Decay of interplanetary coronal mass ejections and Forbush decrease recovery times

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[1]   We investigate the relation between Forbush cosmic ray decrease recovery time and coronal mass ejection transit time between the Sun and Earth. We identify 17 Forbush decreases from ground-based neutron count rates between 1978 and 2003 that occur during the same phase in the solar cycle and can be associated with single coronal mass ejections (CMEs) in the SOHO LASCO CME Catalog or previously published reports and with specific interplanetary coronal mass ejections (ICMEs) crossing the vicinity of Earth. We find an anticorrelation between Forbush recovery times and CME transit time that contradicts the predictions of simple cosmic ray diffusive barrier models. The anticorrelation suggests that the decay rate of ICMEs is anticorrelated with their travel speed. Forbush recovery times range from seven times the transit time for the fastest disturbance to a fifth the Sun-Earth transit time for the slowest. To account for the large range of measured recovery times, we infer that the slowest disturbances must decay rapidly with radius, whereas the fastest ones must remain strong. The longest recovery times suggest that the fastest disturbances in our sample decayed less rapidly with radius than the ambient solar wind magnetic field strength.

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1.   Introduction

[2]   Forbush decreases are transient depressions in the galactic cosmic ray intensity which are characterized by a sudden onset, reaching a minimum within about a day, followed by a more gradual recovery phase typically lasting several days. Though originally thought to be associated with geomagnetic storms [*Forbush*, 1937], it is now known from spacecraft measurements that Forbush decreases are also observed distant from planets and so are present in the interplanetary medium [*Webber et al.*, 1986, 2002]. These decreases are most likely produced by perturbations in the interplanetary magnetic field and particle flow which propagate away from the Sun [e.g., *Morrison*, 1956; *Parker*, 1963].

[3]   Variations in the local cosmic ray distribution can be predicted from a time dependent model of the transport of galactic cosmic rays in the heliosphere [*Parker*, 1965]. The reduced flux of galactic cosmic rays in the vicinity of an interplanetary disturbance could be due to a variety of physical factors, related to different terms in the cosmic ray transport equation [*Parker*, 1965]. An enhanced solar wind speed leads to increased advection, whereas variations in the magnetic field topology, strength, or/and irregularities lead to differences in the diffusion and drift rates. Some models have focused on enhanced drift [e.g., *Cheng et al.*, 1990; *Rana et al.*, 1996] while others have concentrated on diffusive or scattering models [e.g., *Lockwood et al.*, 1986; *Webber et al.*, 1986; *Wibberenz and Cane*, 2000; *Chih and Lee*, 1986; *Badruddin*, 2002]. For an overview, see *le Roux and Potgieter* [1991]. Both drift and scattering mechanisms suggest that the magnitude of a Forbush minimum is proportional to the magnetic field strength and irregularities in the associated interplanetary disturbance.

[4]   Galactic cosmic ray decreases are often associated with coronal mass ejections (CMEs) and their associated interplanetary counterparts, interplanetary coronal mass ejections (ICMEs) [*Cane et al.*, 1996, 1997; *Cane*, 2000]. *Cane et al.* [1996] studied 30 years of neutron monitor data and found 86% of cosmic ray decreases to be attributable to CMEs. *Cane et al.* [1997] have associated CME ejecta with short-term particle decreases observed by Helios 1 and 2.

[5]   The observed depth of a Forbush event is found to depend on one's trajectory through the ICME [*Cane et al.*, 1996]. Since forward shocks are wider than the driving ejecta, it is possible to pass through a shock but not intercept the CME ejecta. Forbush decreases are generally of lesser magnitude when only the forward shock is present [*Cane et al.*, 1996]. *Cane et al.* [1996] also found that the depth of a Forbush decrease is dependent on the heliolongitude of the active region which ejected the associated CME. The depth is largest when the associated CME originates near solar meridian, and the vast majority of Forbush events are caused by CMEs originating within 50 degrees of 0 degrees heliolongitude [*Cane et al.*, 1996]. Chromospheric events more than 50 degrees from the solar meridian are rarely associated with ICMEs at the Earth [*Cane and Richardson*, 2003].

[6] Following the passage of an interplanetary disturbance which causes a Forbush decrease, the cosmic ray flux slowly recovers to its initial level. We refer to the timescale over which the cosmic ray flux recovers as the Forbush recovery time, t_{recov}. The Forbush recovery time could depend on a number of factors, including the decay rate and speed of the ICME, the angular size of the ICME, and the properties of the ambient solar wind [*Lockwood et al.*, 1986; *Chih and Lee*, 1986; *le Roux and Potgieter*, 1991]. Because the cosmic ray flux at Earth is dependent upon the strength of the ICME after it passes the Earth, it may provide a unique way to probe the structure of ICMEs at radial locations where we lack spacecraft.

[7] The recent availability of data measured from space-born observatories allows better constraints on many of these factors. LASCO on board SOHO has allowed the measurements of CME ejection speed, acceleration, size, and location at the Sun. Recent measurements of CMEs have been compiled by Seiji Yashiro and Grzegorz Michalek and made available in the SOHO LASCO CME Catalog (http://cdaw.gsfc.nasa.gov/CME_list/); for details see *Zhao and Webb* [2003] and *Yashiro et al.* [2004]. The Wind and ACE spacecraft allow measurements of gas density and magnetic field vector as a function of time as the ICME crosses the vicinity of Earth. To compliment the information available on ICMEs are real time measurements of the Galactic cosmic ray flux as measured from the ground. For example, the Moscow Neutron Monitor provides online (http://cr0.izmiran.rssi.ru/mosc/main.htm) pressure-corrected neutron hourly and per minute counts since 1958. The rich diversity of modern data allows for the accurate identification of CME-ICME pairs and measurement of their Sun to Earth transit times. This information can be used to constrain models of Forbush decreases.

[8] In this paper we compile a list of Forbush events associated with CMEs that have well-identified ICME counterparts at the location of Earth. We combine information on these three components to probe the relation between ICME transit speed, Forbush size and recovery time, and ICME decay. In section 2 we describe our procedure for obtaining a sample of Forbush events with well-associated CME-ICME pairs and the data collected regarding these events, including a description of the procedure used to measure recovery times. In section 3 we describe our observations of the Forbush recovery time's dependence on transit speed. Section 4 summarizes and discusses models for the observed correlation.

