CORONAL MASS EJECTIONS AND FORBUSH DECREASES

HILARY V. CANE
School of Mathematics and Physics, University of Tasmania, Tasmania, Australia

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Abstract. Coronal Mass Ejections (CMEs) are plasma eruptions from the solar atmosphere involving previously closed field regions which are expelled into the interplanetary medium. Such regions, and the shocks which they may generate, have pronounced effects on cosmic ray densities both locally and at some distance away. These energetic particle effects can often be used to identify CMEs in the interplanetary medium, where they are usually called ‘ejecta’. When both the ejecta and shock effects are present the resulting cosmic ray event is called a ‘classical, two-step’ Forbush decrease. This paper will summarize the characteristics of CMEs, their effects on particles and the present understanding of the mechanisms involved which cause the particle effects. The role of CMEs in long term modulation will also be discussed.

1. Introduction

Decreases in the cosmic ray count rate which last typically for about a week, were first observed by Forbush (1937) and Hess and Demmelmair (1937) using ionisation chambers. It was the early 1950s work of Simpson using neutron monitors (Simpson, 1954) which showed that the origin of these decreases was in the interplanetary medium. There are two basic types. ‘Non-recurrent decreases’ are caused by transient interplanetary events which are related to mass ejections from the Sun. They have a sudden onset, reach maximum depression within about a day and have a more gradual recovery. ‘Recurrent decreases’ (Lockwood, 1971) have a more gradual onset, are more symmetric in profile, and are well associated with corotating high speed solar wind streams (*e.g.*, Iucci *et al.*, 1979a). Historically, all short term decreases have been called ‘Forbush decreases’. However, some researchers use the name more selectively to apply to only those with a sudden onset and a gradual recovery, it i.e., the non-recurrent events associated with transient solar wind disturbances. In this paper, the term Forbush decrease (Fd) will be used in this way, and only this type of short-term cosmic ray decrease will be discussed.

Figure 1 shows an example of a ‘classical’ Forbush decrease. In this figure a measure of the isotropic intensity (shown by the thick line) is obtained by averaging the count rate measured by three neutron monitors (Deep River, Kerguelen and Mt. Wellington) with similar responses and spaced approximately equally in longitude. The rates from the individual monitors are shown (using thin lines) in order to illustrate the variability which occurs between stations. The presence of two steps is indicated. The first decrease occurs in the turbulent field region

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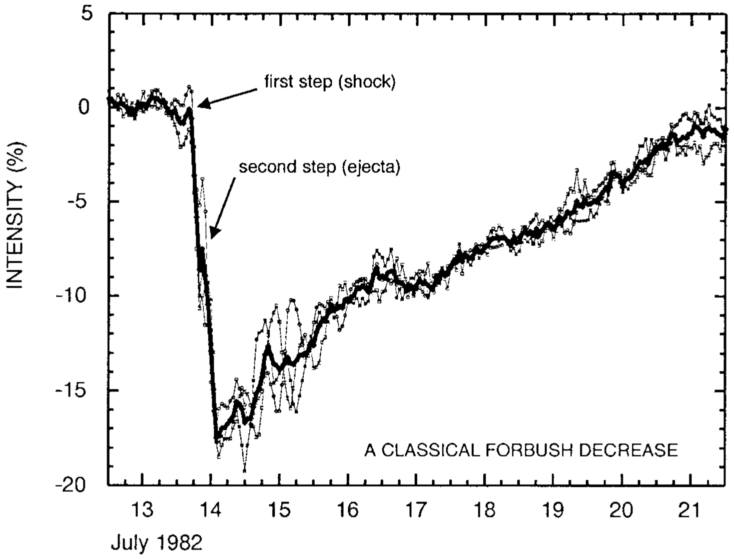

Figure 1. Percentage decrease for three neutron monitor stations spaced about equally in longitude (Deep River, Mt.Wellington, Kerguelen). The heavy line indicates the average of the count rates which is an approximate measure of the isotropic intensity. The two steps are indicated. Note the greater variability between stations (it i.e. more anisotropy) for about a day after the second step.

that is generated behind the shock which this fast ejecta creates in the medium ahead of it. A reduction in the cosmic ray density also occurs inside the ejecta because of its closed field line geometry. This paper is about such two-step particle decreases. The various features seen in Figure 1 are discussed in Section 3. Since it is important to understand the characteristics of the coronal mass ejections (CMEs) which create the ejecta, in order to understand Fds, this paper presents some of the basic characteristics of CMEs before discussing the particle observations and their interpretation. Of particular importance is the topology of CMEs and in particular whether their magnetic field lines are completely closed, it i.e. not connected to the ambient interplanetary magnetic field. Also of importance is the variation of the occurrence rate of CMEs during the solar activity cycle since this tells us what we should expect for the occurrence rate of Fds. The CME rate is also important if we want to understand the contribution of Fds to long term (11- and 22-year) modulation.

