Heliospheric Magnetic Fields and Termination Shock Crossing: Voyager 1

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Abstract. After launch in 1977 and 27 years of continuously studying the Heliospheric Magnetic Field (HMF) from 1 to > 98 AU, the dual magnetometers on the Voyager 1 spacecraft detected a single crossing of the Termination Shock (TS) when at 35 degrees north heliographic latitude and 94.0 AU from the Sun. As the innermost boundary of the heliosphere’s interaction with the local interstellar medium, the TS was found to be a quasi-perpendicular MHD shock with a sudden jump in average field magnitude by a factor of $\approx 3$, from 0.04 nano-Tesla (nT) to 0.13 nT. This chapter discusses the observed characteristics of the HMF, both pre- and post-TS crossing. The latter data demonstrate the discovery of a new astrophysical plasma regime in the heliosheath, wherein fluctuations, some might consider turbulence, are primarily compressive, isotropic and have a Gaussian distribution of components and magnitude.

6.1 Introduction

Measurements of the interplanetary magnetic field with the dual magnetometer system (Behannon et al., 1977) on the twin USA Voyager 1 and 2 spacecraft (V1 and V2) began immediately after their launches in 1977. Nearly fulltime daily reception of the telemetry signals and scientific data by the JPL Deep Space Network (DSN) continued until the V1 Neptune encounter in 1989. Thereafter, scheduling conflicts of the DSN capability with other spacecraft missions led to a reduction in coverage of V1 and V2 due to overlapping plane-of-the-sky positions of the Voyagers with other NASA and joint ESA-NASA missions.

Fortunately, V1’s priority rank in the DSN list of mission responsibilities has provided fairly good data return each day up to the present moment. Typically data coverage is up to 50% each day although even that fraction is sub-divided so that continuous 12 hours of data is not routinely available.

This chapter presents a brief overview of the observed structure of the Heliospheric Magnetic Field (HMF) from 1 to 96 AU as observed by V1 from 1977 to the
crossing of the Termination Shock (TS) in late 2004 and subsequent entry into the heliosheath. The actual TS crossing was not observed due to lack of data coverage and most likely occurred partially or perhaps primarily as a result of the inward motion of the TS past V1 (Whang et al., 2004).

That the quasi-perpendicular TS was crossed is not in doubt, however, in spite of the data gap, due to the permanent increase in average field strength by a factor of 3±1, the ratio depending upon scale size chosen. In subsequent data obtained in 2005, two sector boundaries were observed in the subsonic heliosheath. Additionally, significantly different characteristics of the fluctuations of the subsonic heliosheath have been observed, identified and studied, when compared to the characteristics in the supersonic solar wind within the heliosphere, i.e., inside the TS.

6.2 Overall global structure of HMF from 1 to 96 AU

Figure 6.1 from Ness et al. (2005b) presents the annual averages of the magni-
6.2. Structure of HMF from 1 to 96 AU

Figure 6.2: Schematic representation of evolution of individual, identifiable corotating high speed solar wind streams changing through interactions to Corotating Merged Interaction Regions (CMIR).

tude of the HMF as measured by V1 since launch. A comparison with the expected field, based upon Parker’s theory (Parker, 1963) for an Archimedean field structure, is shown as a solid line. Deviations of the estimated field due to lower or higher average solar wind speeds used are shown as dashed lines and are bounded by 400 km/sec and 800 km/sec.

The HMF estimate is based upon actually measured HMF fields at 1 AU and V1 measured, or estimated, solar wind speeds. The V1 solar wind plasma probe failed shortly after Saturn encounter in 1979. Clearly evident in the V1 observed magnetic field data and model is the 11 year variation associated with the solar magnetic polarity and activity cycles.

From many different spacecraft missions, including V1 and V2, the overall structure of the heliosphere is known to change significantly from close to the Sun to far from it (Burlaga, 1995). Figure 6.1 illustrates the change from the near-solar region, < 10 AU, where individual high-speed solar wind streams can be readily identified and easily followed on successive solar rotations. They are known to be associated with specific long-lived coronal hole regions on the Sun.