2. Forbush Decreases and Associated CME and ICME Sample

[9] Our goal is to find a sample of isolated Forbush events with well-identified corresponding CMEs and ICMEs. Finding a large sample for this study is difficult because it is necessary to find correspondence between three independent sets of observations. Solar events identified at the Sun (e.g., by SOHO) must be related to ICMEs detected at Earth (e.g., by ACE, Wind, or GOES). Our CME-ICME associations were taken from published studies by *Cane et al.* [1996], *Sheeley et al.* [1985], *Lindsay et al.* [1999], and *Fry et al.* [2003]. These events must in turn correspond with Forbush events detected by ground-based
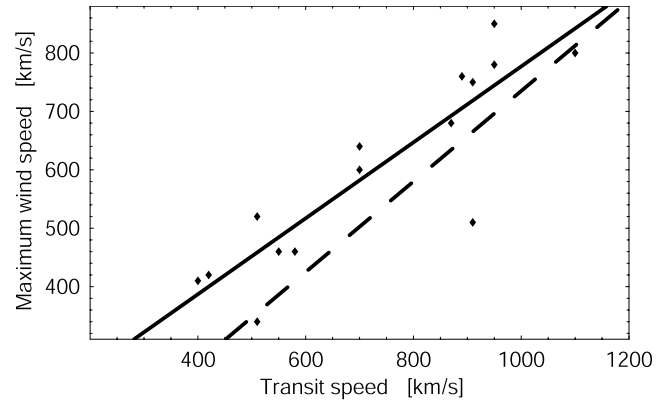

Figure 1. Maximum solar wind speed flow versus shock transit speed for events 1 and 3–16. Solar wind speed data was not available for events 2 and 17. The solid line is the least squares fit to the data. The dashed line is the empirical relation obtained by *Cliver et al.* [1990]. The close agreement of the data and the empirical relation supports the validity of the CME-ICME associations.

neutron or/and muon monitors. The Forbush decreases must be sufficiently deep and isolated to allow a good measurement of the recovery time.

[10] A primary reason for the relatively small size of our sample is that we only selected events for which the Sun-Earth link has been verified by several independent parameters. For events 1–7 of our sample, the CME-ICME pairs were identified and associated with Forbush events by *Cane et al.* [1996]. They identified ICMEs primarily based on in situ measurements of plasma temperature and models relating the plasma temperature to the solar wind flow speed [*Richardson and Cane*, 1995]. For these seven ICMEs, they found the associated solar event (i.e., a fast, massive CME) based on the rapid onset of solar particles at the time of a solar flare event.

[11] For events 8–12, 14, and 15, the CME-ICME associations were first reported by *Gopalswamy et al.* [2001]. They used Wind spacecraft data to identify ICMEs and then examined SOHO LASCO images of all CMEs from up to 5 days before the ICME arrival. SOHO/EIT, Yohkok/SXT, and optical observations were used to eliminate the backside events (*Gopalswamy et al.* [2000]). This allowed identification of a unique source CME for each ICME.

[12] For events 13 and 16, the associations were made by *Cho et al.* [2003]. They applied an ensemble of shock propagation models to CMEs and found a unique ICME in the threshold window for each CME.

[13] For event 17, the CME-ICME association was recently reported by *Bieber et al.* [2005] with high confidence, based on X-ray and energetic particle data from multiple spacecraft and neutron monitors throughout the time of the event.

[14] *Cliver et al.* [1990] obtained an empirical relation between the Sun-Earth transit speed of interplanetary disturbances and the maximum solar wind flow speed at the time of the ICME at 1 AU. In Figure 1, we compare the transit speeds and solar wind speeds for events 1 and 3–16 with the empirical prediction of *Cliver et al.* [1990]. Solar

Table 1. CME-ICME Pairs and Related Forbush Events[a]

	CME			ICME			Forbush Event			
	Time			Arrival			Onset			
Event	Date	UT	Position, deg.	Date	UT	$t_{transit}$, hours	Date	UT	Decrease, %	t_{recov}, hours
1	1978 Jan 1	2200	21S 06E	1978 Jan 3	2100	47	1978 Jan 4	0700	4	91
2	1978 Apr 8	0200	19N 11W	1978 Apr 10	1300	59	1978 Apr 10	2200	6	89
3	1978 May 31	1100	20N 43W	1978 June 2	0900	46	1978 June 2	1500	6	120
4	1978 Nov 10	0100	17N 01E	1978 Nov 12	0100	48	1978 Nov 12	0400	5	120
5	1989 Mar 23	2000	18N 28W	1989 Mar 27	0000	76	1989 Mar 27	0000	4	41
6	1989 May 5	0800	30N 04E	1989 May 7	0600	46	1989 May 7	0900	3	27
7	1989 Nov 26	1800	25N 03W	1989 Nov 28	0800	38	1989 Nov 28	1200	9	84
8	1997 Aug 30	0200	30N 17E	1997 Sept 3	1200	106	1997 Sep 3	1200	2	20
9	1997 Nov 4	0600	14S 33W	1997 Nov 7	0600	72	1997 Nov 7	0600	3	37
10	1997 Nov 19	1200	. . .	1997 Nov 22	2100	81	1997 Nov 22	2100	4	48
11	1998 Jan 2	2300	47N 03W	1998 Jan 7	0300	100	1998 Jan 7	1200	2	20
12	1998 Nov 5	2100	22N 18W	1998 Nov 8	0900	60	1998 Nov 8	1400	5	66
13	1999 June 22	1900	. . .	1999 June 26	0500	82	1999 June 26	1900	3	24
14	2000 Feb 10	0300	27N 01E	2000 Feb 12	1500	60	2000 Feb 12	1500	4	92
15	2000 June 6	1600	21N 15E	2000 June 8	1200	44	2000 June 8	1400	6	120
16	2000 Sep 16	0500	. . .	2000 Sep 18	0100	44	2000 Sep 17	0400	7	90
17	2003 Oct 28	1100	16S 08E	2003 Oct 29	0800	21	2003 Oct 29	1200	21	150

