0.02 to 0.06 nT +/- 0.02 nT.

A unique aspect of the characteristics of the HMF in the pre-TS crossing data and in the Heliosheath is the different statistical distribution of the field magnitude. This is shown in Figure 1, right panels. The Heliosheath field (A) of hourly averaged magnitude is found to be well represented by a Gaussian with a most probable value, Bmp, = 0.141 nT +/- 0.02 nT while the hourly averaged SW field (B) in 2003 is well represented by a log-normal with Bmp = 0.033 nT +/- 0.02 nT. A log normal distribution has been a common feature of the SW field measured since launch by both V1 and V2 [7].

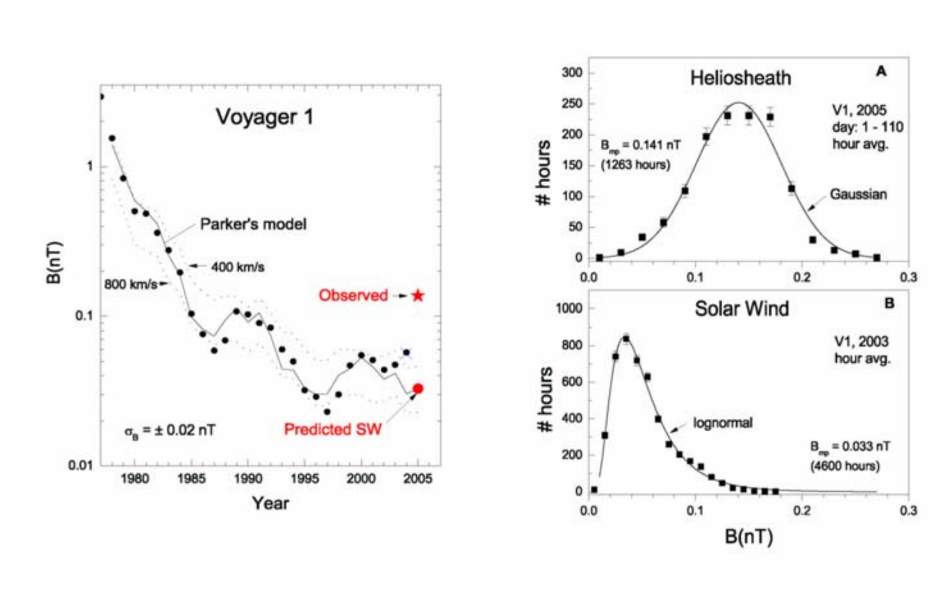

Figure 1. Left Panel – Comparison of V1 annual averaged HMF magnitude with estimated value.
Right Panel – Statistical distributions of observed HMF in Heliosheath (A) in 2005 and Solar Wind (B) in 2003.

The hourly averaged HMF observations during 2004-2005, 61 days before and 76 days after the TS crossing on day 351, 2004 are shown in Figure 2. The field vector is represented by the magnitude, B, and the direction by the heliographic longitude and latitude angles λ and δ. Readily evident in the longitude angle plot is that it displays a well defined bi-modal distribution, characteristically near 270º or 90º. These correspond to Parker's Archimedean spiral angles at this distance for fields with a sense pointing outward from or inward toward the Sun. Sudden changes in λ correspond to crossings of the well known and long studied sector boundaries between HMF regions of uniform but opposite polarity in the SW: a manifestation of the Heliospheric Current Sheet (HCS).

The large field values from day 352 onward are accompanied by large fluctuations of the magnitude while the longitude angle remains fixed near 270º. These field orientations and the sudden large increase in the average field magnitude indicate that the observed TS is, as expected, classified as a perpendicular shock.

There appear to be a few sector boundaries observed shortly after the TS crossing but for most of the time that V1 is in the Heliosheath, the polarity of the field remains the same. Since polarities of the fields across sector boundaries or the HCS are expected to be transmitted through the TS without any field polarity reversal, this long duration of a fixed polarity is somewhat of a puzzle at the present time. One suggested explanation is that the TS may be in motion relative to V1.