As these streams propagate outward from the Sun, they interact and evolve by overtaking each other to create Merged Interaction Regions (MIR). Some MIRs are observed to co-rotate with the Sun, recurring every 27 – 29 days and have been denoted as CMIR’s (Burlaga et al., 1997). Depending upon their 3-dimensional structure, certain CMIRs at > 30 – 40 AU are more appropriately described as Global MIRs or GMIRs at great distances.
Another aspect of the heliosphere at greater distances, > 30 AU, is the increasingly important role played by pick-up ions in the solar wind plasma-magnetic field dynamics. These ions originate as a result of the interaction of the solar wind ions with neutral atoms entering the heliosphere from the Local Inter-Stellar Medium (LISM), into which the heliosphere is moving.

A very important feature of the average direction of the HMF is the polarity of the field, either pointing towards (−) or away (+) from the Sun along the spiral arms of the Parker field for extended periods of time, typically several to many days. The pattern of the + and − sectors is roughly repetitive with a period of 27 − 29 days, indicating that the origin of the changes in polarity is due to the rotation of the Sun.

This alternating uni-polar sector structure was discovered by Explorer 18 in 1963 (see review by Ness, 1987). It has been extensively studied since then by many missions including the USA Pioneer 11 and the ESA-NASA Ulysses spacecraft. P11’s trajectory crossed the Solar System from Jupiter encounter in 1975 to Saturn encounter in 1979. P11 thus moved well out of the ecliptic to moderate heliographic latitudes. Observations by P11 (Smith et al., 1986) detailed the 3-dimensional characteristics of the theoretically studied Heliospheric Current Sheet (Schulz, 1973) as the boundary of the uni-polar regions which had been named as sectors.

V1 has tracked and mapped this HCS in its long-lived trajectory (Ness and Burlaga, 2001). A sample of the nature of the 3-dimensional variations in the HCS position is illustrated in Figure 6.3. This shows the positions of V1 and V2 in a meridian plane projection relative to the superimposed location of the changing HCS during the indicated year. In 1997, V1 and V2 were located in oppositely directed uni-polar HMF regions associated with the opposite poles of the solar field and well removed at higher latitudes than the HCS excursions.

Each was overtaken subsequently in 1998 − 1999 by the HCS extending to higher heliographic latitudes during the solar cycle. Thus each spacecraft began to measure the alternate polarities of the HMF as the HCS crossed over them.

### 6.3 HMF and cosmic ray variations and pre-cursor TS particle events

Throughout the Voyager missions, especially at planetary encounters, variations in observed energetic particles over a wide range of energies and of different species and charge states have been correlated with fluctuations of the HMF. These studies have been conducted on short time and spatial scales.

The period 1990 − 1996 is shown in Figure 6.4 to illustrate the manner of how the stronger HMF during days 260 − 280, 1991 of a GMIR sweep out the cosmic ray particles with energies > 70 Mev/nucleon. Another aspect of these data is that as V1 continued to move away from the Sun, the intensity of the cosmic rays steadily increased as long as the HMF magnitude remained fairly steady.

Studies of the time correlated variations of the intensity of these cosmic rays with the magnitude of the HMF has revealed a straightforward mathematical relationship between the decrease and recovery of the cosmic ray intensity.
6.3. HMF and cosmic ray variations and pre-cursor TS particle events

Figure 6.3: Meridian plane projection of positions of V1 and V2 from 1997 to 2001 as solar cycle variations in tilt of Heliospheric Current Sheet (HCS) leads to overtaking of each spacecraft as the HCS co-rotates with the Sun.

A simple empirical relationship has been derived, shown in Figure 6.5, and is illustrated for data from 1991 comparing the observed and predicted CR intensity using the HMF magnitude. Results for different years have shown a nearly constant set of the two parameters: the rates of the decrease (D) and increases (C) of cosmic ray flux. Close inspection of Figure 6.5 shows the surprisingly good agreement between observations and predictions based upon the decreases and increases of the HMF.

