STATISTICAL BEHAVIOUR OF THE IMF DURING THE LAST SOLAR CYCLE AND ITS IMPLICATIONS FOR GEOMAGNETIC ACTIVITY STUDIES

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ABSTRACT

Strong interplanetary magnetic fields (IMFs) with strong out-of ecliptic components (B_Z) are well- known magnetic signatures of coronal mass ejections, the primary cause of major geomagnetic activity. Here we analyze the solar cycle variations of these quantities and show to what extent they can be used as a lone diagnostic of CME activity since other indicators, such as bidirectional electron streaming, are not generally available. In particular, we find that the variation of the annual median IMF strength over the previous solar cycle appears to have been governed by variations in the solar source field rather than CME activity. However, the high field tail of the IMF occurrence distribution and the history of the B_Z component magnitude show sunspot number correlations like the CMEs.

1. INTRODUCTION

From the viewpoint of solar-terrestrial predictions, interplanetary magnetic field observations are useful in several ways: (1) they provide easily-measured signs of a disturbance traveling in the solar wind, (2) they indicate the potential strength of the interaction of the disturbance with the magnetosphere, since the latter depends on the magnitude and direction of B_Z (the out-of-ecliptic component of the field), and (3) they are available for long periods of time, thereby permitting historical and statistical studies.

It has been convincingly demonstrated (e.g., Gosling et al., 1991; 1992) that fast coronal mass ejections (CMEs) are the major external factor in causing major magnetospheric disturbances provided that they occur at low heliolatitudes and within ~45° heliolongitude of the earth. Gosling et al. (1991) also showed that major storm-inducing CMEs in the solar wind are perhaps best identified by using a combination of measurements of electron heat flux distributions (bidirectional heat fluxes pointing parallel and antiparallel to the local magnetic field direction are the electron signatures of CMEs) and interplanetary shock observations. However, one of the manifestations of a CME event is an enhancement in the interplanetary magnetic field magnitude accompanied by larger than normal B_Z components of both signs. It is shown here that while the more available interplanetary magnetic field measurements alone can be used as a proxy measurement of CME occurrence, some cautionary measures are necessary. In particular, solar cycle variations in average total field magnitude over the previous solar cycle appear to be dominated by changes in the solar source field. These changes do not reflect the occurrence history of major geomagnetic storms, although they probably influence the history of moderate and weak activity levels. In contrast, the temporal behavior of the high-field tail of the IMF magnitude and $|B_Z|$ distributions appear to reflect the rate of CME occurrence.

2. OBSERVATIONS

Gosling et al. (1992) found that there is a close correlation between the occurrence rate of CMEs in the solar wind at 1 AU and sunspot number as shown in Figure 1. (Earlier, this relationship was also seen in the low corona by Howard et al. (1986).) If we assume that CMEs are the primary cause of large magnitude B fields in the solar wind at 1 AU, then we might expect that, on the average, IMF $|B|$ should also vary with sunspot number. However, Figure 2c, which shows annual medians of IMP-8 five minute resolution measurements of the interplanetary field strength between 1979 and 1988, gives the impression that, statistically, the largest fields occurred during the declining phase of the last solar cycle as indicated by the sunspot number in Figure 2a (also see Slavin et al., 1986; Smith, 1989; Luhmann et al., 1992). For comparison, the variation in the median magnitude of $|B_Z|$ is shown in Figure 2b. In this case, a sunspot number correlation is evident, as was found for the preceding cycle by Siscoe et al. (1978). The nature of these differences in behavior is worth considering in view of the fact that researchers sometimes use the magnitude of B for assessing the likelihood of a major disturbance.

