Correlation of magnetic field intensities and solar wind speeds of events observed by ACE

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[1] The relationship between the magnetic field intensity and speed of solar wind events is examined using ~3 years of data from the ACE spacecraft. No preselection of coronal mass ejections (CMEs) or magnetic clouds is carried out. The correlation between the field intensity and maximum speed is shown to increase significantly when $|B| > 18$ nT for 3 hours or more. Of the 24 events satisfying this criterion, 50% are magnetic clouds, the remaining half having no ordered field structure. A weaker correlation also exists between southward magnetic field and speed. Sixteen of the events are associated with halo CMEs leaving the Sun 2 to 4 days prior to the leading edge of the events arriving at ACE. Events selected by speed thresholds show no significant correlation, suggesting different relations between field intensity and speed for fast solar wind streams and ICMEs. *INDEX TERMS:* 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2134 Interplanetary Physics: Interplanetary magnetic fields; 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; *KEYWORDS:* field intensity, speed correlation, solar wind

1. Introduction

[2] Geomagnetic storms transfer energy and momentum from the solar wind into the Earth's magnetosphere [e.g., *Gonzalez et al.*, 1994]. Such storms can have adverse effects on a number of both ground- and space-based technical systems [e.g., *Feynman and Gabriel*, 2000]. In order to predict the onset of such hazardous conditions a detailed understanding of the solar wind parameters that give rise to such storms, and the physical processes behind them, is required.

[3] During periods of southward interplanetary magnetic field (IMF), magnetic reconnection between the solar wind and the magnetosphere injects solar wind plasma into the magnetosphere. The rate of reconnection is enhanced when the solar wind impinging on the dayside magnetosphere has both a high flow speed and a large southward magnetic field component [*Dungey*, 1961].

[4] There are a number of solar phenomena that can give rise to such conditions at 1 AU, but it is widely believed that the most geoeffective solar wind events are the interplanetary manifestations of coronal mass ejections (ICMEs) [e.g., *Gosling*, 1993; *Cargill*, 2001], which often contain extended periods of southward IMF. A particular subset of ICMEs, magnetic clouds (as defined by *Burlaga et al.* [1981]), are characterized by a smooth rotation in the magnetic field direction occurring over a period of hours (often including an extended period of southward IMF), accompanied by a reduction in the plasma temperature and density [*Burlaga et al.*, 1981; *Klein and Burlaga*, 1982]. Approximately one third of ICMEs encountered by spacecraft exhibit a rotation in the magnetic field direction [*Gosling*, 1990].

[5] The velocity of an ICME at 1 AU is determined by its interaction with the solar wind, which, in turn, depends on the speed of the ICME relative to the solar wind. Slow ICMEs will be accelerated toward the solar wind speed, and fast ICMEs will be decelerated [*Cargill and Schmidt*, 2002], such that the ICME and solar wind speeds approach each other. In the latter case, fast ICMEs can be preceded by a shock wave, and, in general, the ambient IMF becomes draped around the ICME. These effects can enhance existing regions of southward IMF associated with the ejecta.

[6] The forecasting of geomagnetic activity depends on evaluating the arrival time of a geoeffective event at 1 AU and on predicting both the velocity and magnetic field of the event there. It is further desirable to do this on the basis of solar observations. Recently, *Gopalswany et al.* [2000] proposed a linear relationship between the speed of a CME at the Sun and an ICME. However, an analagous prediction of the magnetic field at 1 AU using a correlation with the field at the Sun is not feasible since determination of the coronal magnetic field is not possible.

[7] One possible way to estimate the ICME magnetic field strength at 1 AU is through a correlation between the magnetic field strength and speed at 1 AU. If such a correlation exists, it may (in principle) be possible to make forecasts of the magnetic field strength of ICMEs based on solar observations. *Gonzalez et al.* [1998] showed that for a very restricted set of magnetic clouds there existed a positive correlation between the maximum field magnitude ($|B|_{max}$) and the maximum speed (V_{max}).

[8] The purpose of this paper is to examine completely and systematically (without any preselection of interplanetary events) the existence of such a correlation between $|B|_{max}$ and V_{max} by the use of a much larger data set (~3 years of ACE data), so as to establish the general validity of the *Gonzalez et al.* [1998] scaling.

