Day the Solar Wind Almost Disappeared: Magnetic Field Fluctuations and Wave Refraction

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Abstract. On May 11, 1999 the Advanced Composition Explorer (ACE) spacecraft observed a rarefied parcel of solar wind that has come to be known as "The Day the Solar Wind Disappeared." Little if any change is seen in the large-scale interplanetary magnetic field during this time, but the magnetic field fluctuations are depressed and significantly more transverse to the mean field. The high Alfvén speed resulting from the constant field intensity and low ion density enhances wave refraction, and we examine this as a possible explanation for the fluctuation properties.

INTRODUCTION

Midday on May 10, 1999 (day 130), the ACE spacecraft observed the beginning of a period of depleted solar wind ion density that continued until midday on May 12 with a density minimum that lasted ~6 hours at the end of May 11. During this extended 48-hour period the density dropped from a fairly typical value of ~5 cm\(^{-3}\) to ~0.1 cm\(^{-3}\). We hereinafter refer to this entire 48-hour period as the "rarefaction interval" without intending to attribute any particular source explanation [3, 5, 8]. During this interval the Alfvén speed was exceptionally high, while the ion temperature and wind speeds were low. The exceptional nature of this parcel of solar wind provides an opportunity to examine in some detail two distinct physical processes that operate in the solar wind. One involves macrophysics (refraction) and the other involves microphysics (dissipation).

Although our presentation at the meeting discussed our analysis of magnetic dissipation and demonstrated that the onset of the dissipation range for interplanetary magnetic fluctuations occurs at the ion inertial scale \(L_i \sim V_A/\Omega_{ic}\), where \(V_A = B/\sqrt{4\pi N_p m_p}\) is the Alfvén speed, \(B\) is the interplanetary magnetic field (IMF) intensity, \(N_p\) is the proton density, \(m_p\) is the proton mass, and \(\Omega_{ic} = eB/m_pc\) is the proton cyclotron frequency, space prevents us from discussing this result here [6]. We therefore limit this discussion to refraction effects only.

ANALYSIS

Figure 1 shows an abreviated overview of the plasma and field measurements during May 10–12, 1999 (days 130–132). The IMF magnitude \(B\) is shown. Not shown is the field latitude \(\delta\), and longitude \(\lambda\) which are equally unremarkable. The IMF magnitude and direction on day 131 are more steady than on the days before and after, but not unusually so. There is no depletion of the field magnitude during the time in question.

The root-mean-square fluctuation level of the IMF, \(B_{\text{RMS}}\), computed from 3 vectors s\(^{-1}\) data using a 16-s mean is shown. We draw attention to the fact that \(B_{\text{RMS}}\) is unusually small (0.1-0.2 nT) during the rarefaction interval. Before and after this interval, \(B_{\text{RMS}}\) is close to 1 nT. During the rarefaction interval, \(B_{\text{RMS}}\) undergoes a factor of 5-10 reduction compared to the neighboring plasma.

The proton density \(N_p\) is shown to decrease through ~2 orders of magnitude with a minimum at ~1800 UT on day 131. The wind speed \(V_{SW}\) (not shown) is seen to decrease monotonically at the same time. The proton temperature \(T_p\) (not shown) is unusually low for typical solar wind observations during the last 6 hours of day 131, but Richardson et al. [5] demonstrate that \(T_p\) and \(V_{SW}\) display the nominally expected correlation for solar wind observations.

The Alfvén speed \(V_A\) is shown. The low \(N_p\), in combination with the nearly constant \(B\), leads to an elevated \(V_A\) during this time. The simultaneously decreasing \(V_{SW}\) leads to nearly sub-Alfvénic wind flow during the last 6 hours of day 131.

The apparent depletion of magnetic fluctuations on
FIGURE 1. Days 130 through 132, 1999, when the solar wind density is observed to drop to 0.1 p cm\(^{-3}\). IMF intensity \(B\) (nanoTeslas) as well as RMS level of the IMF fluctuations \(B_{\text{RMS}}\) (nanoTeslas) are provided by the MAG instrument. The proton density \(N_p\) (cm\(^{-3}\)) is provided by the SWEPAM instrument. The Alfvén speed \(V_A\) (km s\(^{-1}\)) is computed from data supplied by both instruments. The anisotropy of the IMF fluctuation spectra \(E_B^c / E_b^p\) in the inertial range is shown along with the anisotropy of the wave vector (expressed in terms of percent slab component also in the inertial range).

Day 131 begs an explanation. We draw our inspiration from solar physics. MHD waves propagate through the magnetically structured corona in a predictable manner. Specifically, fast-mode waves are refracted away from regions of high Alfvén speed [7]. Conversely, fast-mode waves are focused toward regions of low Alfvén speed. If this mechanism is to explain the observations here, then several predictions must be satisfied: (1) Evidence must be provided that the fluctuations are indeed waves, (2) The fluctuations must be less compressive within the high-\(V_A\) region from which the compressive fast-mode waves are expelled, and (3) The fluctuation energy outside the refraction region should (hopefully) demonstrate an excess wave energy due to the build up of waves in the low-\(V_A\) region.