[a]CME-ICME pairs and associated Forbush events. Under the CME header are listed the date and time of the CME's first appearance in the LASCO chronograph aboard SOHO and the heliographic latitude and longitude of the associated source regions. Under the ICME header is the ICME's time of arrival at the L1 Lagrange point (events 8–17) or when this is unknown, the time of geomagnetic storm sudden commencement is used, which is a proxy for the shock passage (events 1–7). Net transit time, $t_{transit}$, is simply the difference of the first appearance and arrival times listed previously. CME and ICME arrival times are taken from listings by *Gopalswamy* [2001], *Cho et al.* [2003], and *Cane et al.* [1996], or in the case of event 11 from *Skoug et al.* [2004]. Under the Forbush event header is the onset time of the second step Forbush decrease at Earth, a proxy for the ICME arrival, and our measurements of the events' depths and recovery times, t_{recov}, at 1 AU using neutron fluxes measured by the ground-based Moscow Neutron Monitor.

wind speeds were not available for events 2 and 17. All of the events plotted in Figure 1 fall within the scatter of the *Cliver et al.* [1990] relation. The agreement of our sample with the *Cliver et al.* [1990] data strengthens our confidence in the CME-ICME associations. Solar wind speed measurements are from the IMP8 spacecraft (events 1, 3–9, and 11–14), or when IMP8 data is unavailable, from Wind (event 10) and ACE (events 12, 15, and 16).

[15] As a result, we can find only from zero to four Forbush events each year suitable for analysis. We limited our data to a particular phase in the solar cycle, specifically, we searched for events from 3-year periods at the start of maxima in the 11-year solar cycle, from 1997–2000, 1986–1989, and 1975–1978. The solar cycle modulates the GCR distribution, perturbs the heliosphere, and causes structural changes in CMEs. For example, during solar maximum the average solar wind speed is lower and the average kinetic energy flux in the solar wind is as much as 80% higher [*Kallenrode*, 1998]. *Cane and Richardson* [2003] has shown that on average, the magnetic fields of ICMEs have a more well-organized structure at solar minimum.

[16] To identify a suitable sample of events, we studied the set of 57 ICME-CME pairs from 24 December 1996 to 9 October 2000, identified in previous studies by *Gopalswamy et al.* [2001] and *Cho et al.* [2003], and added to this a subset of the list tabulated by *Cane et al.* [1996] containing 180 Forbush events occurring during the years 1964–1994.

[17] We investigated the 57 ICME-CME pairs identified by *Gopalswamy et al.* [2001] and *Cho et al.* [2003] for associated Forbush events. We discarded those ICME-CME pairs that were not coincident with Forbush decreases in the neutron count rates measured by the Moscow Neutron Monitor. We used magnetic field and solar wind measure-

ments from the ACE spacecraft to guarantee that the ICME was separated from other significant disturbances by more than 24 hours. When a Forbush event was coincident with arrival of the ICME, we required that the Forbush event also be isolated in time. This criterion nearly always applied since there are typically only 1–2 significant (depth >1.5%) Forbush events each month. When overlaps do occur, they are clearly visible in the neutron monitor data and we are confident they have not been introduced into our sample.

[18] The arrival times of ICME shocks at Earth are known to high accuracy (with uncertainty less than 2 hours). When an ICME results in a Forbush event, the Forbush event commences within ~10 hours of the ICME's arrival at Earth [*Cane et al.*, 1996]. Since this is much shorter than the timescale between occurrences of ICMEs and Forbush events, we have a high level of confidence in the validity of our associations of individual ICMEs and Forbush events. If the Forbush decrease is extremely shallow compared to diurnal variations then measuring the recovery time becomes difficult. Consequently, we discarded from our study Forbush events with decrease depths less than 1.5%.

[19] Of the 57 ICME-CME pairs identified by *Gopalswamy et al.* [2001] and *Cho et al.* [2003], only 22 were found to coincide with Forbush decreases. Only nine of these Forbush decreases are above 1.5% in depth and sufficiently isolated in time. These 9 events are listed in Table 1 (events 8–16).

[20] To expand our sample, we added seven events from the list of cosmic ray decreases compiled by *Cane et al.* [1996]. We searched this list for Forbush events satisfying our suitability criterion over the years 1975–1978 and 1986–1989, years which correspond to the same phase in the solar cycle as the period 1997–2000 investigated by *Cho et al.* [2003] and *Gopalswamy et al.* [2001]. Out of the

12 cosmic ray decreases listed for these years, we found seven acceptable Forbush decreases. In addition to this sample we have added the great "Halloween" Forbush event of 29 October 2003 because of its extreme properties.

[21] To distinguish between the different parts of each CME-ICME-Forbush event, the information in Table 1 is separated into three groups. For events 1–16 the first appearance times of the CMEs are those reported by *Gopalswamy et al.* [2001], *Cho et al.* [2003], and *Cane et al.* [1996] based on either the LASCO coronagraph aboard SOHO [*Gopalswamy et al.*, 2001; *Cho et al.*, 2003] or else Solar-Geophysical Data [*Cane et al.*, 1996]. For event 17, the appearance time is taken from the online SOHO LASCO CME Catalog. Also under this header we include the heliographic coordinates of the solar source region, whenever an accepted position is available. The source positions are determined by relating the time of a solar flare to the commencement of a low-energy (<200 MeV) particle event detected by near-Earth spacecraft [see, e.g., *Cane et al.*, 1996]. Three events in our sample are not associated with a flare or known filament disappearance and thus their source positions are unknown. In each case where a source position is available, we find the origin is close to disk center; the average distance from the solar equator is 23 degrees and the average solar longitude is 14 degrees. This agrees with the fact that two steps (shock plus driver) were observed for each event in our sample (see below).