2. Data Used and Analysis Techniques

[9] *Gonzalez et al.* [1998] showed that high-speed magnetic clouds tended to have high magnetic field intensities. The clouds were selected using the *Klein et al.* [1982] definition from a range of previously published events observed by a variety of spacecraft (IMP 8, ISEE 3, and Wind). In addition, an enhanced field strength (typically >10 nT), and a duration of ~24 hours for the event to pass the spacecraft were required. A strong, positive linear correlation (coefficient of 0.75) was found such that

$$|B|_{max}\mathrm{nT} = 0.047\,\mathrm{V}_{max}\ \mathrm{km/s} - 1.1 \qquad (1)$$

Driver gas events, defined as regions of the solar wind with a smooth magnetic field, a high field strength, and a low proton

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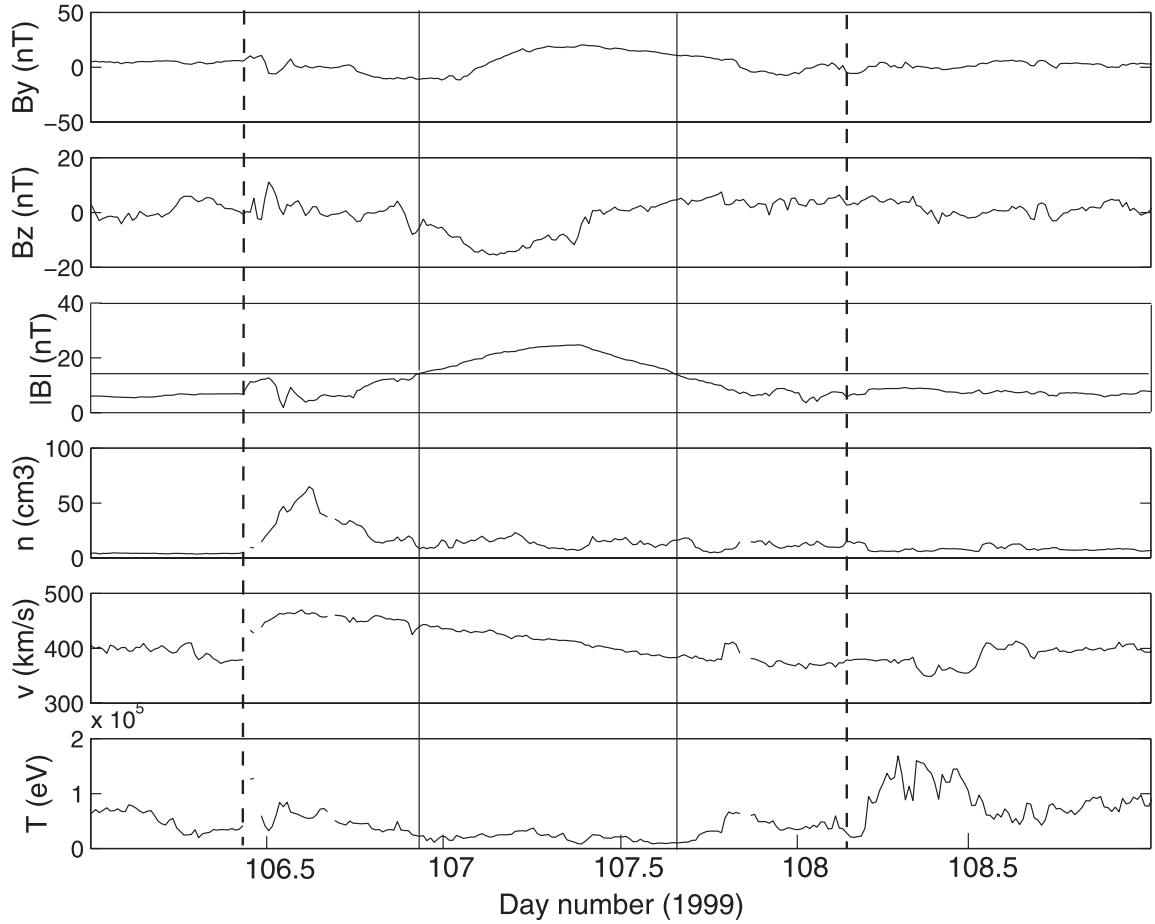