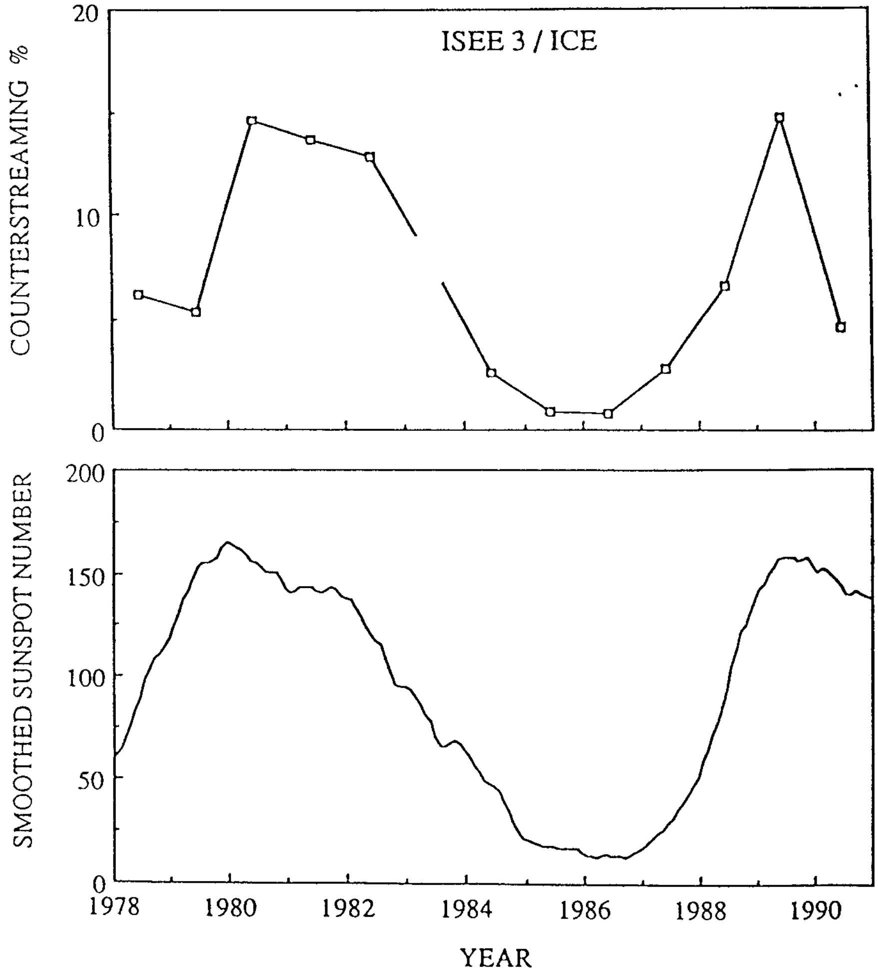

Figure 1. The occurrence rate of fast CMEs (inferred from bidirectional electron streaming events preceded by interplanetary shocks) compared to the sunspot number. (From Gosling et al., 1992)

3. INTERPRETATION

An interpretation of the field magnitude variations is revealed by histograms of occurrence of field strength, divided according to solar cycle phase, as given in Figure 3. Here it is seen that the tail of the field strength distribution is indeed strongest at solar maximum, although the peak in the main body of the distribution shows the aforementioned maximum value in the declining (intermediate) phase. A sunspot cycle relationship is clearly apparent in the integrated occurrence rate of the high (>25 nT) total fields shown in Figure 4. Thus $|B_Z|$ and high $|B|$ are like CMEs in their solar cycle behavior, but CMEs do not appear to control the solar cycle dependence of median $|B|$.

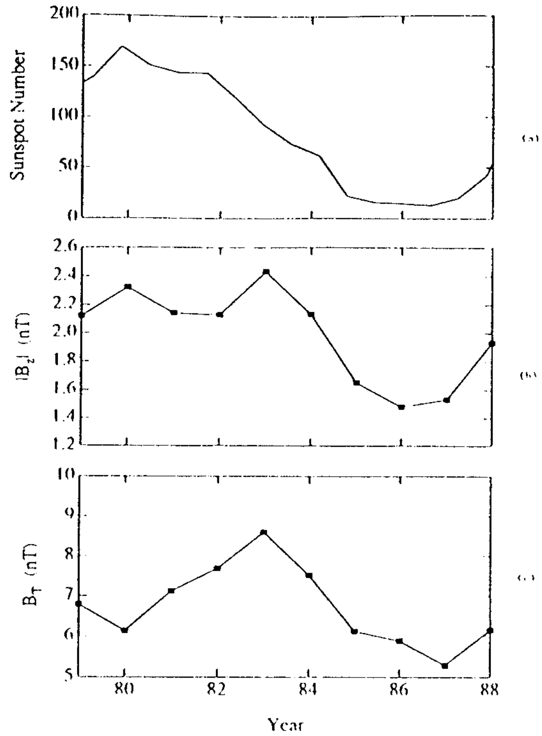

Figure 2. Sunspot number and IMF parameters for the period studied. Top (a): Sunspot numbers. Center (b): Time histories of annual means of $|B_Z|$ in GSE coordinates. Bottom (c): Time history of annual means of $|B|$.