[22] Data on the associated ICMEs are grouped in the second part of Table 1. We list the arrival time of each ICME at the L1 Lagrange point and then the net transit time from the Sun to the L1 point ($t_{transit}$). For events 1–7, the ACE and Wind spacecraft were not available to detect the ICME's arrival at L1. Thus the estimate of their arrival times is taken to be the sudden commencement of a geomagnetic storm, as reported by *Cane et al.* [1996]. Since these storms often correspond to the arrival of the ICME shock rather than the ejecta, this can lead to an error of up to 12 hours in the transit time [*Gopalswamy et al.*, 2003]. However, given the very good agreement of both our data sets (see Figure 3), the actually error in the transit times is probably much less than this. Also, the fact that both shock and ejecta are present for all the events in our sample (see below) eliminates much of the potential for inconsistent measurements and further reduces error in $t_{transit}$.

[23] For events 8–16, the ICME L1 arrival times have been measured directly in previous studies using solar wind and magnetic field measurements from ACE and Wind spacecraft at L1 [*Gopalswamy et al.*, 2001; *Cho et al.*, 2003]. Recently, *Skoug et al.* [2004] determined the ICME L1 arrival time for event 17 based on measurements of counterstreaming suprathermal electrons, low proton temperatures, enhanced He^{++}/H^+ density ratios, and smooth rotations of the magnetic field.

[24] In the last two columns of Table 1 we list the depth and recovery times of the associated Forbush events. We measured the relative depths of the Forbush decreases using pressure corrected cosmic ray count rates from the Moscow Neutron Monitor. This percentage is the ratio of the minimum cosmic ray flux compared with the average over a period of a few days preceding the event. The uncertainty in the measured depth is less than 1%. This corresponds approximately to the level caused by diurnal variations in the count rate. We

also used the neutron count rate to measure the recovery times of the 17 Forbush events listed in Table 1. To do this, we fit exponentials of the form $\exp(-t/t_{recov})$ to their recovery phases. The best-fitting exponentials to the 17 events in our sample are shown in Figures 2 and 3.

[25] Recovery time measurement errors are caused by diurnal variations in the cosmic ray flux, noise in the count rate, precursors, and slow increases or decreases in the count rate which lead to differences between the mean count rate before and after the decrease. To reduce errors caused by diurnal variations, we removed a characteristic diurnal variation from the time series before we fit an exponential to the recovery phase. We assumed a sinusoidal oscillation with an amplitude given by the mean diurnal fluctuation during a month of undisturbed conditions. This month of background data was chosen separately for each event because the magnitude of the diurnal variation changes during the year and from year to year. However, even after the correction is performed, diurnal effects persist in many cases. This is in agreement with previous studies which have found that the amplitude of the diurnal variation is often higher during periods of enhanced solar activity [*Lockwood*, 1971; *Duggal and Pomerantz*, 1976; *Nagashima et al.*, 1992]. The recovery time of the most unusual data point, event 6, is probably incorrect because variations in the cosmic ray rate before and after this event are about half the size of the Forbush decrease itself, making it difficult to measure the depth of the event accurately.

[26] To fit the recovery phase, we used hourly averaged cosmic ray counts for most of the events. To improve the quality of the fit for events 1–4, 6–8, and 11, we fit the recovery phase using data averaged over 2-hour intervals.

[27] Forbush events are often preceded by strong enhancements in the cosmic ray anisotropy [*Lockwood*, 1971; *Duggal and Pomerantz*, 1976; *Nagashima et al.*, 1992], which increases the difficulty of measuring the steady preevent level. To minimize these uncertainties, we estimated the steady count rate from the average cosmic intensity over several undisturbed days preceding and following the Forbush event. Events 10 and 13 occur during prolonged and slow increases in the cosmic ray flux, and so we subtracted baseline count rates from both events before fitting the recovery phase. In these cases the baseline was assumed to be a straight line and was determined from the cosmic ray count rate using the days preceding and following the Forbush event. Extremely long recoveries are sometimes interrupted by other decreases. In such cases only the uninterrupted data has been used for fitting an exponential.

[28] To estimate the uncertainty of our recovery time measurement, we artificially created data sets of a decrease with size and noise variance similar to that of our weakest event, event 8. We then applied our fitting procedure to these simulated data sets. Taking into account our fitting process, we estimate that the net uncertainty in our measured recovery times t_{recov} is approximately 20%. We find that the largest source of error is caused by slow variations in the mean neutron monitor count rate.

