Magnetic Fluctuation Properties of Interplanetary Magnetic Clouds

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Abstract

Analysis of a magnetic cloud recently observed by the WIND spacecraft demonstrated that the magnetic fluctuations were more nearly transverse to the mean magnetic field than is commonly seen in the solar wind. It was also apparent that the wave vectors were oriented at large angles to the mean field to a degree that exceeded normal solar wind conditions. This orientation is particularly ineffective at scattering energetic charged particles. We examine a number of magnetic clouds observed by the ACE spacecraft near 1 AU with the intention of confirming or refuting the general validity of the above results.

1 Introduction:

A wide range of interplanetary magnetic field (IMF) conditions can contribute to the scattering and propagation of energetic charged particles. These conditions include the familiar and most fundamental considerations, such as the level of magnetic turbulence as it contributes to resonant scattering, the variability of B as it contributes to mirroring, and the geometry or orientation of the wave vectors as this can remove wave energy from participating in resonant scattering. Less well understood processes such as a range of magnetodynamic processes can also affect the scattering of energetic particles, particularly at large pitch angles. As we move to develop more accurate theories for particle scattering, a better understanding of the IMF turbulence and how it varies is warranted.

Belcher & Davis (1971) performed a classic analysis of the interplanetary magnetic field (IMF) and showed that IMF fluctuations over spacecraft-frame timescales of a minute to several hours (spatial scales from $\sim 10^4$ to $\sim 10^7$ km) were strongly correlated to fluctuations in the bulk proton velocity. In addition, fluctuations were predominantly transverse to the mean magnetic field. Both observations were particularly strong in "high-velocity solar wind streams and on their trailing edges." We now know these conditions to be typical of high-latitude, high wind speed conditions as observed by Ulysses (Smith et al. 1995) which can also be observed at low heliographic latitudes. These two observations were central to the interpretation of IMF fluctuations as outward-propagating, transverse Alfvén waves. These conclusions have subsequently been used to develop theories for energetic charged particle propagation (Jokipii 1966; Fisk et al. 1974) which have been tested (Palmer 1982; Bieber et al. 1994) to reveal a wide range of problems and unanswered questions concerning the nature of IMF turbulence that are central to gaining a better predictive capability when computing particle pitch-angle scattering and mean free paths. In spite of these continuing questions, it remains widely acknowledged that transverse fluctuations play the key role in resonant scattering of energetic particles.

Leamon, Smith & Ness (1998) examined a magnetic cloud observed by the WIND spacecraft in January 1997 and reported that a high degree of IMF fluctuation anisotropy was present within the cloud which greatly exceeded the nominal conclusions of Belcher & Davis. In spite of the highly transverse nature of IMF fluctuations, generally, fluctuations within the cloud were more highly transverse than for open field lines with the ratio of perpendicular to parallel power $P_\perp/P_\parallel$ as much as a factor of 10. Here we examine several magnetic clouds observed by the ACE spacecraft (we show only one) to see whether this result is supported by other cloud events.

2 Analysis:

Figure 1 shows interplanetary plasma conditions before, during and after a magnetic cloud as observed at L1 by the ACE spacecraft (McComas et al. 1999; Smith et al. 1999). The cloud interval begins at ~18:00 UT on day 175 and probably lasts until the beginning of day 177. The true end of the cloud interval is difficult to determine as there is a shock at ~15:50 UT on day 176 that has propagated into the trailing end of the cloud, thereby disturbing the IMF rotation, heating the background protons and increasing the level of IMF fluctuation energy relative to the undisturbed cloud interval. Within the undisturbed region of the cloud the magnetic turbulence level and the proton $\beta = 8\pi n_p k_B T_p B^{-2}$ are characteristically low. The former suggests that energetic charged particles should propagate through the cloud with relatively long mean free paths given the low level of magnetic turbulence available for scattering. This cloud is buried within an interplanetary coronal mass ejection (ICME) that lasts from ~3:00 UT on day 176 and ending ~20:00 UT on day 177. There is another ICME following this for the next 2 days, providing the driver for the shock seen on day 176, but these are thought to be two distinct ICME events.