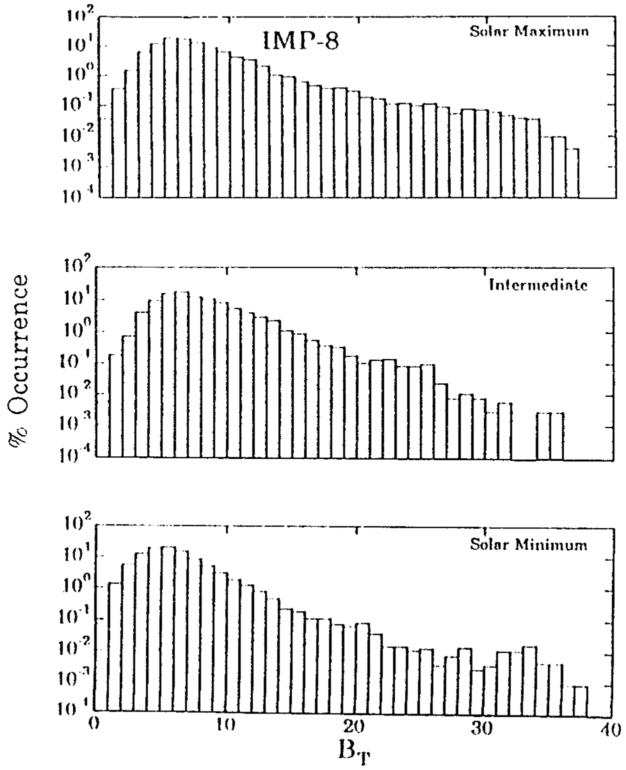

Figure 3. Histograms of occurrence of $|B|$ values (5-minute averages). Top: Solar maximum (1979-1981). Center: Declining phase (1982-1984). Bottom: Solar minimum (1985-1987). The IMP-8 magnetometer for the components of the field was restricted to $\pm$ 36 nT for most of the mission, but the distributions suggest that few data points were lost by using this cutoff.

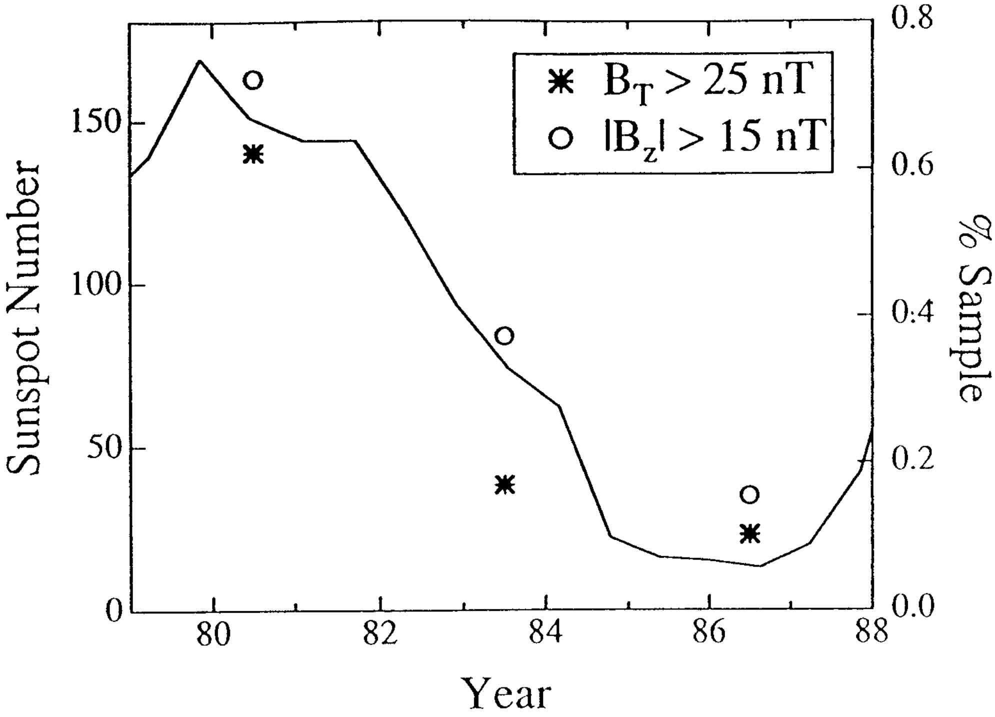

Figure 4. Integrated occurrences of high field tails (see Figures 3 and 7) overlaid on the sunspot cycle.