Figure 1. A sample "event" observed by ACE. The solid horizontal line in the middle (i.e., $|B|$) panel shows the threshold criterion of 13 nT used to define an event. The event boundaries defined by the threshold are shown as the two solid vertical lines. With this definition the maximum speed associated with the event (fourth panel down) is not sampled. Thus 0.5 days before and after the $|B|$ boundaries is also sampled (the dashed vertical lines).

temperature, were also investigated but no correlation between field strength and velocity was found so that *Gonzalez et al.* [1998] concluded that the relationship between $|B|_{\max}$ and $V_{\max}$ was peculiar to magnetic clouds.

[10] In our study all the data was collected by a single spacecraft; NASA's Advanced Composition Explorer (ACE), situated at the L1 point [*Stone et al.*, 1998] between August 1997 and December 2000. Magnetic field data (intensity and x, y, and z components in GSE coordinates) were measured by the MAG instrument [*Smith et al.*, 1998], and solar wind bulk speed data by the Solar Wind Electron Proton Alpha Monitor (SWEPAM) instrument [*McComas et al.*, 1998]. Both data sets were obtained from the ACE Science Centre [*Garrad et al.*, 1998] and were originally averaged over 5 min, which we subsequently averaged over 15 min. Interpolation of data gaps was not attempted, so that any period for which data were missing from either the MAG or SWEPAM instruments was disregarded.

[11] Unlike *Gonzalez et al.* [1998], magnetic clouds (or other geoeffective events) were not chosen per se; instead, an "event" was defined as a period of time during which the solar wind magnetic field intensity was above a threshold value for 3 hours or more. A duration of 3 hours was chosen as it has been argued that this is the minimum time required for interplanetary conditions to induce an intense magnetic storm [*Gonzalez et al.*, 1998]. An example is shown in Figure 1, the event defined as being the time when the field intensity exceeds 13 nT for 17 hours. In this example the event boundaries as defined by the 13-nT threshold do not contain the maximum speed associated with the event. Thus a period of 0.5 days before and after these $|B|$ threshold boundaries is taken into account, as this is generally long enough to cover the entirety of an event without sampling large amounts of unassociated solar wind data. (cf. the average size of a magnetic cloud at 1 AU is 0.25 AU; consequently, it passes a stationary spacecraft in $\sim$1 day [*Klein and Burlaga*, 1982]).

3. Results

3.1. General Correlation Trends

[12] A straight-line regression of the form

$$|B|_{\max}\mathrm{nT} = \mathrm{mV}_{\max}\ \mathrm{km/s} + \mathrm{c}. \tag{2}$$

was fitted, and the linear correlation coefficient calculated. The significance of this linear correlation and its robustness to outlying points was tested using the Spearman rank-order correlation coefficient [*Press et al.*, 1989]. Whereas linear correlation compares the absolute values of variables, Spearman correlation compares the rank of a variable within the distribution. Thus Spearman correlation greatly reduces the effect of any outlying points. Furthermore, this nonparametric approach makes no assumptions about the nature of the distribution functions of the variables, meaning the Spearman correlation coefficient is more