When V1 was near 85 AU, Krimigis et al. (2003) reported that the Termination Shock had been crossed twice: once in mid-2002 and again in early 2003. The basis for this interpretation was two-fold. There was a period in which sudden increases of lower energy charged particles were observed. Also, the deduced solar wind speed, obtained from estimates of the Compton-Getting factor and observed anisotropies, changed from supersonic to subsonic and back to supersonic. This was interpreted to mean a temporary entry of V1 into the heliosheath.

However, the higher energy cosmic ray particles, i.e. $> 70$ MeV, showed no such correlated temporal behaviour. For the same 2002–2003 event, McDonald et al. (2003) interpreted these particle flux variations differently. They did not support the thesis that the TS had been crossed. Rather, their interpretation was that the observed particle events were pre-cursors to any TS crossing, and named the Krimigis et al. Heliosheath Immersion event as Termination Shock Precursor event #1, TSP-1. This interpretation meant that V1 was approaching the TS and that the observed particle enhancements had simply been due to parti-
Figure 6.4: Relationship of cosmic rays > 70 MeV/nucleon with HMF magnitude. Note sudden decrease in 1991 associated with strong HMF pulse of limited duration. Five day running averages are used for both parameters.

Burlaga et al. (2003) carefully studied the HMF during these purported TS crossing events and concluded that the HMF variations were not consistent with the two alleged TS crossings. The HMF averaged magnitude did not change as was to be expected. The HMF showed no increased average following the 1st alleged crossing but did increase at the 2nd alleged crossing. This is exactly the opposite of what is to be expected from MHD theory.

In a further study of the HMF and its fluctuations during the event, its short term fluctuations and the cosmic ray variations, Ness et al. (2005) showed that the 2nd alleged TS crossing event was most likely that associated with a travelling HMF shock preceeding a modest GMIR. Figure 6.6 summarizes the HMF and cosmic ray data for 2002-2003 and identifies the alleged TS crossings as TS-1? and TS-2? A measure of the field fluctuations is also shown (SD is defined in Figure 6.8).

Zhang (2005) analyzed the Krimigis et al. (2003) data and showed that there may have been an error in estimating the solar wind speeds in the Compton-Getting computations of Krimigis et al. (2003). This was due to the failure to correctly consider the effects of the instrument background and the correct orientation of the HMF. Subsequently there were additional observations of similar pre-cursor
6.4. V1 termination shock crossing

At the end of 2004, V1 crossed or was crossed by the Termination Shock. HMF hourly averaged magnitude observations from a ≈5 month period in 2004 – 2005
Figure 6.6: Observations of cosmic rays (> 70 MeV/nucleon) and HMF field magnitude and fluctuations (SD) in 2002 – 2003. Daily and running 5 day averages are shown for each parameter. (See Figure 6.8 for quantitative definition of SD parameter).
6.4. V1 termination shock crossing

Figure 6.7: Hourly averages of HMF during period in 2004−2005 when Termination Shock crossing occurred. Average HMF magnitude jumps by factor of 2−4 from 15 to 17 December, 2004. Data gap on 16 December precludes study of microstructure of shock interface.

are shown in Figure 6.7. The increase in the averaged HMF ranges between 2−4, depending upon the time scale chosen. This large jump is characteristic of a classic perpendicular or quasi-perpendicular MHD shock. These are seen near all the Solar System’s planets associated with the solar wind interactions with either the planetary magnetic fields or their atmospheres and/or ionospheres. These are also seen on occasions in the heliosphere, i.e. propagating shocks associated with solar disturbances such as coronal mass ejections.

Figure 6.8 presents a much finer time scale coverage of the TS crossing event during an 18 day interval in 2004 using 48 second averaged magnitudes and standard deviations over 16 minute periods of the Pythagorean mean of the 1.92 second sampled vector HMF fluctuations. This figure also illustrates the discontinuous coverage of the V1 telemetry signal by the JPL-DSN.

The TS crossing is identified by the large increase, ≈3, in the averaged HMF magnitude occurring between data from DOY 350 and 352−353. 16 December (plus or minus small fractions of adjacent days) is chosen as the time of the TS crossing. There is also a significant change in the daily average of the SD parameter, defined quantitatively in the figure, indicating a substantial increase in the total energy in fluctuations of the HMF (up to 0.26 Hz, the Nyquist frequency for the detailed 1.92 second vector sampled data).