We have repeated the analysis technique of Belcher & Davis (1971) wherein an interval of IMF data is rotated to mean-field coordinates and the power spectral matrix is computed. Belcher & Davis concluded that a $5:4:1$ ratio of power was commonly observed and for the purposes of this analysis we can equate this to a $9:1$ ratio of power for fluctuations perpendicular and parallel to the mean field. This is what is generally meant by the transverse fluctuations of the IMF. We repeat this analysis in two frequency regimes: from 5×10^{-3} to 7×10^{-2} Hz (within the inertial range) and from 3×10^{-1} to 7×10^{-1} Hz (within the dissipation range). The results are shown in the bottom panel of Figure 1 where circles denote inertial range fluctuation anisotropies and squares represent the same for the dissipation range. We use 3-hour intervals, pre-whiten the dataset using a first-order difference before computing the Blackman-Tukey autocorrelation function. From this the spectrum is computed and post-darkened to remove the effects of the pre-whitening filter. Lastly, the spectra of the individual components are fitted to a power law form omitting a band of frequencies around the spin period of the spacecraft. The ratio of magnetic power over the fit intervals is then computed.

What is evident in Figure 1 is that when the proton β drops the IMF fluctuations become increasingly transverse to the mean field reaching sustained ratios of $20:1$ to $30:1$ within the low-β region of the cloud. This is true at both inertial range (circles) and dissipation range (squares) frequencies. Although Leamon, Smith & Ness (1998) reported that the dissipation range within the January 1997 cloud observed by WIND was less anisotropic than the inertial range for the same interval, this result is only marginal within the cloud shown here.

We have examined several other magnetic clouds observed by the ACE spacecraft and repeatedly we find abnormally high degrees of anisotropy for the IMF fluctuations. This high anisotropy is associated most reliably with the low proton β of the clouds and not the larger ICME structure as denoted by the counterstreaming electrons. Zank & Matthaeus (1992) have argued that this should be a regular feature of low-β plasmas. In apparent support of this claim, we note that there is a strong degree of correlation between the proton β and the anisotropy: following the onset of the cloud the β ramps down to ~ 0.03 over a period of 9 hours. At the same time the anistropy of the IMF fluctuations ramps up from values that are fairly typical of the Belcher & Davis conclusions to peak anisotropies when the β is at its lowest values. The passage of the shock heats the background plasma only minimally on this scale with little or no change to the anisotropy of the magnetic fluctuations. The anisotropy is consistently lower following passage of the cloud, but shows a suggestive increase over the ~ 3 hour interval starting ~15:00 UT on day 177 when the β is smaller than the surrounding times. Finally, the β increases to ~ 1 by the end of the time interval plotted and the IMF anisotropy returns to values < 10.