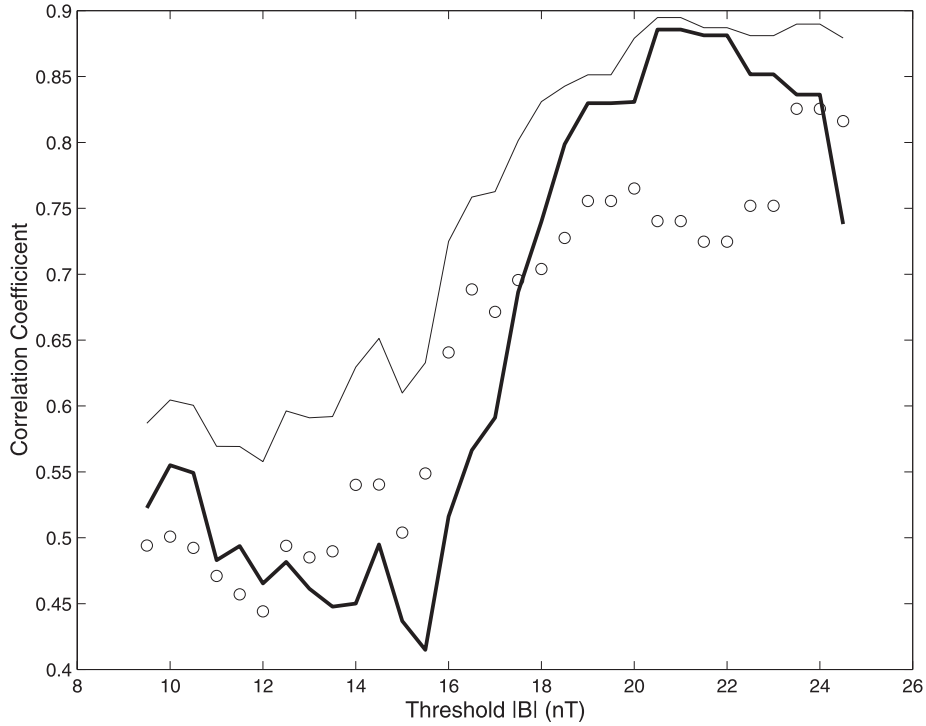

Figure 2. Correlation of maximum magnetic field intensity to maximum speed of events selected by increasing $|B|$ thresholds. For an event to qualify it must have a magnetic field intensity above the required threshold for a period of 3 hours. The thin line shows the linear correlation coefficient, and the heavy line shows the rank-ordered Spearman correlation coefficient. The circles represent the gradient of the $|B|_{\max} - V_{\max}$ scatterplots for events chosen by the $|B|$ threshold. There is a strong association between the gradient of the scatterplots (m in equation (2)) and their correlation coefficients. (Note that the gradient has been scaled up ($\times 15$) so that it can be more easily compared to the correlation coefficients).

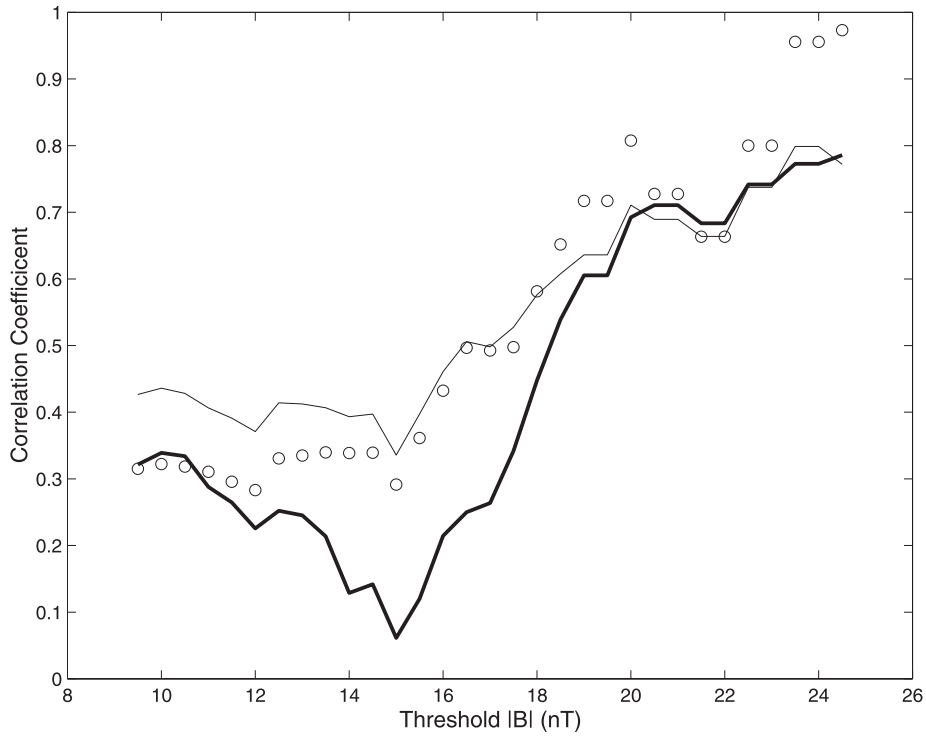

Figure 3. Correlation of the maximum southward magnetic field component to maximum speed of events selected by increasing $|B|$ thresholds. The notation is the same as Figure 2. (Note that the gradient has been scaled up ($\times 15$) so that it can be more easily compared to the correlation coefficients).

