

Central axial field direction in magnetic clouds and its relation to southward interplanetary magnetic field events and dependence on disappearing solar filaments

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Abstract. Extended periods of strong southward interplanetary magnetic field B_s are the primary cause of intense geomagnetic storms. Most such intervals are associated with magnetic clouds in the solar wind. We define a magnetic cloud B_s event as the interval of southward interplanetary magnetic field observed as a magnetic cloud passes by the Earth. For the 26 well-characterized events studied here, we find that (1) magnetic cloud central axial field directions are almost evenly distributed between -90° and 90° ecliptic latitude, the longitudinal distribution is slightly peaked around the east and west, (2) the duration and intensity of magnetic cloud B_s events correlate linearly with the direction of the cloud's central axial field, and (3) cloud central axial field directions are correlated with the central axial field directions of the associated disappearing filament on the Sun. These findings are useful in predicting from solar observations the duration and intensity of those magnetic cloud B_s events that hit Earth.

1. Introduction

Long intervals of large southward interplanetary magnetic field (IMF) are the primary cause of intense geomagnetic storms [Tsurutani *et al.*, 1992]. Thus understanding the causes of and predicting the length and strength of southward IMF intervals is a key goal of space weather research. In what follows, we call an interval of southward IMF a B_s event and label the maximum strength of the southward IMF as the event's intensity.

B_s events usually occur within the interplanetary material associated with a coronal mass ejection (an ICME) or in the sheath region just behind a forward interplanetary shock. A smaller number of events are associated with large-amplitude Alfvénic fluctuations [Tsurutani *et al.*, 1992]. Most of the long-duration, strong-intensity B_s events consist of the driver gas and the shock sheath B_s events [Tsurutani *et al.*, 1988; Zhao *et al.*, 1993]. The driver gas is a fast ICME [Sheeley *et al.*, 1985]. Thus a driver gas- B_s event is actually a part of the internal magnetic field of a fast ICME. Of course, the IMF in an ICME may have undergone interplanetary dynamic changes. In contrast, a shock sheath B_s event is caused by compression and draping of preexisting southward magnetic field lines at the leading edge of a driver gas. The preexisting southward field may include a part of the internal field of a slow ICME

[Burlaga *et al.*, 1987] as well as the ambient southward IMF. A shock sheath B_s event may also be caused by the interaction of the trailing edge of a slow ICME with a following high-speed steady stream [Zhao, 1992]. In any case, nearly every long-duration, large-intensity B_s event is associated with an ICME. However, the opposite association, the one that is actually useful for storm predictability, is weak; only a fraction of ICMEs cause significant B_s events.

What are the characteristics of the internal magnetic field of ICMEs that cause occurrence of B_s events and affect their duration and intensity? The answer to this question may also answer the question of what makes ICMEs geoeffective.

Most studies of the topology of the ejected magnetic field in ICMEs involve observation and modeling of magnetic clouds and bidirectional electron heat flux events [Gosling, 1990 and references therein]. Magnetic clouds are defined as intervals of high magnetic field strength with a smoothly rotating field direction [Burlaga *et al.*, 1981; Klein and Burlaga, 1982]. The coherent field rotation in magnetic clouds has been reproduced quite well using equilibrium flux rope models [Marubashi, 1986; Burlaga, 1988; Farrugia *et al.*, 1993]. The models provide a convenient means of summarizing the observations of magnetic clouds and suggest a method for determining the characteristics of magnetic clouds, such as the direction and strength of their central axial field.

Using central axial field directions computed for 26 magnetic clouds [Lepping *et al.*, 1990; Marubashi, 1997], we analyze their directional distribution with respect

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to ecliptic latitude and longitude (section 2). To identify the characteristics of ICMEs and coronal mass ejections that significantly affect the formation of B_z events, we measured the duration and intensity of magnetic cloud (MC) B_z events (defined as intervals of continuous southward IMF that occur within magnetic clouds). Section 3 shows how the duration and intensity of MC B_z events are associated with the characteristics of clouds. In section 4 we calculate the correlation coefficient of the axial field direction of the interplanetary magnetic clouds with that of the associated disappearing solar filaments (DSFs). Section 5 summarizes the results and discusses how to improve the correlations studied here.