Burlaga et al. (2005) and Burlaga et al. (2006) studied the characteristics of the HMF fluctuations in the heliosheath and found a notable distinguishing difference in their statistical properties. Figure 6.9 shows that the hourly averages of the
HMF magnitude have a Gaussian distribution in the subsonic heliosheath. This is in sharp contrast to the supersonic solar wind where the HMF has consistently shown a log-normal distribution, illustrated by data from 2003 in Figure 6.9.

Continued HMF observations in 2005 are summarized in Figure 6.10 presenting the daily averages of the vector HMF in the magnitude, heliographic latitude and longitude format. An important feature of this data is the extremely long duration of the 1st uni-polar sector to be observed in the heliosheath. The sector polarity remained constant for ≈125 days. It has been suggested that the obvious reason for this is because the heliosheath solar wind speed is so much reduced after passage through the TS (Jokipii, 2005).

Figure 6.10 also includes a plot of the 6 hour averaged flux of cosmic ray ions with energies > 0.5 MeV/nucleon. There are several short term temporal peaks in the flux prior to and at the TS crossing. These pulses are followed by a slow and very steady increase beyond. Especially interesting is the fact that the level of flux fluctuations decreases significantly after the TS crossing. This suggests that V1

Figure 6.8: Forty eight seconds averaged HMF magnitude and associated daily averaged standard deviation of Pythagorean mean over 16 minutes of detailed 1.92 second vector sampled HMF during TS Crossing. Data gaps readily evident.
has entered a plasma-field-particle region beyond the TS in which the acceleration of such CR particles is continuously and uniformly occurring.

An interesting single pulse of a very strong HMF is identified in Figure 6.10 at point A in early 2005, shortly after the TS crossing. An expanded time scale of 48 second averaged vector data surrounding this pulse is shown in Figure 6.11 in heliographic coordinates. A new result in the observations of the HMF is well-illustrated here. The direction of the HMF remains constant throughout the pulse, from DOY 8.8 to DOY 9.2. Beyond that interval, the HMF becomes sufficiently weak that the intrinsic spacecraft and instrument noise, ±0.02 nT, and intrinsic ambient field fluctuations preclude accurate and precise determination of HMF directions.

In order to examine more comprehensively the more detailed characteristics of the HMF fluctuations in the heliosheath, 48 second averaged data from DOY 50 – 70 2005 was examined for its statistical properties. The results for the magni-
Figure 6.10: Interval of HMF vector observations in 2004–2005, including TS crossing in heliographic coordinates in format of magnitude-latitude-longitude. First heliosheath sector ever observed is noted by its boundaries. Plot of simultaneous energetic particle flux shows sharp change in intensity and level as well as character of fluctuations at TS crossing.

titude and individual three orthogonal R, T and N components are shown in Figure 6.12. The distributions of these four parameters again show well defined Gaussian characteristics with nearly identical widths for the component fluctuations. Thus, Figures 6.11 and 6.12 lead to the surprising and unpredicted conclusion that he-
Certain micro-structural features of the heliosheath field have been identified which are reminiscent of characteristics of the supersonic solar wind throughout the heliosphere. The 1st of these is illustrated with 48 second averages in Figure 6.13 by a relatively short-lived dip in the field magnitude, while the direction is essentially invariant. This feature is similar to a microstructure which had been identified and elaborated upon in earlier studies of MHD discontinuities often observed in the solar wind plasma near 1 AU. They were referred to as “magnetic holes” (Turner et al., 1977) and studies have shown that they are observed to occur at a rate of ≈1.5 each day.
The long time duration of this “hole,” $\approx 150$ minutes, by comparison with those in the supersonic solar wind, a few minutes, is consistent with a contribution from time dilation caused by the sub-sonic solar wind speed in the heliosheath. But it is probably due to the physical fact that the scale size of such micro-structures is determined more by the gyro-radius of the pick-up protons in the heliosheath, $\approx 12000$ km for an HMF field of 0.10 nT.