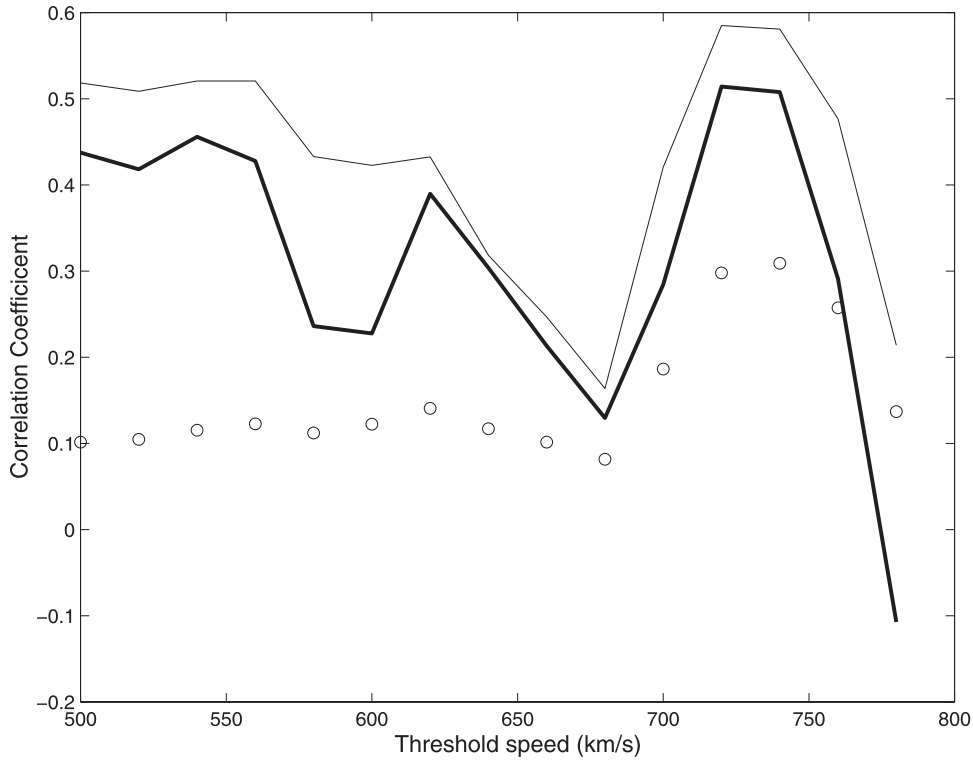

Figure 4. Correlation of maximum magnetic field intensity to maximum speed of events selected by increasing speed thresholds. The notation is the same a Figure 2. (Note that the gradient has been scaled up ($\times 15$) so that it can be more easily compared to the correlation coefficients).

