The role of CMEs and interplanetary shocks in IMF winding angle statistics

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Abstract. We examine the possible role of CMEs and interplanetary shocks in past analyses of the large-scale winding of the IMF by extracting CME and shock observations from the ISEE-3 dataset and analyzing periods of the disturbed and undisturbed solar wind separately. We use the full ISEE-3 dataset representing the entire L_1 mission (1978 – 1982). We conclude that CMEs, the shocks upstream of CMEs and other interplanetary shocks are responsible for the apparent overwinding of the IMF spiral relative to the Parker prediction. The IMF winding angle asymmetry appears to be preserved after the removal of the interplanetary disturbances.

Introduction

Past studies of the spiral winding of the interplanetary magnetic field (IMF) using the omnitape dataset as well as Pioneer-Venus Orbiter and Voyager observations have revealed an overwinding relative to the *Parker* [1958] prediction [*Smith and Bieber*, 1991; 1992]. On average the difference between the observed and predicted winding angle as computed from the omnitape dataset is $1.5° \pm 0.5°$. Neither uncertainties in the source surface height nor reasonable variation of the solar rotation rate at that surface can account for the observations.

An asymmetry between the winding angle of the northern and southern hemispheres has also been observed [*Bieber*, 1988; *Smith and Bieber*, 1992; 1993]. The IMF north of the heliospheric current sheet is generally more tightly wound than the field south of the current sheet. Analysis of the omnitape dataset reveals this difference to be $2.5° \pm 0.8°$ at Earth's orbit for the years 1965 through 1987. Analysis of the Pioneer-Venus Orbiter dataset reveals similar behavior at 0.7 AU. Both the overwinding and the asymmetry are seen to persist over many years and are statistically significant. Both results have implications for cosmic ray propagation in the heliosphere.

There is the suggestion in these past analyses that the apparent overwinding is greatest during times of solar magnetic reversal and heightened solar activity when interplanetary disturbances such as coronal mass ejections (CMEs) and interplanetary shocks are most frequent. By examining the ISEE-3 dataset from the years 1978 through 1982, we include the years of solar maximum surrounding the 1980 magnetic solar reversal when the apparent overwinding was greatest. No enhancement in the asymmetry is associated with times of peak solar activity. In fact, the years of greatest asymmetry appear to occur during solar minimum. By simple association the possibility that these disturbances may account for the overwinding of the IMF cannot be discounted a priori although there is little evidence to suggest that heightened solar activity yields increased spiral asymmetry.

The presence of bidirectionally streaming suprathermal electrons has been used as an indicator of closed magnetic structures interpreted as CMEs [e.g., *Gosling et al.*, 1987]. The characteristics of the counterstreaming beams suggest that most CMEs remain magnetically attached to the Sun at Earth's orbit, rather than disconnecting to form closed plasmoids [*Phillips et al.*, 1992]. Many CMEs have flux rope magnetic structures suggesting partial disconnection from the corona [e.g., *Gosling*, 1990]. Regardless of their specific field topologies, the closed fields associated with CMEs constitute structures outside the Parker description of the IMF. Deflection of the IMF both upstream and downstream of the structures must also deviate from the Parker description in so far as field line draping is involved [e.g., *McComas et al.*, 1989].

Shocks form in the solar wind due to a variety of sources including the propagation of CMEs and may be either forward or reverse. Compression of the plasma across the shock causes the downstream field to be more nearly perpendicular to the shock normal and may result in an apparent overwinding in the IMF statistics.

The *Parker* [1958] theory is a steady-state prediction that avoids discussion of transient structures. Interplanetary dynamical processes such as overtaking high speed streams, CME propagation into the undisturbed medium, and shock processing of the interplanetary plasma are outside this description and contribute to the statistics in a manner that a steady-state theory cannot describe. It is possible that the resulting alterations in the IMF are asymmetrical about the predicted field orientations or that the sampling of these regions is not evenly distributed and that this possibility may account for the overwinding and asymmetry observations.