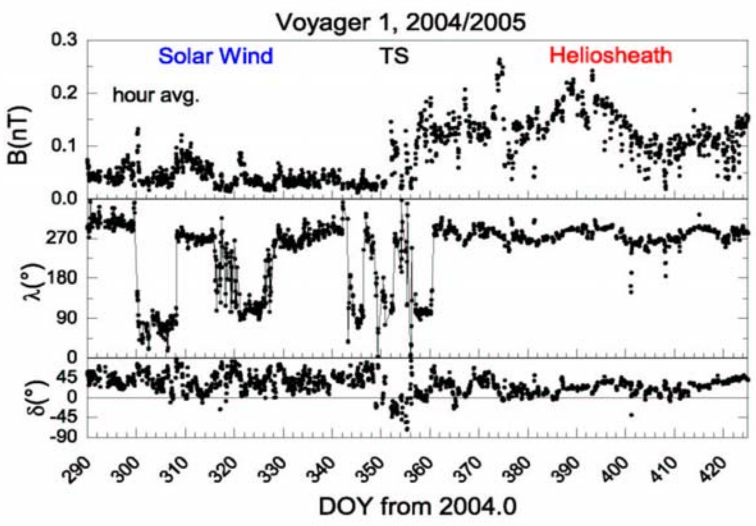

Figure 2. V1 observed hourly average HMF in heliographic coordinates. Crossing of TS occurs at day 351 2004. Sector boundaries, crossings of HCS, readily evident in 2004 but not yet seen in 2005.

Notice should be made that there are actually periodic data gaps because data transmitted from V1 are not continuously recorded by the antennas of JPL's Deep Space Network (DSN) stations due to scheduling conflicts with other space missions. Overall, the coverage is approximately 8-12 hours each day in 2004.

An expanded time scale of field magnitude and fluctuations across the TS crossing are shown in Figure 3. Field magnitude is represented by 48 second averaged values in the top panel and the JPL-DSN data gaps mentioned are readily evident. Also noted is the unfortunate reality that no data was recorded on day 351, the day most likely to be when the TS was actually crossed. The horizontal bars on either side of the TS represent the average values during the periods indicated and show a field jump by a factor of ~3.

Figure 3 includes, in the lower panel, a measure of the fluctuations of the HMF during each day. The metric used, SD, is the daily averaged Standard Deviation of the Pythagorean mean of the 3 field components over 16 minutes. Each of the 3 vector components is sampled every 1.92 seconds. This SD parameter is a measure of the higher frequency fluctuations, up to 0.25 Hz. The Pythagorean mean is used since it is an invariant measure of energy in the fluctuations, independent of coordinate system.

The sudden large and sustained increase in this SD parameter, coincident with the field magnitude increase, suggests that the Heliosheath is a different astrophysical plasma regime than observed in earlier studies of the HMF. Throughout the many years prior to the TS crossing, the typical value of this SD parameter was 0.012-0.014 nT except during passage of a propagating Merged Interaction Region [8]. We are presently studying all aspects of these HMF data and correlating them with simultaneous observations of energetic charged particle on V1.

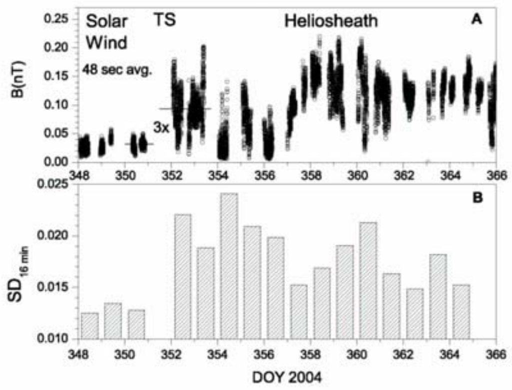

Figure 3. V1 observed 48 second averaged HMF magnitude (upper panel) near crossing of Termination Shock on day 351. Lower panel presents measurement of daily averaged higher frequency fluctuations up to 0.25 HZ over 16 minute intervals.

An earlier V1 report alleged the observations of twice crossing the TS in 2002-2003, while entering and then exiting from the Heliosheath [3]. This interpretation was rejected and referred to the several observed charged particle events as simply implying proximity to and possible HMF direct connection with the TS [9]. Simultaneous V1 HMF observations in 2002-2003 were shown to be completely inconsistent with this interpretation [1, 2]. The HMF observations reported herein have resolved this controversy with all involved now agreeing that the TS was first crossed in late 2004.

3. Conclusions

The Termination Shock was observed by the V1 Magnetic Field Experiment in late 2004 when V1 crossed or was crossed by the TS at 94.0 AU and 35ºN and entered the Heliosheath.

4. Acknowledgements

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