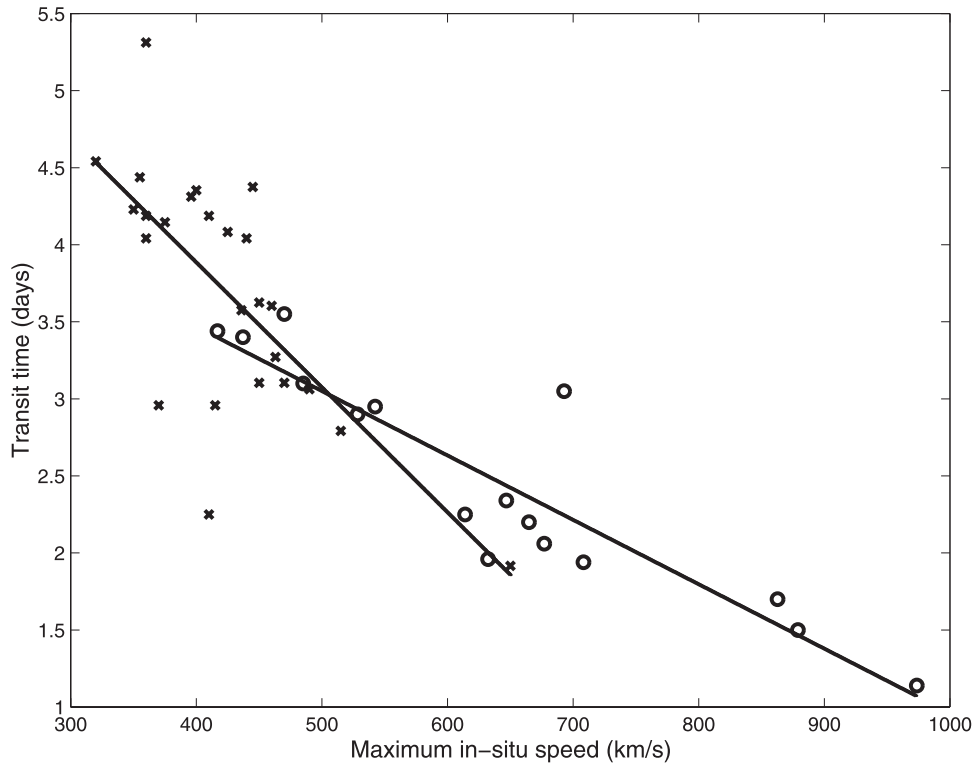

Figure 5. A scatterplot of τ (the time between the observation of a halo coronal mass ejection (CME) by Large-Angle Spectrometric Coronograph (LASCO) and the arrival of the associated event at ACE) to V_{max} (the maximum in situ speed) for the 16 events associated with halo CMEs (open circles). The line of best fit is given by τ (days) = $-0.0042V_{max}$ km/s + 5.14. For comparison, the CMEs studied by *Gopalswany et al.* [2000] are shown as crosses. The line of best fit given by τ (days) = $-0.0081V_{avg}$ km/s + 7.13.

Table 1. Nature of the 24 Events Corresponding to $|B|$ >18 nT for 3 Hours

Event Type	Halo CME Associated	No Halo CME observed	Data Gap
Magnetic cloud	9	1	2
Noncloud event	7	4	1

statistically significant. In this study the linear correlation coefficient is used to quantify the degree of linearity in $|B|_{max} - V_{max}$ relationship, and the Spearman coefficient is used as a measure of the statistical significance and robustness of the correlation.

[13] The degree of correlation between $|B|_{max}$ and V_{max} depends strongly on the magnetic field threshold used to define events. Figure 2 shows how the correlation between $|B|_{max}$ and V_{max} varies for events selected by increasing $|B|$ thresholds. The linear (Spearman) correlation coefficient is shown by the thin (thick) solid line. The gradient of the best fit to the $|B|_{max} - V_{max}$ scatterplot (i.e., m in equation (2)) is shown as the circles in Figure 2, with a scaling factor (see Figure 2 caption).

[14] There is a general trend for events selected by a higher $|B|$ threshold to exhibit an increased level of both linear and Spearman correlation between $|B|_{max}$ and V_{max}. An abrupt increase in correlation occurs for events with selection thresholds of 15 and 18 nT, which is strongly associated with an increase in the gradient (m). Individual $|B|_{max} - V_{max}$ scatterplots reveal that the gradient (m) increase is largely due to the higher $|B|$ threshold values omitting events with high V_{max} but low $|B|_{max}$ (see Discussion). As the threshold is increased still further (i.e., above ~23 nT), the Spearman coefficient decreases owing to a reduction in the robustness of the correlation caused by too few events being selected.

[15] The correlation between the maximum southward magnetic field component of an event and the maximum speed is shown in Figure 3. Again, correlation only becomes significant at higher $|B|$ thresholds but to a lesser extent than the correlation between field magnitude and speed.

[16] Correlation between maximum magnetic field intensity and speed at the point of maximum field intensity gives a similar result to $|B|_{max}$ and V_{max} correlation. Events selected by velocity (rather than $|B|$) thresholds show no significant $|B|_{max}$ and V_{max} correlation, as shown in Figure 4.