If we assume that the main bodies of the distributions in Figure 3 represent the ambient interplanetary field, then the ambient interplanetary field must have been greatest during the declining phase of the last solar cycle. This magnitude change may have occurred either on the region of the source surface where the IMF seen at 1 AU originates, or by virtue of modifications of the field that occur in the interplanetary medium. The latter are generally related to the presence of stream interactions (e.g., Gosling et al., 1978).

Examination of figures presented by Hoeksema et al. (1983) and Behannon et al. (1989) shows that during the declining phase, the neutral line was in the appropriate configuration to allow high speed flows from polar coronal holes at high heliomagnetic latitudes to influence the solar wind in the ecliptic plane. These would produce IMF enhancements through stream interactions. Also associated with the heliomagnetic latitude gradients in wind speed are gradients in the radial field at the source surface such that B_r increases with latitude (Hoeksema et al., 1983). Thus both stream interactions and the source field were capable of increasing the average IMF strength. To examine the effect of changes in the field at the sun, one can examine the radial component of the field (B_r or B_x) because, in theory, that component is not modified by the (radial) solar wind velocity (e.g., King, 1981). Figure 5 shows that the median value of $|B_x|$ peaks during the declining phase as does $|B|$. Of course, this does not mean that stream interactions do not also contribute to the observed variation in $|B|$. The IMP-8 measurements of velocity were used to calculate the medians shown in Figure 6. The existence of higher average velocities (relative to solar maximum) during the declining phase implies that stream interactions were also more likely during that time period. Nevertheless, the similar appearance of the histories of $|B|$ and $|B_x|$ suggest that the main reason why the highest median field magnitudes during the last solar cycle occurred in the declining phase was the higher solar source field at that time. In this regard, it is noteworthy that Slavin et al. (1986) used solar magnetogram observations to argue that the solar cycle before this (cycle 20) had relatively weak solar source field changes and thus much weaker IMF variations. These results explain why the same average IMF behavior pattern should not be expected for every cycle. However, the integrated occurrence frequency of the highest fields in the field magnitude distribution should regularly follow the sunspot cycle like the CMEs.

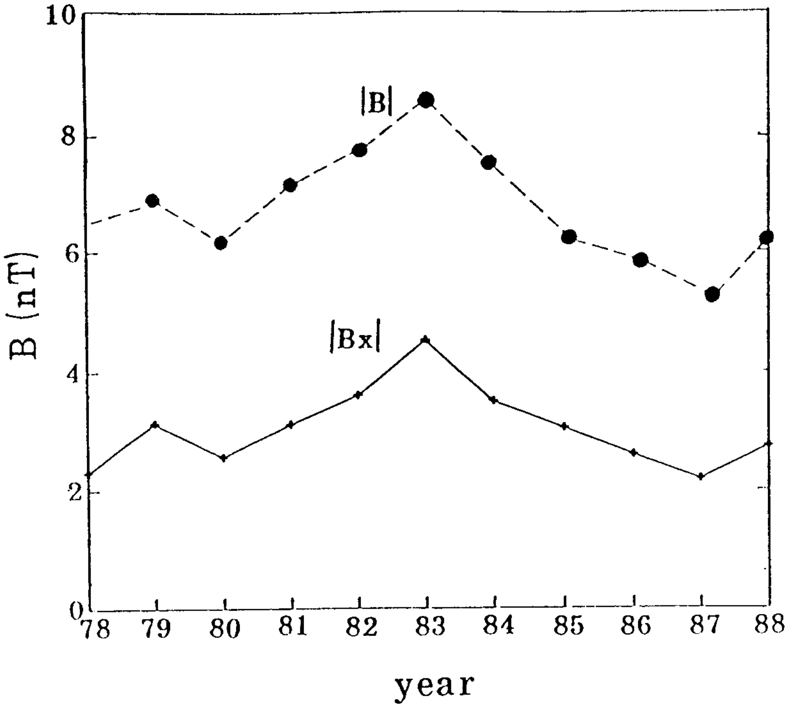

Figure 5. Comparison of time histories of median $|B_x|$ (radial component) and $|B|$.