2. Coronal Mass Ejections, CMEs

2.1. AT THE SUN

CMEs are observed with ‘white-light’ coronagraphs and were first imaged in the early 1970s (Tousey, 1973; Gosling *et al.*, 1974). Coronagraph images show Thompson-scattered light from coronal electrons and provide information on the coronal density and how it changes with time. A good summary of our knowledge of the characteristics of CMEs has been presented by Hundhausen (1998) with particular emphasis on the Solar Maximum Mission (SMM) results. CME speeds occur in the approximate range 20–2000 km s^{-1} with the average speed being about 400 km s^{-1}. The extremely fast events tend to occur near solar maximum. In general, the faster CMEs are associated with flares and the flare-associated events decelerate close to the Sun whereas other CMEs accelerate (Gosling *et al.*, 1976; Sheeley *et al.*, 1999; and references therein). Angular sizes (latitudinal extents) projected against the plane of the sky occur in the range 5°–120° with the average size slightly less than 50°. (In addition, there are events that are viewed head-on which have apparent sizes of 360°.) The average CME kinetic energy is about 5×10^{30} ergs. Since 1996, our knowledge of CMEs has been greatly enhanced by observations from the LASCO coronagraphs on SOHO. However the observed CME characteristics (*e.g.* speeds, sizes) are consistent with the previous coronagraph observations (St. Cyr *et al.*, 1997).

Although CMEs take a number of different forms, it is believed that the processes which form loop-like ejections may be applicable more generally. CMEs tend to occur near magnetic neutral lines and often are preceded by the swelling of a coronal helmet streamer. The helmet streamer gets distorted and finally disrupted by the expansion of the underlying closed field region. This closed field region is an arcade of field lines which often contains a prominence. Thus prominence eruption is a common, but not necessary, occurrence in conjuction with CME lift-off. (When prominences are observed on the solar disk they are called filaments and thus prominence eruption is the same thing as filament disappearance.) Flares also often occur in association with CMEs but they are not necessary and are certainly not the instigators of mass ejection (see, *e.g.* Gosling, 1993) as has been sometimes assumed. Flares are believed to be generated by the heating resulting from reconnection of field lines blown open by the CME. Flares and prominence eruptions are different phenomena but often occur simultaneously. When CMEs occur outside active regions the prominence eruption is often associated with only a ‘flare-like brightening’. Note that somewhere between 30%–∼50% of CMEs have no associated flares or prominences St. Cyr and Webb, 1991). However the association rate with other on-disk phenomena (*e.g.* dimmings, arcades, waves) is greatly enhanced by the UV and soft X-ray observations now available from SOHO and Yohkoh respectively. Usually the flares associated with CMEs are of long duration and also have associated meter wavelength type II and, particularly, type IV radio

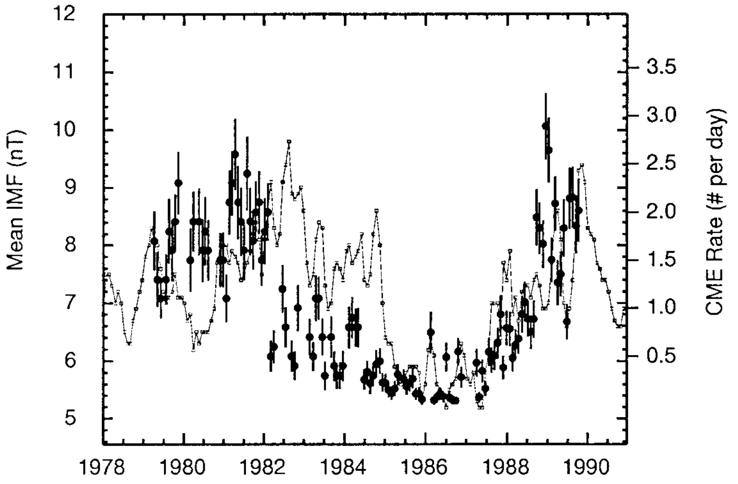

Figure 2. The CME rate (*large, filled circles*) compared with the interplanetary magnetic field (*small, open squares*) (IMF). Carrington rotation averages are used. The IMF has been smoothed using a running mean over 3 rotations. (The CME data were provided by O. C. St. Cyr.)

bursts (Robinson *et al.*, 1986). It is not yet clear whether the shock-generated type II emissions are generated by shocks driven by CMEs or from shocks associated with the flare process.