Weber and Davis [1967, 1970] considered the effects of angular momentum in the winding of the IMF and concluded that the azimuthal wind speed which diminishes with heliocentric distance would allow the winding of the IMF to approach the Parker prediction by ~ 1 AU. This effect has been considered and dismissed as a possible explanation for both the overwinding and the

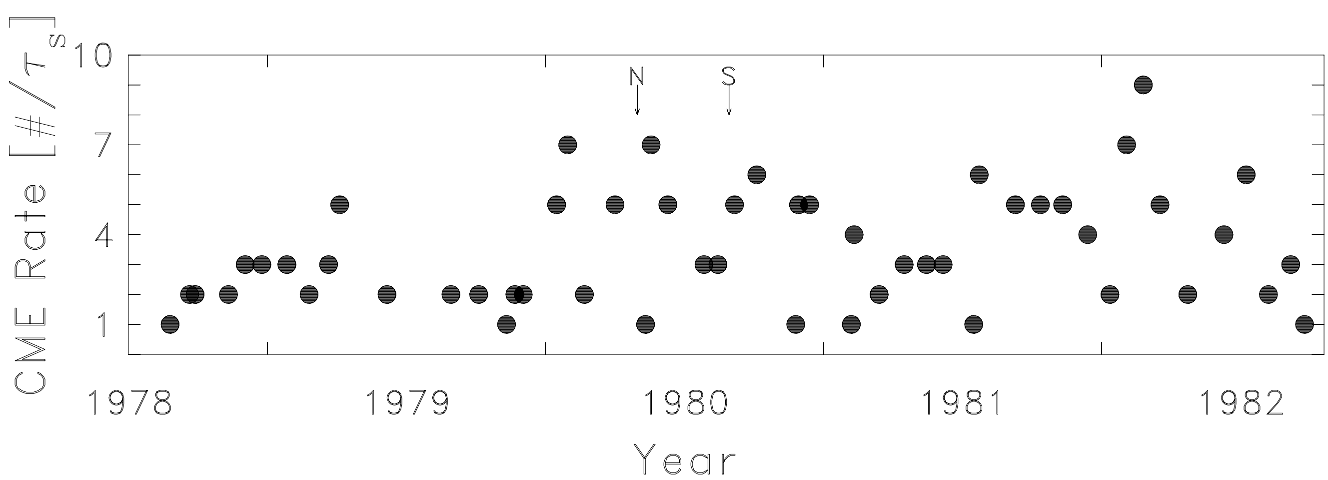

Figure 1. Number of CMEs per solar rotation as recorded by the ISEE-3 spacecraft. Times of north (N) and south (S) solar magnetic pole reversals are noted at top of panel.

asymmetry of the IMF.

ISEE-3 at L_1

ISEE-3 spent approximately 51 months (from August 1978 through October 1982) upstream of the Earth at the L_1 libration point. This places the spacecraft ahead of the foreshock in solar wind plasma that is largely undisturbed by the presence of the Earth. An exhaustive catalog of CME and shock times for this dataset has already been compiled [e.g., *Phillips et al.*, 1993].

That catalog lists 179 CME observations, 82 forward shocks upstream of or within the CMEs, 85 shocks unassociated with any obvious CME event (we will call these "non-CME" shocks), and 4 reverse shocks. A significant fraction of the non-CME forward shocks are thought to be driven by corotating interaction regions (CIRs), while the rest are probably driven by CMEs that were not directly sampled by ISEE-3. Most CIRs do not have observable reverse shocks at 1 AU. The few reverse shocks actually identified were weak. For these reasons, we have disregarded reverse shocks in this analysis.

Figure 1 shows the number of CMEs recorded within the catalog per solar rotation. CME activity is particularly high during 1980 (the year of magnetic solar reversal) and the two years following which coincides with the same general time when the overwinding of the IMF appears greatest.

During the $3\frac{1}{2}$ years in question, CMEs alone represent 8% of the data. CMEs together with their upstream shocks represent 10%. Non-CME shocks represent another 12% of the data if 48 hours is added following each shock to account for the processed plasma.

By examining the 24 hour period before and after each disturbance, we can assign a toward or away sector identity to the location of each disturbance based on the dominant polarity of the interval. In turn, that interval can be denoted as being either north or south of the current sheet as determined by the solar polarity. CMEs are seen to be nearly equally divided between the two hemispheres with 58 north and 55 south of the current sheet. The non-CME shocks are divided 33 north of the current sheet and 22 south.

Overwinding and Asymmetry Results

We have repeated the earlier examinations of the overwinding and asymmetry of the IMF spiral windings using ISEE-3 data from the L_1 mission. Five-minute data resolution has been used to better resolve the passage of disturbances. The catalog of CME and shock observations has been used to remove or focus upon these disturbances in an effort to determine if they have been a significant contributor to the previously observed winding angle statistics.