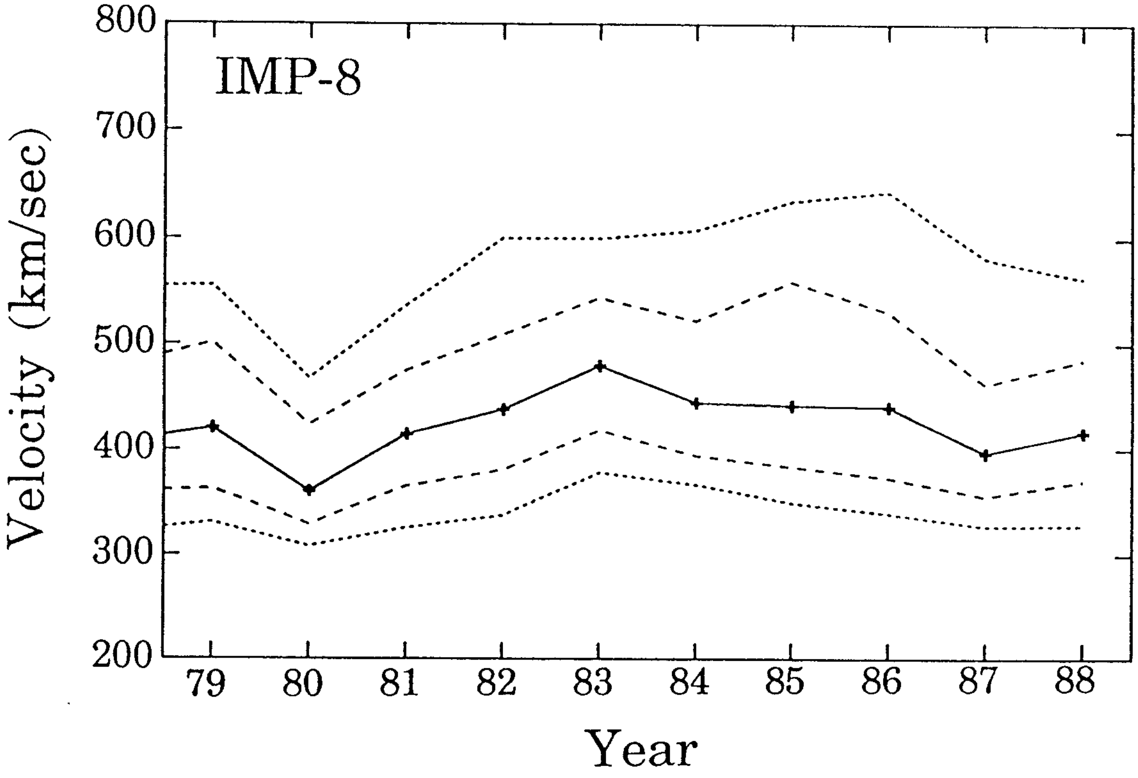

Figure 6. Median solar wind speeds from IMP-8 plasma data. The dashed lines show quartiles and the dotted lines in the first and last deciles of the annual velocity distribution.

The interpretation of the double peak in $|B_Z|$ (Figure 2b) is not straightforward although it may be a regular feature of the solar cycle (it occurred in the previous cycle, as reported by Siscoe et al. (1978)) and is seen in indices of geomagnetic activity (Gosling et al., 1977). Crooker et al. (1977) and Gosling et al. (1977) suggest that the first peak might accompany CMEs related to flares, while the second (later) peak is from enhanced high speed stream activity. To test this hypothesis, one can separately examine the time history of the high $|B_Z|$ tail of the histograms of B_Z occurrence shown in Figure 7. The integrated occurrence rates of the $|B_Z| > 15$nT data shown in Figure 4 peak in 1980 like the high $|B|$ tail and thus suggest that both are related to CME occurrence (statistics do not allow a higher time resolution version of this plot). Nevertheless, further analysis is required to determine whether stream interactions are responsible for the substantial $|B_Z|$ values that produced the second peak in average $|B_Z|$ at the end of the period of maximum sunspot number.