[29] The range of depths (2–21%) and recovery times (1–7 days) we measured is consistent with those measured by previous studies [*Lockwood et al.*, 1986; *Cane et al.*, 1996]. From Table 1 it is evident that the Forbush events in
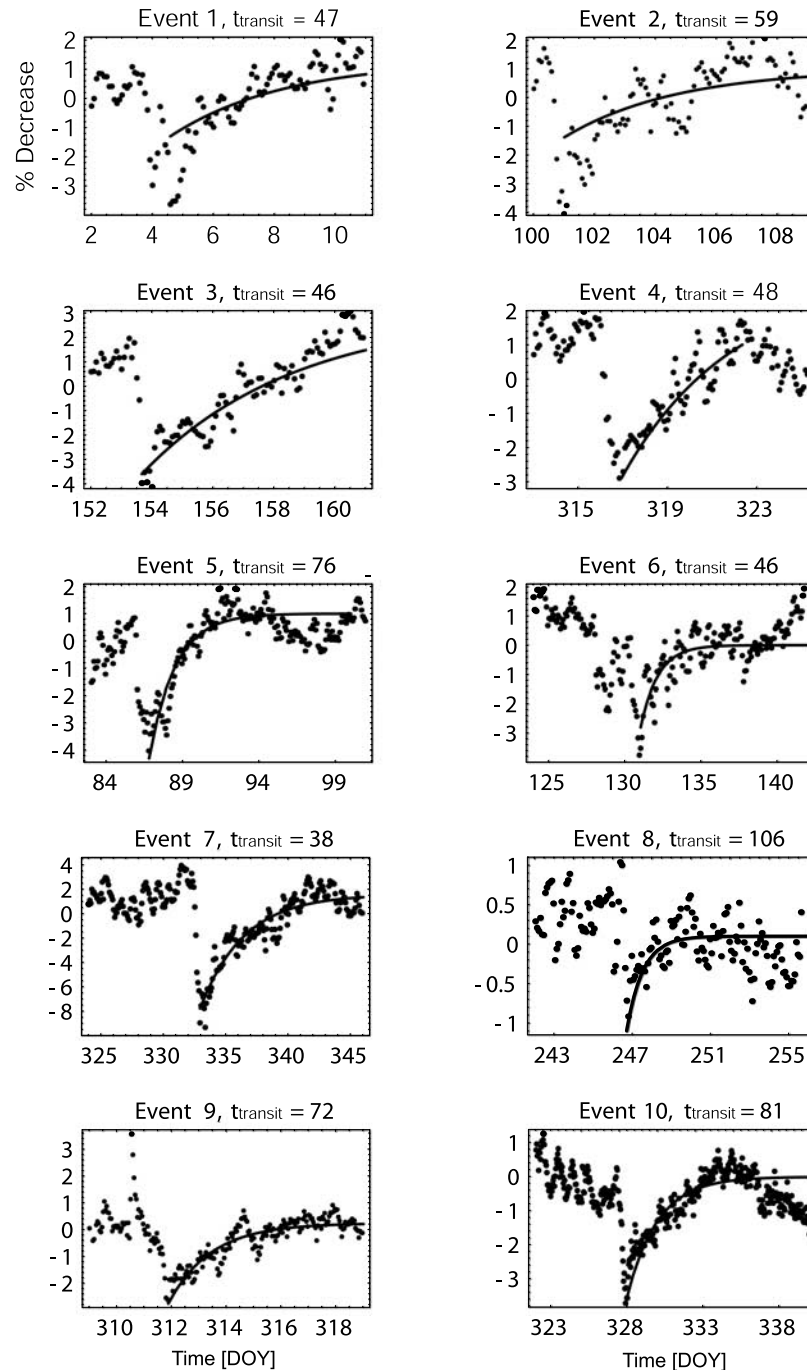
Figure 2. Neutron monitor cosmic ray counts (% decrease) as a function of time for events 1–10 of our sample. The best fit exponentials to the recovery phases of the Forbush events are also shown. As can be seen, Forbush events associated with fast ICMEs (short transit times) tend to recover slowly.

our sample with shorter recovery times tend to have smaller decreases and shorter transit times. Even for small or weak decreases of depth ~2% (such as events 8 and 11 in Table 1), the recovery phases remain nearly exponential and are distinguishable from noise, diurnal, and slow variations in the mean count rate. Events with moderate depths, such as events 1, 5, 10, and 14 which have depths of 4%, can show either fast (~27 hours) or slow recovery times (~92 hours). We infer that the fast recovery times

measured are likely to be real and not an artifact due to poor measurement of weak Forbush events.

[30] Previous observational studies have shown that the depth of the Forbush event is dependent on the magnetic field strength [*Cane et al.*, 1996]. Theoretical studies suggest that the depth is also dependent on turbulence in the associated ICME and the ICME's width. Recovery times on the other hand, are expected to be independent of event width and magnetic field strength during the event. Recov-
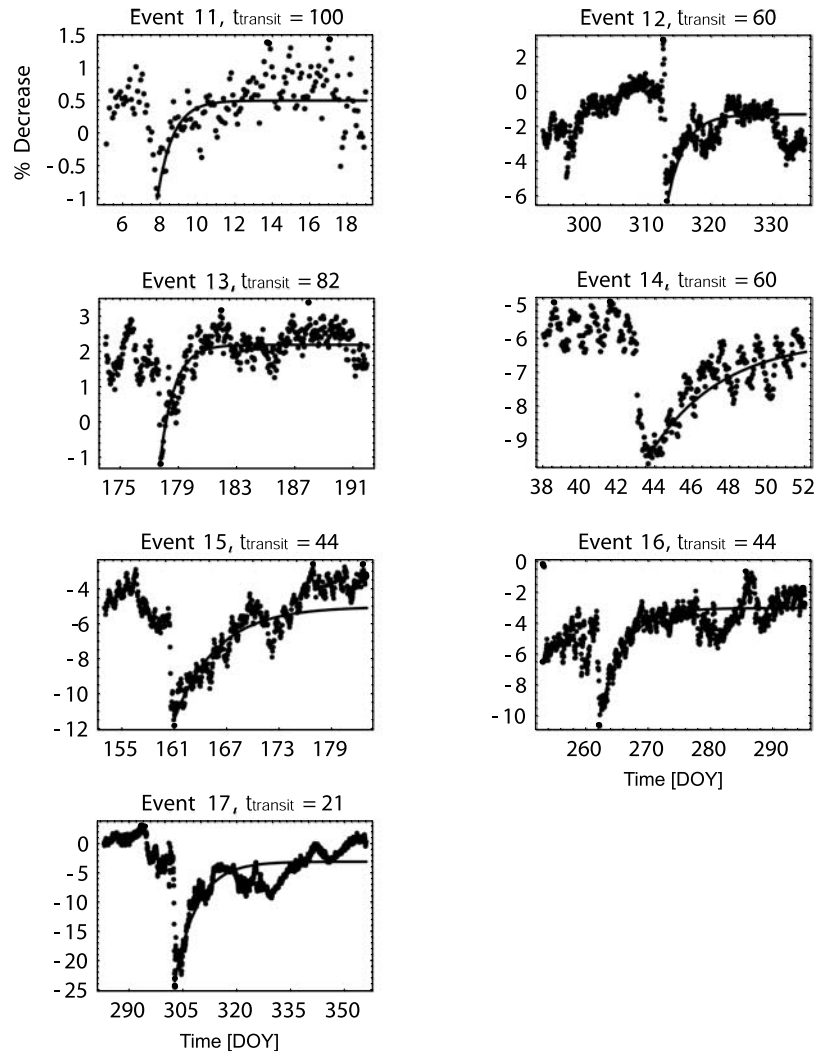
Figure 3. Neutron monitor cosmic ray counts (% decrease) as a function of time for events 11–17 of our sample. The best fit exponentials to the recovery phases of the Forbush events are also shown. As can be seen, Forbush events associated with fast ICMEs (short transit times) tend to recover slowly.

ery times are expected to only depend on the decay and speed of the ICME after it passes the Earth [e.g., *le Roux and Potgieter*, 1991]. Even though the fast events tend to be stronger (have larger depths), our sample can be used to probe how Forbush events recover. We note that the previous studies by *Cane et al.* [1996] found a correlation between transit time and Forbush decrease depth [*Cane et al.*, 1996], a correlation which we confirm here. Faster ICMEs (those with shorter transit times) tend to produce stronger or deeper Forbush decreases.