2. Directional Distribution of Magnetic Cloud Central Axial Fields

The direction of the central axial field is one of the cloud's characteristics that directly affects the characteristics of MC B_z events and that is predictable from currently available solar observations, as shown below. The familiar view is that the axis of the magnetic rope in a magnetic cloud lies approximately in the ecliptic plane and is perpendicular to the Earth-Sun line, though, in fact, a broad range of orientations are observed [Lepping *et al.*, 1990]. In this view the transverse field component of a cloud will be the major contributor to MC B_z events. In order to obtain the directional distribution

of magnetic cloud central axial fields, we consider the direction of the magnetic cloud central axial field determined by Lepping *et al.* [1990] for 18 clouds using the static rope model [Burlaga, 1988] and by Marubashi [1997] for 12 clouds using the expanding rope model [Farrugia *et al.*, 1993]. There are four common events in the two data sets. The characteristics of the four clouds obtained using the static rope model significantly differ from that using the expanding rope model. We will show the analytical results for each data set as well as for the combined data set in what follows. The expanding rope model is supposed to be better than the static rope model. The combined data set used in Figures 1 and 2 (bottom rows) includes results for 14 clouds from Lepping *et al.* [1990] and 12 clouds from Marubashi [1997].

The central axial field direction is indicated locally by its ecliptic latitude (the angle between the central axial field direction and the ecliptic plane) and longitude (the angle between the projected axial field in the ecliptic plane and the Sun-Earth line). There is not a definite longitude if the ecliptic latitude is close to $\pm 90^\circ$. Fortunately, all samples in the two sets have ecliptic latitudes less than 90° . Figure 1 shows histograms of the occurrence frequency of magnetic clouds with respect to the ecliptic latitude and longitude of the central axial field direction. The bin size is 10° for latitude and 20° for longitude. The central axial field directions are distributed broadly in both latitude and longitude.

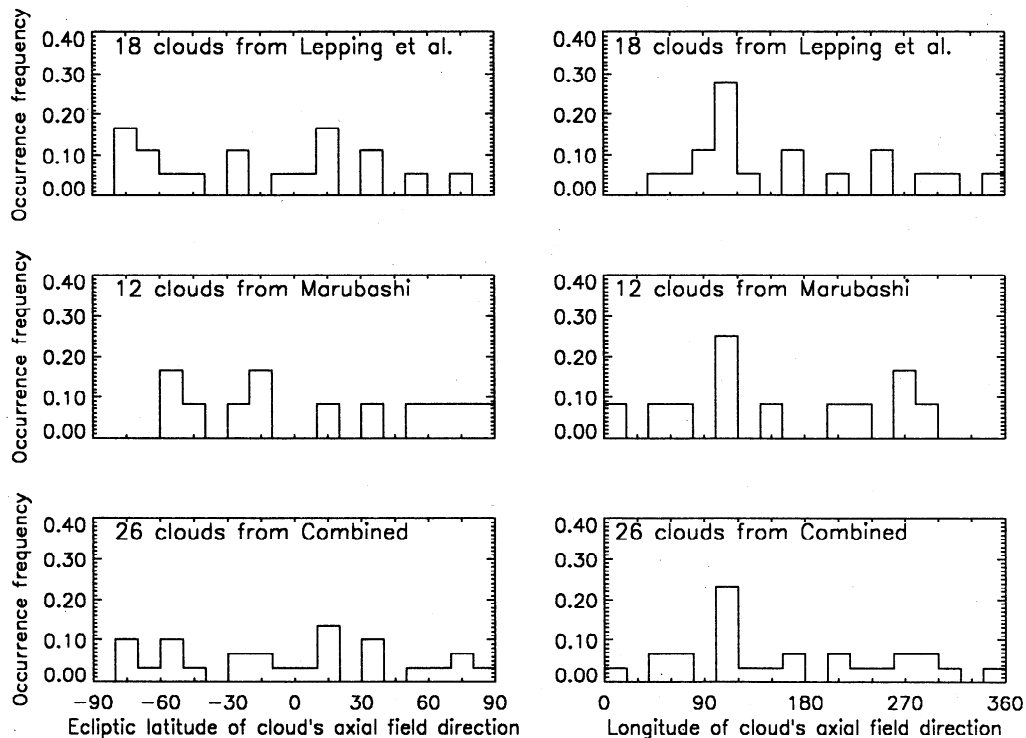


Figure 1. Histogram of the occurrence frequency of magnetic cloud with respect to the ecliptic latitude and longitude of central axial magnetic field directions. The bin size is 10° (left column) and 20° (right column). The diagrams (top to bottom) display histograms obtained using data sets from Lepping *et al.* [1990], Marubashi [1997], and their combination.