A fine time scale view of a textbook example of a sinusoidal fluctuation of the HMF magnitude, while the direction remains unchanged, is shown in Figure 6.14, which presents 48 second averages during a fortunately continuous data interval $> 12$ hours. The constancy of the vector direction while the magnitude varies by a factor of $\approx 5$ is impressive support for the initial conclusion from studies of the
6.5. HMF micro-structure

Figure 6.13: Magnetic hole observed in 48 second averaged vector data with large variation in magnitude, but essentially no change in direction, except immediately adjacent to HMF minimum.

V1 HMF statistical data that the fluctuations of the HMF in the heliosheath are mainly compressive.

Another micro-structural feature in the heliosheath and an important one are sector boundaries. The two observed by V1, SBa and SBb, are both identified as such in Figure 6.10. The trailing boundary, SBb, in Figure 6.15 is an extremely thin one and fortuitous data coverage permits identification and study of its details. The boundary SBb appears to be a paradigm for a classical D-Sheet, across which there may be merging or re-connection. The leading sector boundary, SBa, is rather more extended and complex, which merits further study. It is compromised by the several data gaps which exist in the changing polarity of the field from one uni-polar sector to the other.

Initial studies of the Power Spectral Density (PSD) of the HMF magnitude and individual component fluctuations before and after the TS crossing have shown a characteristic decrease with increasing frequency. The PSD is found to decrease at nearly a uniform $-5/3$ exponent for frequencies greater than the proton cyclotron frequency, which ranges between 0.003 to 0.0025 HZ for the intervals studied.
There is no evident peak or even increased band of energy near these frequencies either before or after the TS crossing. But there is a slight difference in the amount of energy at lower frequencies. A decreased energy by up to a factor of 10 pre-TS crossing is noted when compared to intervals post TS crossing. This means that HMF fluctuations and turbulence increase in the heliosheath at the lowest frequencies.

6.6 Summary

The Termination Shock was observed in late 2004 when V1 was at 94 AU and 35 degrees north heliographic latitude. The TS is inferred to have the characteristics of a quasi-perpendicular MHD shock with a sudden and large jump in field magnitude by a factor of \( \approx 3 \) and an insignificant change in direction. This is as to be expected for the location of V1 relative to the stagnation point of flow of the Local Interstellar Medium as the heliosphere interacts with it.

Fluctuations of the sub-sonic HMF are found to be compressible and isotropic and well described as Gaussian. Structural features such sector boundaries, micro-
6.6. Summary

Figure 6.15: 48 second averaged vector data for trailing sector boundary, SBb. Appears to be paradigm classic D-sheet structure across which merging and reconnection may be occurring as HMF on either side change polarity.

Structural D-sheets and magnetic holes are observed which are reminiscent of those seen in the supersonic solar wind inside the TS. They have quantitative physical properties appropriate for a pickup ion dominated, weakly magnetized solar originating plasma. The heliosheath is thus identified to have a new set of parameters and, no doubt, processes. It is therefore an example of an astrophysical plasma regime not previously studied in-situ and which has also not been studied theoretically to any degree.

It is to be noted, as shown in Figure 6.16, that the cosmic ray flux and HMF magnitude in the heliosheath are no longer correlated in the same way as in the heliosphere. Although the HMF magnitude increases and decreases substantially, there are no, as yet, readily identifiable corresponding changes in the flux of particles with $>70$ MeV/nucleon.

Moreover, their flux continues to steadily increase deeper into the heliosheath suggesting that the acceleration source(s) of these particles is more uniformly distributed thought the heliosheath and is also well beyond V1, which in mid-2005 was at $\approx96.5$ AU. These data and this observation may also lead to the rejection of the thesis that the TS is a global source for anomalous cosmic rays. Additional future observations and studies are needed to fully understand the origin of the heliosheath’s unique characteristics.
Note added in proof

Since this manuscript was submitted, additional reports by Burlaga et al. (2006a, b, c, d) on new studies of the magnetic field data have been published or are in press.

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Bibliography