3.2. Solar Events Corresponding to High Correlation

[17] The events having $|B| \geq 18$ nT for 3 hours or more (i.e., those events for which the correlation is significant), were cross-referenced with the Large-Angle Spectrometric Coronograph (LASCO) CME list from the SOHO spacecraft (R. Howard and S. Plunkett, Preliminary SOHO LASCO coronal mass ejection list, maintained by SOHO Experimenters' Operations Facility, available at http://lasco-www.nrl.navy.mil/cmelist.html, 2000, hereinafter referred to as Howard and Plunkett, CME List, 2000). Of these 24 events, 16 were associated with halo CMEs leaving the Sun 2 to 4 days prior to the leading edge of the event being arriving at ACE [*Webb et al.*, 2000]. (A coronagraph observation of a full or partial halo CME (typically defined by a span >140°) suggests the

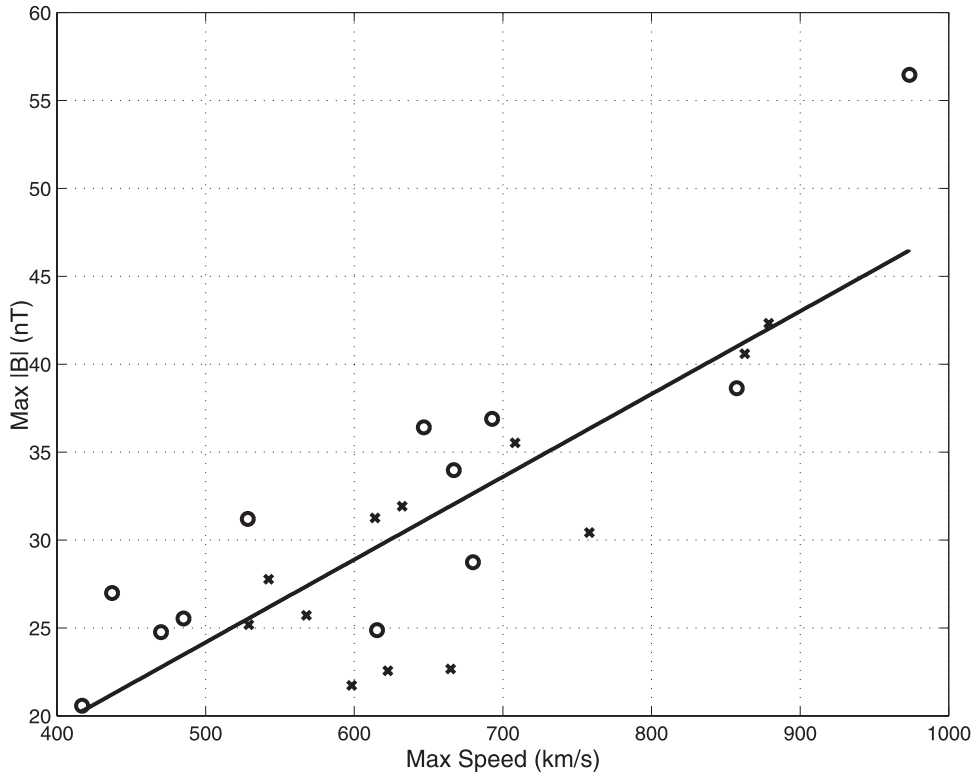

Figure 6. The 24 events corresponding to the selection criterion that gives significant correlation; $|B|$ >18 nT for 3 hours. The open circles indicate the 12 events that had a magnetic cloud-like structure, the 12 events with no field rotation are represented by crosses. The line of best fit is given by $|B|_{max}$ nT = 0.047 V_{max} km/s + 0.644. *Gonzalez et al.* [1998] found a line of best fit of $|B|_{max}$ nT = 0.047 V_{max} km/s − 1.1 for their magnetic cloud selection.

launch of an ejecta close to the Sun-Earth line. Front and back side events can then be differentiated by looking for activity close to the center of the solar disc.) Figure 5 shows the CME transit time from the Sun to 1 AU (τ), plotted against the maximum in situ speed ($V_{\max}$) of the associated ICME. The transit time and average in situ speeds used in the study of *Gopalswany et al.* [2000] are also shown. Note that only two of the events in this study and that of *Gopalswany et al.* [2000] were the same CME due to the small overlap in the periods considered. The difference in the best fits to the $\tau - V_{\max}$ scatterplots is due to the use of different characteristic ICME speeds.