Figure 1 shows the results of two additional analyses. The computed anisotropy of the magnetic fluctuation energy for components parallel \(E_B^p\) and perpendicular \(E_B^c\) to the mean field is shown for frequencies \(2 \times 10^{-3}\) to \((1 - 2) \times 10^{-1}\) Hz representing the high frequency end of the inertial range. Horizontal bars represent the data interval used in the analysis while vertical bars give the variance of the computed ratio. The key feature of the anisotropy analysis is that during the period of low solar wind density the IMF fluctuations in the inertial range are distinctly more transverse to the mean field than elsewhere. Belcher and Davis [2] state that the typical IMF fluctuations in the inertial range possess an anisotropy \(E_B^c / E_b^p\) that is 9:1 on average. We find that on days 130-133 the anisotropy \(E_B^c / E_b^p\) is significantly smaller than this before and after the interval in question, but more than twice this value during the period of lowest solar wind density. On day 131 the inertial range fluctuations are exceptionally transverse and demonstrate high anisotropy (\(E_B^c / E_b^p > 20:1\) and briefly exceeding 28:1). Transverse fluctuations are frequently cited as an indication for the presence of noncompressive Alfvén waves, implying that the usual compressive component is absent from the high-\(V_A\) region but present in excess of typical levels immediately outside the high-\(V_A\) region.

Bieber et al. [1] and Leamon et al. [4] demonstrate that on average only 20% of the fluctuation energy at 1 AU is associated with wave vectors that are parallel to the mean field (one-dimensional (1-D) or slab geometry...
generally regarded as parallel-propagating waves). The remaining 80% of the fluctuation energy is associated with wave vectors that are normal to the mean field (2-D turbulence). We employ this same analysis in the bottom panel in Figure 1. It is interesting to note that the percent slab geometry in the inertial range early in the rarefaction interval (when $V_A < 50 \text{km s}^{-1}$) is consistently higher than previously seen by Bieber et al. and Leamon et al. However, when ACE lies deep inside the rarefaction interval, the slab fraction is consistent with the earlier analyses and less than the values immediately outside the high-$V_A$ region. There appears to be an enhancement of the slab wave component early and late in the 3-day period when $V_A$ is more nearly typical of solar wind values at 1 AU, but a depletion of the slab component deep within the rarefaction interval where $V_A$ is high. This is consistent with the refraction argument.

From the apparent fact that our 3-day interval is more wavelike than typical IMF observations and less compressive while at the same time it demonstrates a reduced overall fluctuation level, we argue that wave refraction is (or has been) effective at attenuating the wave component within the region of high $V_A$ leading to reduced RMS levels there. An apparent build-up of compressive wave energy is implied in the surrounding region.

**STATISTICS**

Figure 2 shows the distribution of $B_{\text{RMS}}$ levels for ACE/MAG measurements from day 1, 1998, through day 169, 2000. The distribution peaks at $\sim 0.2 \text{nT}$ but exhibits a long tail extending to $1.5 \text{nT}$ and beyond. In order to demonstrate the relative rarity of RMS levels $< 0.2 \text{nT}$, we integrate the distribution function in the lower panel. The computed value for $\int_0^{0.1} Pd(B_{\text{RMS}}) = 0.02$ while $\int_0^{0.2} Pd(B_{\text{RMS}}) = 0.24$, $\int_0^{0.5} Pd(B_{\text{RMS}}) = 0.74$ and $\int_0^{1.0} Pd(B_{\text{RMS}}) = 0.93$. This indicates that while $B_{\text{RMS}}$ levels which range from 0.5 to 1.0 both before and after day 131 are larger than the median value, the levels during day 131 tend to the lower limits of the distribution.

**CONCLUSIONS**

We have demonstrated that an extended region of reduced solar wind density resulting in an elevated local Alfvén speed displays reduced magnetic fluctuation levels consistent with wave refraction. A combination of data analysis methods including spectral analysis techniques [6] supports this interpretation.

The interval studied here is not the sole event that demonstrates the behavior described here. Figure 3 shows a 6-day interval 14 days prior to the period studied here that is centered on a 24-hour period when $B$ was constant, $N_P$ was low, $V_A$ was high, and $B_{\text{RMS}}$ was reduced. Other similar intervals can be found in the ACE dataset. Supression of the IMF fluctuation level is evident at the same time that the Alfvén speed is elevated. Preliminary analysis of this interval shows properties similar to that found for the interval studied here and suggests that refraction may explain this interval as well. Moreover, refraction may be one of several competing processes throughout the solar wind that determines the local level of the wave energy and the degree of compressive fluctuations.

Wave refraction is ray optics and requires that the refracting (high-$V_A$) region be large in comparison with the wavelength of the wave. Smith et al. [6] demonstrated that such intervals exist in the solar wind in addition to the one shown here and that large, high-$V_A$ regions have reduced $B_{\text{RMS}}$ on average. However, resolution of the refraction signatures is not always possible owing to competing dynamics including the presence of local sources of turbulence within the wind. With this in mind, one must wonder if refraction in the early stages of ICME formation is not at least in part responsible for the low fluctuation levels generally seen in these high-$V_A$ structures.
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