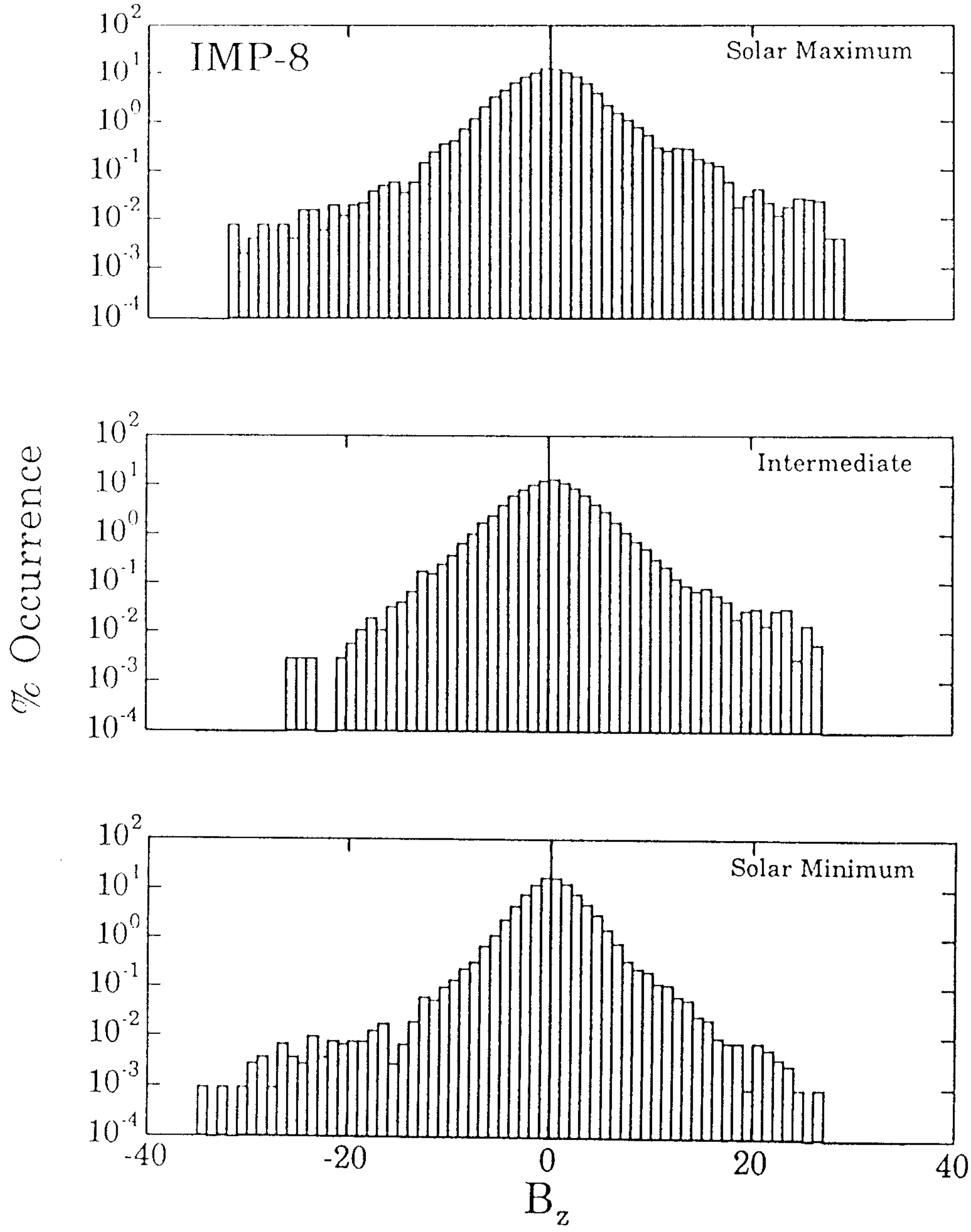

Figure 7. Histograms of occurrence of $|B_Z|$ values (5-minute averages). Top: Solar maximum (1979-1981). Center: Declining phase (1982-1984). Bottom: Solar minimum (1985-1987).

4. CONCLUSIONS

While there are limitations to using interplanetary field measurements alone to predict or represent major geomagnetic activity, Gosling et al. (1991) found that high IBI and/or high $|B_Z|$ is one of the keys to identifying the most "geomagnetically effective" CMEs. Our study shows that these proxies can be used as long as it is understood that 1) the high field magnitudes ($|B|$) caused by CMEs do not substantially affect long term averages of the IMF, and 2) that $|B_Z|$ averages have a second peak near the end of solar maximum that is likely to be due to phenomena other than CMEs.

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