Each five-minute data point is assigned a sector identity according to its orientation relative to the predicted Parker winding angle which is computed using the observed solar wind speed with the source surface altitude set to zero. The latter assumption yields an upper limit estimate for the winding angle prediction. When proton data is no longer available for the computation of the wind speed, electron data is substituted. Averages for toward and away, or north and south, measurements are computed for each solar rotation and these values are reated as independent estimates of the means. This avoids finite correlation length problems associated with treating each five-minute measurement as a statistically independent estimate [*Forbush et al.*, 1982; 1983]. Non-CME shocks are extended by a prescribed time following the shock's passage in an attempt to represent the extent of the shock's influence on the plasma.

We insist that each sector type be represented by at least 100 hours of possibly non-contiguous data for each solar rotation, or that rotation is discarded from the analysis. This insures a meaningful average for the quantities. Because the year 1980 is a time of changing solar magnetic state, we disregard this year in the

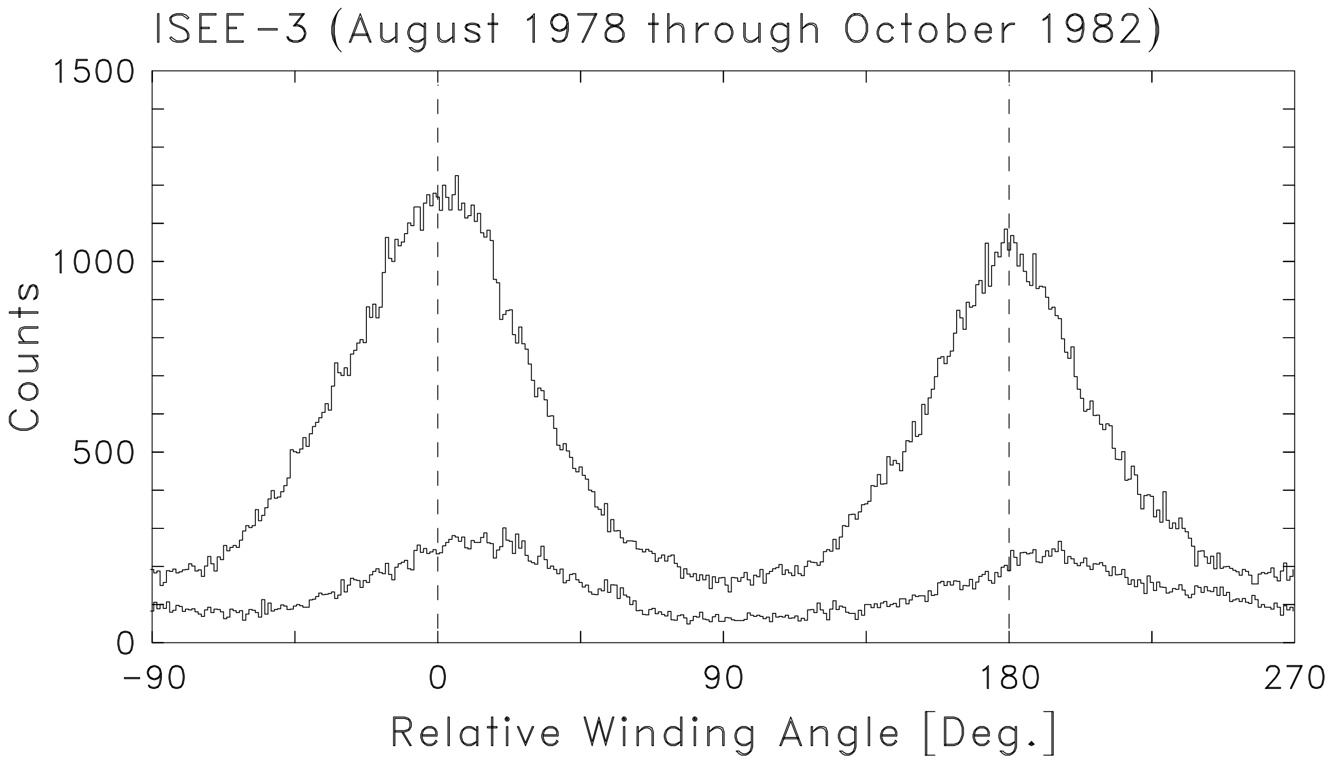

Figure 2. Histograms of winding angles for five-minute averaged ISEE-3 data excluding year 1980. Winding angles are plotted relative to Parker prediction for away sectors using the measured wind speed and 0 R_S source surface. Panel shows distribution for undisturbed periods (top curve) and disturbed CME and post-shock observations (bottom curve). Overwinding of disturbed data is clearly evident while the average and most-probable winding angles of the undisturbed data agree with the Parker prediction.

following analysis.