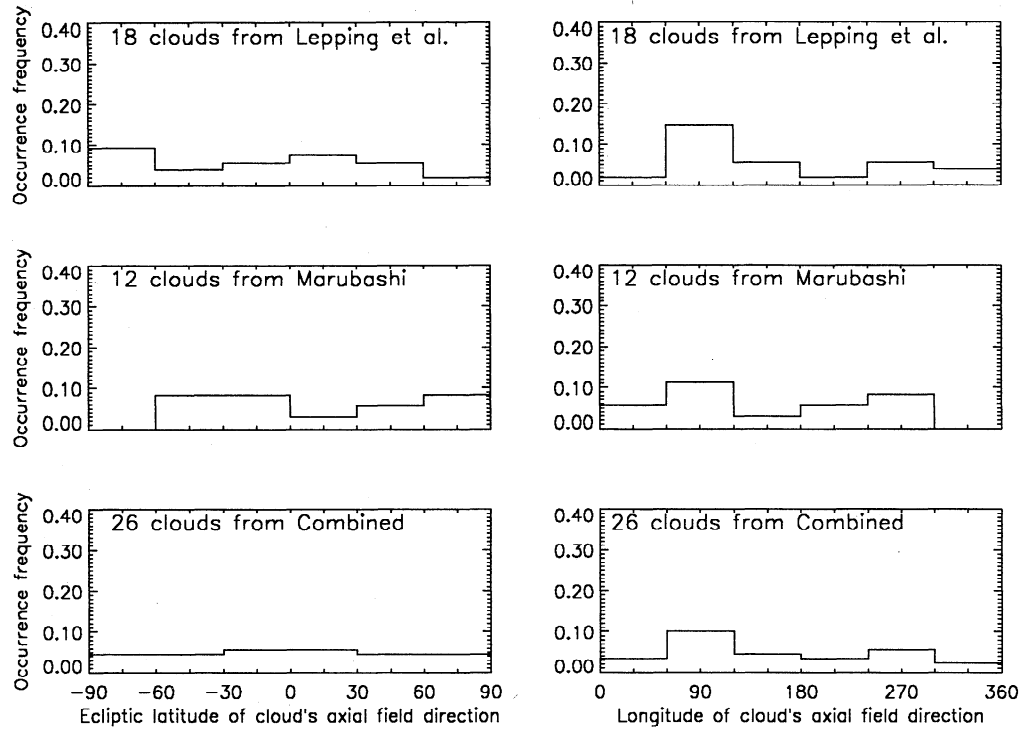


Figure 2. The same as Figure 1 except that the bin size is 30° (left column) and 60° (right column).

Because of the small number of events and small bin size used, no systematic pattern can be identified. The latitude histogram (left column) for the data set from *Lepping et al.* [1990] shows one peak near the ecliptic plane. However, there is a comparable peak near the south. The longitude histograms (right column) show a small peak near 90° (east) and another near 270° (west), though the west peak is less significant.

Figure 2 is like Figure 1 except the bin size is 30° for latitude and 60° for longitude. The latitude histograms using 26 samples (bottom row) show that the occurrence frequency is distributed almost evenly between northern and southern hemispheres, though the occurrence frequency between -30° and $+30^\circ$ is slightly higher. There are two small peaks in the east and west longitude distributions. This directional distribution of magnetic cloud axes may be understood because, as shown in section 4, the magnetic cloud is the interplanetary counterpart of the magnetic field within and surrounding disappearing filaments that have no preferential orientation relative to the solar equator [Webb, 1988].

The 26 independent clouds analyzed by *Lepping et al.* [1990] and *Marubashi* [1997] could be atypical subsets of magnetic clouds that were selected because they were easy to identify and valid to model. In addition, it may be that the rope models used to determine characteristics of magnetic clouds are unable to accurately specify the longitude of the central axial field for some special cases, for example, when the rope axis has a large latitude angle or when the axis lies in the ecliptic plane

and points toward the Sun or Earth. So some caution should be used in drawing firm conclusions about the longitudinal distribution.