[31] It is well known that most Forbush decreases occur in two steps, the first decrease starting at the shock and the second step occurring with arrival of the magnetic cloud [e.g., *Ifedili*, 2004; *Cane et al.*, 1996; *Lockwood*, 1971]. For all 17 decreases in our sample both shock and magnetic cloud are present. For events 1–7 this was known previously [*Cane et al.*, 1996], whereas for events 8–17 we have made this determination with solar wind and magnetic field measurements from the ACE spacecraft. Recovery time is measured from the end of the complete two-step decrease.

Since the two-step effect is the same for all 17 events in our sample, it does not affect recovery time comparisons.

3. Relation Between Forbush Decrease Recovery Time and CME Size and ICME Transit Time

[32] Diffusive barrier models for Forbush events suggest that slower traveling ICMEs will have longer recovery times. The more distant the diffusive barrier, the more limited effect we would expect on the Galactic cosmic ray flux [e.g., *le Roux and Potgieter*, 1991]. In Figure 4 we plot the Forbush decrease recovery times versus the transit times for the events listed in Table 1. Contrary to what we had expected, fast traveling ICMEs seem to cause Forbush events that have longer recoveries than those caused by slow traveling ICMEs. The Spearman rank coefficient for this correlation is −0.73, which gives a significance level of better than 1%.

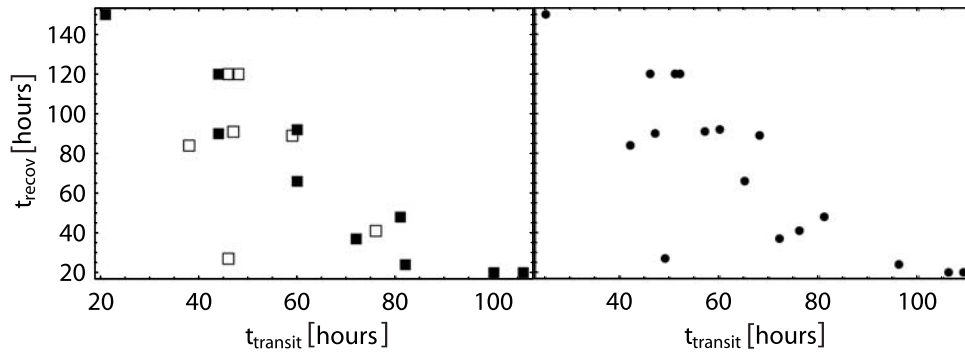[33] As discussed in section 2, even though the slower events tend to be weaker (with shallower Forbush

Figure 4. Forbush event recovery time versus the transit time of the associated ICME. In the left panel, solid squares are events for which the ICME arrival time at L1 was known [e.g., *Gopalswamy et al.*, 2001; *Cho et al.*, 2003; *Skoug et al.*, 2004] and in this case the transit time has an uncertainty of a few hours (events 8–17). White squares are events for which the arrival time of the ICME at L1 is unknown (events 1–7). In this case the time of a geomagnetic storm sudden commencement is used instead, and the error is at most 12 hours [*Gopalswamy et al.*, 2001]. The close agreement of both data sets suggests the error is in fact much less than this. The storm commencement is a proxy for the shock passage; thus the white squares are biased to the left. In the right panel we took the arrival time of the ICME to be the onset of the second step Forbush decrease at Earth. In both panels, there is a clear anticorrelation between ICME's velocity and the recovery time of the associated Forbush decrease. The uncertainty in the recovery time is about 20%. Note that the range of recovery times is large, ranging between 5 times and 1/4 to 1/5 times the transit times. Models predict that the recovery time should be proportional to the transit time, contrary to the trend shown here.

decreases) and so noisier, we are confident that their recovery times are indeed short. The recovery timescales of six events are less than 2 days long, but the magnitude of four of these decreases is at least 3%, large enough that the measurement of the recovery time is likely to be truly short and not a result of measurement errors caused by random variations in the neutron rate or diurnal variations.

[34] While Figure 4 shows a statistically significant anticorrelation between recovery time and transit time, it must be kept in mind that the fast events in our necessarily small sample tend to have larger Forbush decreases and higher magnetic fields. Nevertheless, we do find pairs of events that have similar depths but very different recovery times. For example, events 13 and 14 have similar depths (3.5%). However, event 13 has a fairly short recovery time of 24 hours, whereas event 14 has a much longer recovery time of 92 hours. Even though these two events have similar depths, their transit times also differ, and the one with the longest transit time also has the shortest recovery time. Event 13 has a transit time of 82 hours, whereas event 14 has a transit time of 61 hours. Events 12 and 15 have similar depths of 5% and 6.4% and recovery times of 66 and 120 hours, respectively. Again the largest transit time corresponds to the longest recovery time.

[35] We have displayed Figure 4 so that Forbush recovery times can be directly compared with transit times. We can see from the figure that the slow events have recovery times that are as short as 1/5th their transit times, whereas the fastest events have recovery times that are up to 7 times longer than their transit times. In the following section we discuss the anticorrelation shown in Figure 4 and the range of recovery times covered in this

plot in the context of simple diffusive barrier models for Forbush events.

4. Discussion of Recovery Times

[36] Within the context of diffusive barrier models, the recovery time, t_{recov}, of a Forbush event could depend on a number of factors including (1) the decay rate of the propagating disturbance; (2) the radial gradient of the radial component of the cosmic ray diffusion coefficient; (3) the velocity of the ICME as it crosses Earth's orbit, V_s; (4) the angular size of the ICME; (5) the deceleration rate of the ICME after it crosses Earth's orbit. The recovery time's dependence on the first three factors were explored and discussed theoretically by *le Roux and Potgieter* [1991]. One-dimensional analytical advection diffusion models were explored by *Chih and Lee* [1986]. Recent work has shown that fast ICMEs decelerate due to their interaction with the ambient solar wind [*Gopalswamy et al.*, 2000, 2001; *Wang et al.*, 2001]. However, the extent that this deceleration affects Forbush recovery times has not yet been explored.