[18] For 5 of the 24 events no halo CME was seen by the LASCO instrument up to 6 days prior to leading edges of the event arriving at ACE. The remaining 3 events occurred during gaps in the SOHO data. (Note that 2 events were possibly connected with faint, partial halo CMEs. The partial halo of 18 October 1999 was included, whereas the CME of 25 January 2000 was rejected owing to its classification as a "probable back side event" (Howard and Plunkett, CME List, 2000).

[19] Inspection of the magnetic and plasma data of these 24 events revealed that 12 showed a significant degree of rotation in the magnetic field direction. Thus 50% could be classified as magnetic cloud-like structures (i.e., a magnetic field rotation and intensity enhancement [*Burlaga et al.*, 1981]. Forty-six percent of events defined by $|B|$ >15 nT had a cloud-like signature). The remaining 12 events had a magnetic field intensity enhancement but no appreciable field rotation and thus could not be considered to be cloud-like structures. Table 1 summarizes these results.

[20] Figure 6 shows the scatterplot of $|B|_{\max}$ versus $V_{\max}$ for the 24 events with $|B| \geq 18$ nT for 3 hours, with the nature of individual events highlighted. The line of best fit is given by

$$|B|_{\max}\text{nT} = 0.047 V_{\max}\ \text{km/s} + 0.644. \quad (3)$$

There does not appear to be any obvious trend between magnetic cloud-like events and events lacking a magnetic field rotation.

4. Discussion and Conclusions

[21] The abrupt increase in the correlation between $|B|_{\max}$ and $V_{\max}$ as the event selection threshold increases poses a limitation on the ability to forecast the IMF on the basis of ICME velocities. For events with $|B|_{\max}$ below 18 nT, the correlation between $|B|_{\max}$ and $V_{\max}$ is probably too weak to lead to useful predictions (see also *Formisano et al.* [1974]). For events with a field intensity exceeding 18 nT for 3 hours or more, predictions may be viable. In addition, the southward magnetic field component also correlates with event speed to a reasonable degree.

[22] The cause of the increased correlation does not appear to be an increase in the number of magnetic clouds (this only increases from 41 to 50%), but the elimination of events where the spacecraft crosses an ICME near its outer edge (i.e., high $V_{\max}$ and lower $|B|_{\max}$). In such cases one might expect the entire ICME and neighboring solar wind to be moving at approximately the same speed, but the field intensity falls off as one moves away from the center (as in the *Burlaga* [1988] flux rope model). These events should also have a shorter transit time past the spacecraft than if it had passed through their center (and hence would not have been selected in the *Gonzalez et al.* [1998] study: see above).

[23] The 24 events that had well-correlated field strength and velocity could not be connected readily with any one class of solar or interplanetary event. The majority were associated with halo CMEs seen by LASCO, and 12 of the 24 could be classified as magnetic cloud-like structures. Hence the $|B|_{\max} - V_{\max}$ correlation is not restricted solely to magnetic clouds but exists for all solar wind events with a high magnetic field intensity (typically above 18 nT). From the viewpoint of solar forecasting the main issue is the detection of potentially geoeffective events that are not immediately associated with halo CMEs.

[24] Whether the relation between field intensity and speed is a manifestation of initiation mechanisms at the Sun or the subsequent transit of events through the solar wind is unclear. The reconfiguration of magnetic structures in the corona is a possible energy source for CME acceleration [*Antiochos et al.*, 1999]. Thus it seems reasonable to assume that larger magnetic structures would have more magnetic energy available for their acceleration. Hence the $|B|_{\max}$ and $V_{\max}$ correlation could be a relic of CME release from the Sun. However, this correlation appears to hold for both cloud and noncloud ICMEs, which may have different initiation mechanisms. Furthermore, the evolution of events from the Sun to 1AU is determined by their speed relative to the solar wind. Hence the transit of CMEs from the Sun to 1 AU must also play a role in the relationship between field intensity and speed, as higher speed events will experience a greater level of compression and have their magnetic field intensity further enhanced. The relative importance of initiation and transit effects has yet to be determined.

[25] There are two sources of high flow speeds in the solar wind; transient ICMEs and quasi-steady fast solar wind emanating from coronal holes. The lack of correlation between $|B|_{\max}$ and $V_{\max}$ for events selected by speed rather than magnetic field intensity thresholds suggests that these two sources have very different relationships between field intensity and speed.

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