3. Magnetic Clouds and MC B_s Events

The variations of magnetic field direction associated with the motion of a magnetic cloud past a spacecraft can be explained in terms of a cylindrically symmetric force-free magnetic field configuration. Cylindrical flux ropes are characterized by axial fields near their centers and increasingly transverse fields near their outer edges. At intermediate distances R from the rope axis the field lines are helices with increasingly steeper pitch and decreasing strength away from the axis. Using this model, the cylindrical rope field can be expressed in terms of two components that depend on R alone, the axial and transverse components [Goldstein, 1983]. Both components depend on the strength and direction of the cloud's central axial field. In the familiar view of magnetic cloud axis orientation, MC B_s events are simply determined by the transverse field component of clouds. However, in the view developed here, MC B_s events depend on both the axial and transverse components. In other words, for those events we examined it is primarily the central axial field that determines the intensity and duration of the associated B_s events.

As defined in section 1, MC B_s events are a part of the internal field of magnetic clouds. By surveying the OMNI data, we determine the duration and intensity of the MC B_s events for the 18 magnetic clouds

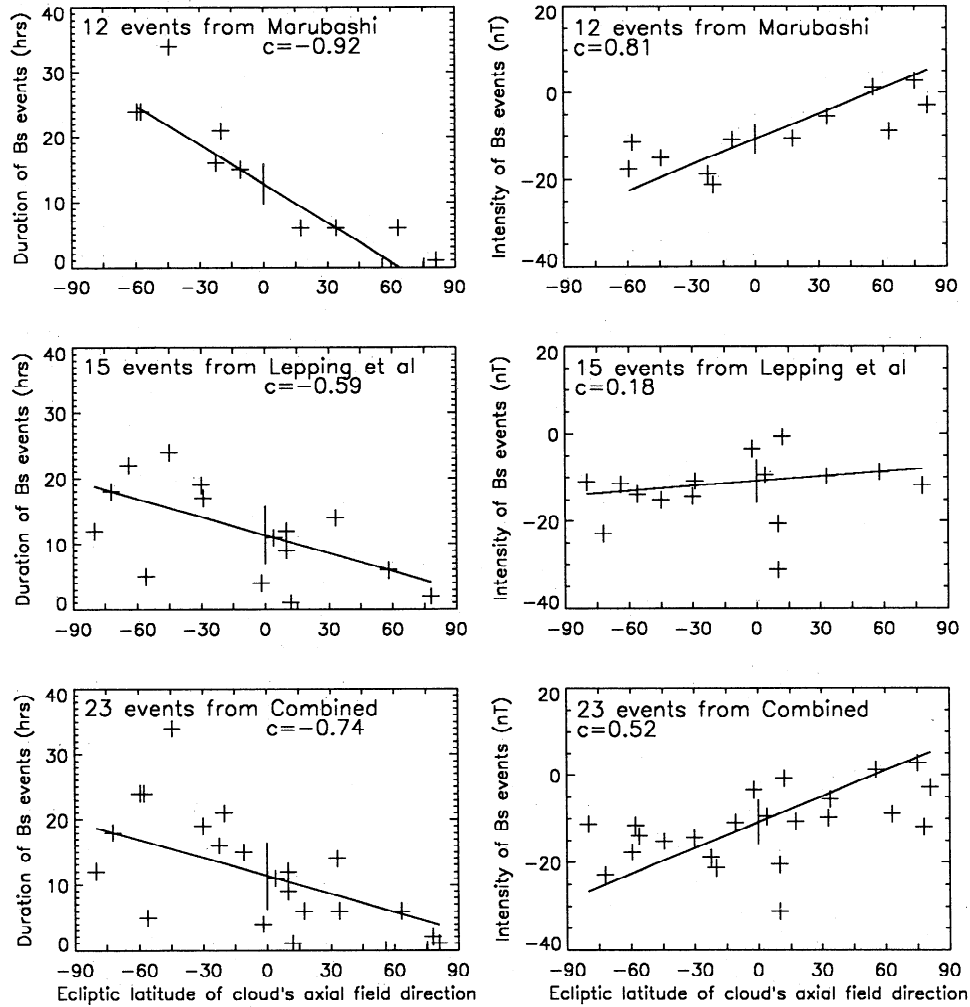


Figure 3. Scatter diagrams of magnetic cloud B_s event characteristics and cloud central axial field directions for *Marubashi* [1997] set (top row), *Lepping et al.* [1990] set (middle row), and the combination (bottom row). The “c” in diagrams denotes the correlation coefficients. The line and accompanying vertical bar are the least squares fit to the scatter diagram and its standard deviation, respectively.