Table 1 lists the basic results of our analysis. Uncertainties are the computed error of the mean. The means and uncertainties are computed from the ensemble of solar rotation averages. The entire ISEE-3 dataset, excluding 1980, was first run for reference followed by subsets of the entire dataset which are defined by what was removed from the analysis: removing only CMEs, CMEs extended to include the upstream shock, non-CME shocks with 24 hours following the shock, the same with 48 hours following the shock, and last all of the above. CMEs, the region between the CME and the upstream shock, and the regions downstream of non-CME shocks appear to account for all of the overwinding of the IMF. The asymmetry is largely unaffected by removal of the disturbances. However, the 1σ significance suggests that this dataset is inadequate to address the relationship of interplanetary disturbances to the possible IMF winding angle asymmetry.

Table 1. Winding Angle Statistics[1]

ISEE-3 subset	Asymmetry	Overwinding
All data in dataset	$1.6° \pm 1.5°$	$1.4° \pm 0.6°$
CMEs removed	$1.0° \pm 1.5°$	$0.8° \pm 0.6°$
CMEs to upstream shocks removed	$1.1° \pm 1.5°$	$0.5° \pm 0.6°$
Non-CME shocks + 24 hours removed	$0.9° \pm 1.5°$	$0.4° \pm 0.6°$
Non-CME shocks + 48 hours removed	$1.3° \pm 1.4°$	$0.3° \pm 0.6°$
CMEs to upstream shocks and non-CME shocks + 48 hours removed	$1.4° \pm 1.4°$	$0.01° \pm 0.7°$

[1]Means and error of the means as computed from the ensemble of solar rotation averages.

The reduction in the overwinding is accomplished chiefly by reducing the overwinding of the northern hemisphere from $2.15° \pm 1.09°$ to $0.71° \pm 1.15°$. The asymmetry remains because the winding of the southern hemisphere changes from overwound by $0.59° \pm 0.75°$ to underwound at $-0.67° \pm 0.73°$ when the various disturbances are removed.

An overwinding and asymmetry for the CMEs themselves can also be computed if we dispense with the 100 hour restriction. In that case, the computed overwinding of the field within the CMEs is $8.4° \pm 2.7°$ while the computed asymmetry is $15.2° \pm 10.1°$. Addition of the CME-associated shocks and the non-CME shocks with 24 hours of trailing data brings these values down to $6.8° \pm 2.3°$ and $6.7° \pm 6.1°$, respectively.

Figure 2 shows the distribution of the difference between the observed winding angle and the predicted winding angle derived from the observed wind speed and the *Parker* [1958, 1963] theory. *Smith and Bieber* [1991; 1992] showed previously that the distribution of relative winding angles for all measurements in the omnitape dataset is shifted to larger values relative to the Parker prediction. Although not shown here, the same is true of the ISEE-3 dataset. Figure 2 shows the separate distributions for the undisturbed data (top curve) and disturbed data (bottom curve) where disturbed data are CMEs extended to include the upstream shock and non-CME shocks plus 48 hours. Undisturbed data are all other measurements. The latter corresponds to the bottom row in Table 1. While the shift to greater winding angles than predicted is no longer evident in the undisturbed data, the disturbed data clearly shows a shift to greater values of the winding angle than the Parker theory predicts.

Conclusions

We conclude that CMEs, their upstream shocks and non-CME shocks account for the apparent overwinding of the IMF reported in earlier investigation. The processing of the interplanetary plasma by these disturbances lies outside the traditional Parker description for the winding of the IMF, and so it is not unexpected that these transient disturbances would skew the statistics.

This fact is made more interesting by the realization that many CMEs and the non-CME shocks represent high-speed plasma. One might expect the fields within CMEs and downstream of shocks to be less-tightly wound than the undisturbed plasma. However, the opposite is true with these high-speed plasmas containing some of the most tightly wound fields.

It is also interesting that these disturbances do not appear to alter the computed north-south asymmetry of the IMF winding angle. Since CME coverage appears to be evenly distributed between the northern and southern hemispheres, the processes which affect the overwinding do not introduce an asymmetry. A persistent north-south winding angle asymmetry remains an apparent attribute of the undisturbed solar wind.

Smith and Bieber [1991] suggested that the apparent overwinding of the IMF might result from a small azimuthal field at the source region. They also postulated how such a field might arise as a remnant of fields from deeper within the chromosphere. This seed field would then contribute a small, but persistent winding of the IMF over the solar poles in contrast to the straight field lines predicted by Parker. There now appears to be no motivation for this small azimuthal field, except to the extent that CMEs are expected to contain non-radial fields at the source surface, and the prediction for a high latitude winding is no longer justified.

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