[37] Neglecting drift, but taking into account advection with the solar wind and diffusion, using a one-dimensional radial approximation, and neglecting energy changes in the particles, the cosmic ray transport equation can be approximated by an advection-diffusion equation

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial r}\left(K\frac{\partial N}{\partial r} - VN\right) \qquad (1)$$

[*Chih and Lee*, 1986], where $N(r, t)$ is the number density of the cosmic ray particles and V is the speed of the solar wind. We can consider a propagating magnetic disturbance as a

traveling perturbation in the radial diffusion coefficient $K(r, t)$. The radial dependence of the diffusion coefficient sets the steady state solution for the cosmic ray number density. We expect the steady state value of the number density to be only weakly dependent on radius at rigidities typical of galactic cosmic rays responsible for producing neutrons detected on Earth (~10 GV). The weak radial gradient in the number density is consistent with observations of the cosmic ray flux at somewhat lower rigidities from spacecraft at different radii in the heliosphere [*Webb and Lockwood*, 1986].

[38] As discussed by *le Roux and Potgieter* [1991], the drop in the cosmic ray flux during a Forbush event is approximately

$$\frac{\Delta j}{j} \sim \frac{VW}{K} \frac{\Delta K}{K}, \tag{2}$$

where W is the radial width of the disturbance and ΔK is the change in the diffusion coefficient during the disturbance.

[39] By assuming that the local cosmic ray flux as a function of time is related to the drop in the cosmic ray number density at the location of the disturbance, we can use equation (1) to estimate the Forbush recovery time at Earth [e.g., *le Roux and Potgieter*, 1991]. We denote the drop in cosmic ray flux at Earth (at radius r_1) due to an ICME at time t_1 by $\Delta j_1/j_1$. The recovery time is then approximately $t_{recov} \sim t_2 - t_1$, where t_2 is the time at which the event reaches r_2 and the drop in cosmic ray flux at that radius $\Delta j_2/j_2$ is $e^{-1} \sim 1/3$ times that measured at Earth. It is convenient to define an amplitude $A(t) = WV\Delta K/K$, which would determine the depth of the cosmic ray flux decrease if the ambient diffusion coefficient were not dependent on radius. This amplitude would be constant if the width of the event did not change in time and if the diffusion coefficient ΔK in the disturbance dropped with radius in the same way as the ambient diffusion coefficient K.

[40] The recovery time can be estimated from the condition

$$3A(r_2, t_2)/K(r_2) \approx A(r_1, t_1)/K(r_1). \tag{3}$$

We expect that the mean diffusion coefficient is inversely proportional to the mean magnetic field in the solar wind. Assuming that the magnetic field strength drops with radius as the solar wind density decreases, we expect $K(r) \propto r^\alpha$. Voyager observations of the solar wind magnetic field imply that $B_r \propto r^{-2}$ and variations $\Delta B/|B|$ are nearly constant [e.g., *Burlaga and Ness*, 1998]. From this scaling we expect $\alpha \sim 2$. We assume a constant velocity for the ICME, $r_2 - r_1 \sim V_s (t_2 - t_1)$, and an amplitude that drops exponentially with time $A(t) \propto e^{-t/t_{decay}}$. We remind the reader that this amplitude depends on the width of the disturbance, the speed of the solar wind and the ratio of the change in the diffusion coefficient in the disturbance divided by the ambient diffusion coefficient. We have described the decay of the disturbance as a function of time in terms of one parameter, t_{decay}. Using the above assumptions, we find

$$3e^{-\frac{t_{recov}}{t_{decay}}} = \left(1 + \frac{t_{recov}}{t_{transit}}\right)^\alpha, \tag{4}$$

where the transit time $t_{transit} = r_1/V_s$ is the ICME travel time between the Sun and Earth. This equation relates the observed quantities shown in Figure 4 and depends only on the decay rate of the ICME (t_{decay}) and on the radial dependence of the diffusion coefficient (set by α). We note that this equation implies that the ratio of the transit time to the the recovery time is independent of the width of the ICME or its magnetic field strength. Thus this ratio should not be related to the depth of the Forbush event. Consequently, even though our sample exhibits a correlation between ICME transit time and Forbush depth (and so magnetic field strength), we do not expect a correlation between the ratio of the recovery time to the transit time.

[41] We now discuss equation (3) in the context of Figure 4. The slow events shown in Figure 4 have recovery times that are well below their transit times. The slowest events have transit times of ~100 hours and recovery times that are one fourth to one fifth as large as their transit times. Equation (3) only allows extremely short recovery times in the limit that the recovery time exceeds the decay rate of the disturbance; $t_{recov} \gg t_{decay}$. In this case the recovery is approximately equivalent to the decay rate; $t_{recov} \sim t_{decay}$. We conclude that the slow events are likely to be decaying rapidly.

[42] In contrast, the fast events shown in Figure 4 have recovery times that are well above their transit times. The fastest event has a recovery time that is approximately seven times the transit time. However, equation (3) places an upper limit on the recovery time. The maximum recovery time allowed is twice the transit time if $\alpha = 1$ and equivalent to the transit time if $\alpha \sim 2$. These limits are reached when the recovery time is far smaller than the decay rate of the disturbance; $t_{recov} \ll t_{decay}$. For both cases, the measured recovery times for the fast events are longer than permissible by equation (3).