used by *Lepping et al.* [1990] and the 12 clouds used by *Marubashi* [1997]. If there is no southward IMF, the duration is defined as zero and the intensity as the smallest northward field strength. Excluding clouds with a data gap greater than 3 hours in the interval, we are left with 15 MC B_s events from the *Lepping et al.* set and all 12 of the *Marubashi* set. Figure 3 shows the scatter diagrams of the duration and intensity of MC B_s events versus magnetic cloud central axial field direction. The combined data set used in the bottom row includes the 12 events from *Marubashi* and the 11 remaining independent events from *Lepping et al.* The lines and accompanying vertical bars are the least squares fit to the scatter diagram and its standard deviation, respectively. Both sets show a similar linear correlation between the ecliptic latitude of the cloud’s central axial field direction and the duration and intensity of the MC B_s event, though there is a significant difference in their correlation coefficients (discussed in section 5). As

a cloud’s central axial field direction turns southward, the duration becomes longer, and the intensity becomes stronger.

4. Magnetic Clouds and Disappearing Filaments

Magnetic clouds have been associated with DSFs [*Wilson and Hildner*, 1986; *Marubashi*, 1986; *Bothmer and Schwenn*, 1994; *Bothmer and Rust*, 1997]. *Marubashi* [1997] inferred the axial field directions of 12 magnetic clouds and compared them in detail with the orientations of nine associated DSFs (no associated DSFs were recorded for three clouds). He found that the orientation of the magnetic cloud axis generally coincided with the orientation of the associated DSFs. In addition, magnetic clouds with field-aligned currents flowing nearly parallel (antiparallel) to the cloud’s local magnetic field were associated with DSFs located in

the southern (northern) hemisphere, irrespective of the solar cycle change of the large-scale photospheric field.

The magnetic fields in solar filaments in the southern and northern hemispheres of the Sun have been found to be preferentially sinistral and dextral heliform, respectively [Martin *et al.*, 1994]. This segregation of filament field helicity by hemisphere suggests that parallel and antiparallel clouds correspond to sinistral and dextral DSFs, respectively. By comparing the sign of magnetic helicity of 16 of the magnetic clouds analyzed by Lepping *et al.* [1990] with the location of their probable solar sources (eight DSFs and eight eruptive flares), Rust [1994] found that most sources of magnetic clouds with positive (negative) helicity are, indeed, located in the southern (northern) hemisphere, further confirming this segregation.

Solar filaments are assumed to be basically parallel to the solar surface and observed in projection against the chromosphere. The orientation of the DSFs's central axial field vector may be expressed in terms of the angular distance from the associated latitudinal line. From the UAG reports on disappearing filaments [McIntosh, 1979; Wright, 1991] and the appropriate photospheric magnetic field polarity data, the central axial field orientation of the 17 DSFs associated with magnetic clouds in the two sets may be quantitatively determined using Martin's rule for handedness of filament field rotation.

The top two scatter diagrams in Figure 4 show the ecliptic latitudes of cloud central axial field directions versus the orientations of the associated DSFs central axial fields for the Marubashi [1997] and Lepping *et al.* [1990] sets. Also shown on the diagram are the least squares fits and standard deviations. The bottom diagram is for the combined set (all nine from the Marubashi set and five from the Rust [1994] set after excluding the three common events). The nearly diagonal line suggests that the rope axial field direction undergoes only slight change while propagating through interplanetary space. This supports the possibility of predicting the axial field directions of interplanetary magnetic clouds from the solar observations of DSFs and the photospheric magnetic field.

5. Conclusions and Discussion

With respect to the ecliptic latitude of the central axial field direction in magnetic clouds, the histogram shows a nearly uniform distribution between the southern and northern poles. This is in agreement with the fact that disappearing filaments have no preferential orientation relative to the solar equator. It should be noted that the sample data sets used here might be biased subsets of magnetic clouds selected because of ease of identification and modeling. Greater sample numbers of magnetic clouds should be used to obtain results which have more robust statistical validity.