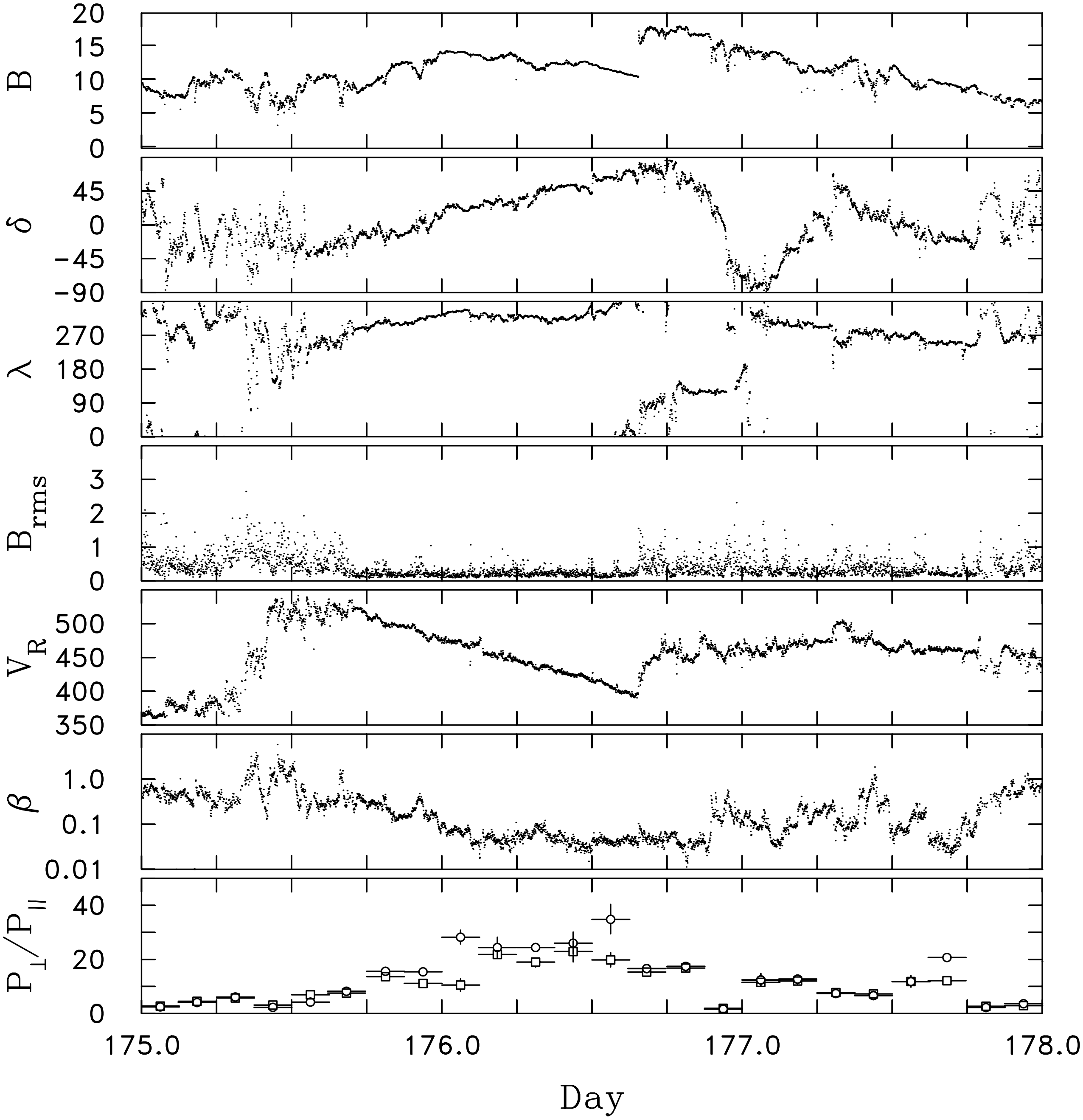

Figure 1: Interplanetary conditions before, during and after the magnetic cloud observed by ACE on days 175 & 176 of 1998. Region of high B (panel 1, counting from the top) associated with a large-scale rotation of the IMF (panels 2 and 3) and low-β (panel 6) conditions mark the cloud interval. The cloud is characterized by lower than normal IMF variability, as determined from the RMS variation computed on 16-s means (panel 4). This cloud displays a decreasing wind speed (panel 5) as the cloud passes, suggesting continued radial expansion of the disturbance, and clearly demonstrates that the cloud is moving faster than the plasma it is moving against. A shock is propagating into the back of the cloud and is evident at ~15:50 UT on day 176. IMF anisotropy is shown in panel 7.

3 Discussion:

Although we have shown only one magnetic cloud result, we have verified that the conclusion shown here is repeatable by other similar events. Low-β periods in the interplanetary medium, most notably those commonly associated with magnetic clouds, show a remarkably high degree of IMF fluctuation anisotropy with fluctuations highly transverse to the mean field direction. While this would nominally assist in the resonant scattering of energetic particles, it is also the case that the fluctuation energy is reduced within these structures (as is evident in panel 4 of the figure), which significantly depletes the energy needed to perform the scattering. On balance, mean free paths of energetic particles within magnetic clouds should be longer than for open field lines with higher β.

There is another consideration for particle scattering that we are presently unable to address for these events: IMF fluctuation geometry. There exists a prescription (Bieber, Wanner & Matthaeus 1996) for assessing the relative energies of the slab geometry component of the fully 3-D fluctuations spectrum (wave vectors aligned with the mean magnetic field) and the 2-D component (with wave vectors at right angles to the mean field). This method employs the $5:4$ ratio of transverse components in the Belcher & Davis mean-field coordinate system. However, a restriction of this analyis is that the ratio of the energy for these two components must be > 1 and $< |q|$ where q is the spectral index of the magnetic power spectrum. Short intervals, such as the 3-hour periods used here, frequently violate this assumption. We are examining possible solutions and alternate analyses that we hope will permit us to address the turbulent geometry within the cloud. If these clouds support the analysis of Leamon, Smith & Ness (1998) and earlier analysis of non-cloud events by Bieber, Wanner & Matthaeus (1996), we would expect to find that the dominant fraction of the magnetic energy is associated with wave vectors at right angles to the mean field. Since these wave vectors are inefficient scatterers of energetic particles, we would anticipate that the mean free paths for energetic particles within these clouds would be larger than slab quasilinear theory (Jokipii 1996) would predict, and probably larger than typical open field line geometries at L1.

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