[43] There are two possible ways to account for the extremely long recovery times of the fast events. The events could be decelerating, or the function $W\Delta K/K$ could be increasing instead of decreasing. We first consider the possibility that the ICMEs are decelerating. Recovery times are longest in the limit that the decay rate is long. We can use equation (2) to estimate the recovery time. Assuming that the mean diffusion coefficient $K \propto r^2$ and that the amplitude of the event ($W\Delta K/K$) is constant with time, the recovery time is equivalent to the time it takes the event to propagate between 1 AU and approximately 2 AU. The very slowest this could occur is the average solar wind speed times 1 AU, or about 100 hours (assuming a solar wind speed of 300 km/s). This assumption is extreme because it would require the disturbance to immediately drop to ambient solar wind velocity just as it passed Earth even though its rapid transit times implies a much higher velocity (greater than 1500 km/s). The observed decay times of the fastest events are uncomfortably near this value or 150 hours long. For deceleration to account for the long recovery times, we would require that the event drop to nearly ambient solar wind speeds within a fraction of an AU. While strong ICMEs do decelerate, even at distances of the Voyager spacecraft in the outer heliosphere, these events are still propagating faster than the ambient solar wind [*Wang et al.*, 2001]. The Halloween event was detected by Cassini on 11 November 2003 and by Voyager in April

2004. The transit time between Earth and Cassini shows that this event was propagating at a speed of ∼1000 km/s at the location of Cassini (9 AU) and 600 km/s at the location of Voyager (75 AU). While this event also provides evidence that the blast wave decelerates, it shows that the deceleration is fairly gradual. At a speed of 1500 km/s the disturbance would have reached 2 AU only 1.5 days after it reached Earth. Taking into account the empirical interplanetary deceleration relation obtained by *Gopalswamy et al.* [2000], the disturbance still would have reached 2 AU in well under 2 days. Again, this timescale is significantly shorter than the observed recovery time, suggesting that the deceleration of the disturbance is not sufficiently fast to account for the long recovery times.

[44] While fast ICMEs do decelerate, we find that they do not decelerate fast enough to account for the associated long Forbush recovery times. Consequently, we must consider alternative explanations for their long recovery times. Above, we defined an amplitude function $A(t) = VW\Delta K/K$ which we assumed would be constant if the disturbance was not decaying. However, this implicitly assumes that expansion of the disturbance as it travels causes the magnetic field (and thus the diffusion coefficient) in the disturbance to decay with the same dependence on radius as is true for the ambient solar wind. For a constant $A(t)$ and reasonable values of $\alpha \sim 1$ or 2, equation (3) does not allow a recovery time above twice the transit time. This conflicts with the observed recovery times of the strongest events which can be 5 times larger than the transit times. To allow such large recovery times, we require $A(t) = WV\Delta K/K$ to increase with radius with respect to the ambient solar wind. If we assume that the diffusion coefficient scales with the mean value of the magnetic field, then an increasing $A(t)$ implies that the magnetic field in the disturbance times its width should decrease less rapidly as a function of radius than the ambient solar wind. Fast CMEs could sweep up larger shocks from the ambient solar wind which precede the arrival of their ejecta. The observed deceleration of ICMEs does imply that energy is lost by the traveling disturbance.

[45] Alternatively, fast and strong Forbush events might be associated with multiple ICMEs which could merge, causing apparently large recovery times. This effect may be relevant to event 17. The ICME associated with event 17 is followed by a second ICME in under a day (but more than 10 hours) and both cause strong geomagnetic storms, which are separated by 36 hours. We can associate event 17 with the first ICME in the pair because it is coincident with the first storm. The second ICME is expected to increase the apparent recovery time. However, because of the extreme size of the observed recovery, we are confident that it is truly long and not merely due to the combined action of the two ICMEs. Even after reducing t_{recov} by half, it remains above the mean time for our sample. In reality the effect of the second ICME is probably much less then a factor of two because the second ICME is smaller than the first.

5. Conclusions

[46] Using ground-based neutron counts available from the Moscow Neutron Monitor, we have searched for Forbush decreases coincident with CMEs that have been matched to ICMEs by previous studies [*Gopalswamy et*

al., 2001; *Cho et al.*, 2003; *Cane et al.*, 1996]. We also added to our sample the 29 October 2003 event because of its extreme transit time and recovery time. After discarding CME-ICME pairs lacking Forbush decreases, decreases of low amplitude, and nonisolated decreases, we obtained a sample of 17 CME and ICMEs matched to observed Forbush decreases. Our sample exhibits a strong anticorrelation between the ICME Sun-Earth transit time and the Forbush recovery time as measured on Earth. This anticorrelation is opposite to the prediction of simple diffusive barrier models for cosmic ray transport. These models predict that the Forbush recovery time should be approximately proportional to the ICME travel speed. However, the recovery times that we measured deviated strongly from this prediction. We found that the fastest events have recovery times over seven times their transit times, whereas the slowest events have recovery times one-fourth to one-fifth times their transit times.

[47] The extreme range of recovery to transit time ratio places strong constraints on the diffusive barrier models for Forbush decreases. The short recovery times of the slow events suggest that they rapidly decay. The long recovery times of the fast events suggest that their amplitudes might even increase with radius rather than decrease. For the fast events, the strength of the ICME could be increasing as it travels because multiple ICMEs merge or because the shock preceding the CME ejecta is enhanced as more ambient solar wind is encountered by the rapidly traveling ICME. These possible explanations can be investigated with better theoretical modeling or simulations and by studying the observed physical properties of ICMEs as they pass through the heliosphere.

[48] Our sample contains a significant bias; the fast (short transit time) events tend to create larger Forbush decreases and the slow events tend to cause weaker Forbush decreases. However, diffusive barrier models imply that the recovery time of a Forbush event is independent of the depth of the decrease and the strength of its magnetic field and is instead primarily dependent on how it decays as it travels through the heliosphere. Consequently, the bias in the sample does not account for the anticorrelation between the transit times and recovery times that we have found here. A model which incorporates a relation between the decay rate of the disturbance and travel speed could explain the anticorrelation found here and would also be consistent with the observed correlations between Forbush depth and speed [*Cane et al.*, 1996].

[49] This work suggests that slow CMEs decay rapidly, in agreement with near-Sun observations of CMEs by *Gopalswamy* [2004], whereas fast CMEs remain strong. As consequence, we expect that slow ICMEs will not pose serious space weather threats, whereas fast ICMEs will. Because space weather forecasting is critical to existing and future space bound missions, we are motivated to further investigate the relationship between ICME strength and decay and CME ejection speed.

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