The duration and intensity of magnetic cloud B_z events that reach the Earth depend on the ecliptic lat-

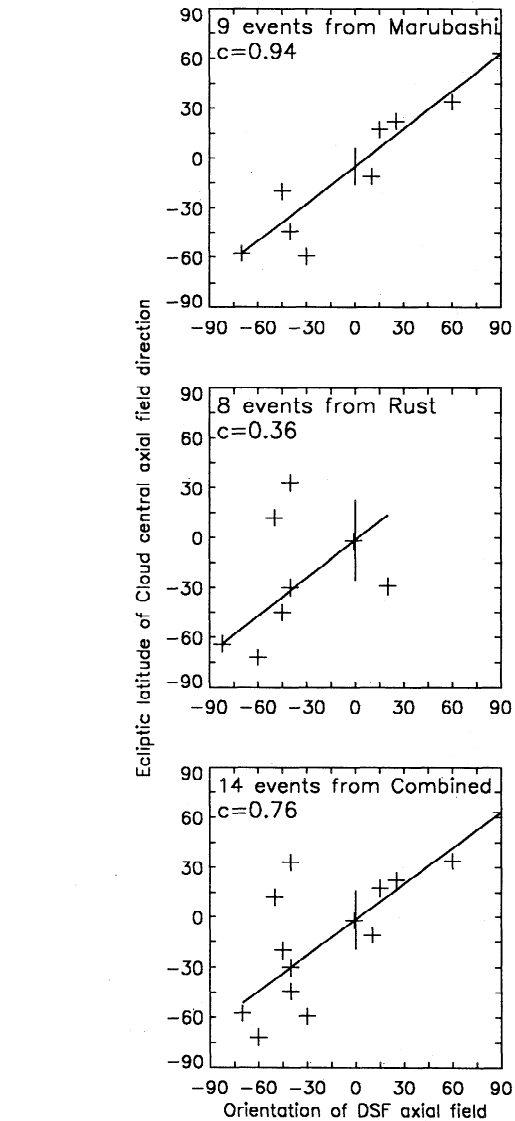


Figure 4. Scatter diagrams of the ecliptic latitude of magnetic cloud central axial field direction versus orientation of disappearing filament central axial field. The 'c' in diagrams denotes the correlation coefficient. The line and accompanying vertical bar show the least squares fit to the scatter diagram and its standard deviation, respectively.

itude of the central axial field in magnetic clouds. The duration and intensity becomes increasingly longer and stronger as the cloud's axis turns from north to south. This suggests that the central axial field is, in general, the major parameter affecting magnetic cloud B_z events. This makes sense because both the axial and transverse components of a flux rope contribute to a B_z event when the cloud axis does not lie in the ecliptic plane and is not perpendicular to the Sun-Earth line, and both components depend on the direction and strength of the central axial field of the rope. Other important factors affecting the characteristics of magnetic cloud B_z events observed near the Earth include both the "impact distance" (the distance from the rope axis

at closest approach point) and the dynamic interaction between clouds and the solar wind. So, in addition to the ecliptic latitude of the cloud's central axial field, the characteristics of a magnetic cloud B_z event will also depend on the longitude and strength of the cloud's central axial field, the impact distance, and the results of interactions between the magnetic cloud and the solar wind. These aspects contribute to the large scatter in the scatter diagrams of magnetic cloud B_z event characteristics versus cloud central axial field direction.

There is a linear correlation between the direction of a cloud's central axial field and the associated filament's central axial field. This confirms the suggestion that magnetic fields within and/or surrounding disappearing filaments may be the source of interplanetary magnetic clouds. The nearly diagonal slope of the least squares fit to the scatter diagram of cloud versus disappearing filament axial field directions suggests that the orientation changes only slightly while propagating through interplanetary space. This supports the hypothesis that it is possible to predict B_z events from solar observations and determine whether or not a CME that encounters the Earth is likely to be geoeffective.

Clearly, further study is needed using greater numbers of magnetic cloud B_z events and disappearing filaments to improve the statistical confidence in this result. This will require identifying more magnetic clouds in in situ observations of solar wind and interplanetary magnetic fields and inferring the central axial field direction of the identified clouds using magnetic flux rope models. Using the Marubashi [1997] data set, the correlation coefficients of cloud central axial field directions with both the duration and intensity of B_z events and filament central axial field directions are -0.92, 0.81, and 0.94, respectively. They are much higher than those obtained using the data set of Lepping *et al.* [1990] (see Figures 3 and 4). Understanding the cause of the difference will improve our results.

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