The CME rate (based on pre-SOHO observations) has been summarised by Webb and Howard (1994). They found a rate of about 0.25 CMEs day^{-1} at solar minimum rising to about 2.5–3 CMEs day^{-1} at solar maximum (see also Figure 2). These rates are a lower limit because of sensitivity limitations but the overall variation of rate as a function of epoch in the solar cycle should be representative. Howard *et al.* (1985) note that the exclusion of minor CMEs from the rates determined from Solwind observations would have decreased the amplitude but would not have substantially affected the phase of the occurrence rate. It is too early to get any long-term rates from LASCO but the St. Cyr *et al.* (1997) study obtained a CME rate of 0.7 CMEs day^{-1} during 3 months in early 1997 it i.e. about a factor of 3 higher than the Webb and Howard solar minimum rate. This is because of the increased sensitivity of LASCO compared to previous coronagraphs.

It is clear, based on their sizes, that CMEs are related to the large-scale components of the solar magnetic field but their role in its long-term evolution is not yet determined. Since the model of Wang and Sheeley (1995) successfully predicts the strength of the radial component of the interplanetary magnetic field (IMF) from photospheric field observations without the inclusion of CMEs, this suggests that CMEs are not generally a significant component of the solar wind. This can also be deduced from Figure 2 which shows that the CME rate (SMM data Carrington-rotation averaged, O. C. St Cyr, private communication) does not track very well the average interplanetary magnetic field strength time profile. Using one technique for identifying CMEs in the interplanetary medium, Gosling *et al.* (1992) estimate that at solar maximum CMEs in the solar wind were present ∼15% of the time.

2.2. IN THE INTERPLANETARY MEDIUM

Some researchers use the term CME for the ejected material identified in situ in the interplanetary medium. Others (including myself) believe that CME should be reserved for the phenomena observed by coronagraphs and that a different name should be used for the material in the solar wind because a) of historical precedent and b) it is not clear how best to identify the complete CME in the interplanetary medium. It was known some years before CMEs were identified that interplanetary shocks are driven by material ejected from the Sun. The so-called ‘driver gas’ had been identified in the interplanetary medium (*e.g.*, Hirshberg *et al.*, 1970) but it was not known how to identify that material at the Sun. Various signatures are known which identify driver gas, it i.e., the interplanetary counterparts of CMEs, which henceforth will be called ‘ejecta’. The signatures of ejecta include depressed plasma proton temperatures, bidirectional particle flows and strong magnetic fields (see Richardson and Cane, 1993, for a comprehensive list of references). Not all are present in every ejecta and the various signatures often do not overlap particularly well. Figure 3 shows solar wind data for an ejecta in April 1979. The solid vertical line indicates the time of shock passage and the dashed lines the boundaries of the ejecta. (Note that there was a reverse shock at ∼12:15 UT on April 25 which is not indicated on Figure 3). The third panel shows the observed solar wind proton temperature along with the expected temperature calculated from the observed wind speed. The black region indicates the region of low temperature indicative of ejecta material. This technique for identifying ejecta using the temperature and speed (see Richardson and Cane, 1995) is more convenient than bidirectional solar wind electron heat flux used by some researchers because it can be calculated from readily available solar wind data. The horizontal lines in the density panel indicate the durations of bidirectional solar wind electron heat flux (BDE) (Gosling *et al.*, 1987) and ∼1 MeV bidirectional ion flows (BIF) measured by ISEE-3 and IMP 8 (Richardson and Reames, 1993). Note that they do not occur at the same times. Since bidirectional flows usually indicate closed field lines, the cessation of bidirectional electrons often seen inside ejecta has been interpreted by Gosling *et al.* (1995) to indicate the presence of open field lines within ejecta which have reconnected with the ambient IMF.

The ejecta shown in Figure 3 is reasonably typical although with an average speed of about 600 km s^{-1} it is faster than average. Since its speed is greater than the upstream solar wind speed this ejecta creates a shock. The region of compressed/heated plasma between the shock and the ejecta (the post-shock compression region) lasts for about 9 hours. The ejecta extent has been determined from the various signatures as indicated in the figure. Based on the duration and the ejecta speed, the radial extent of the ejecta is ∼0.2 AU.

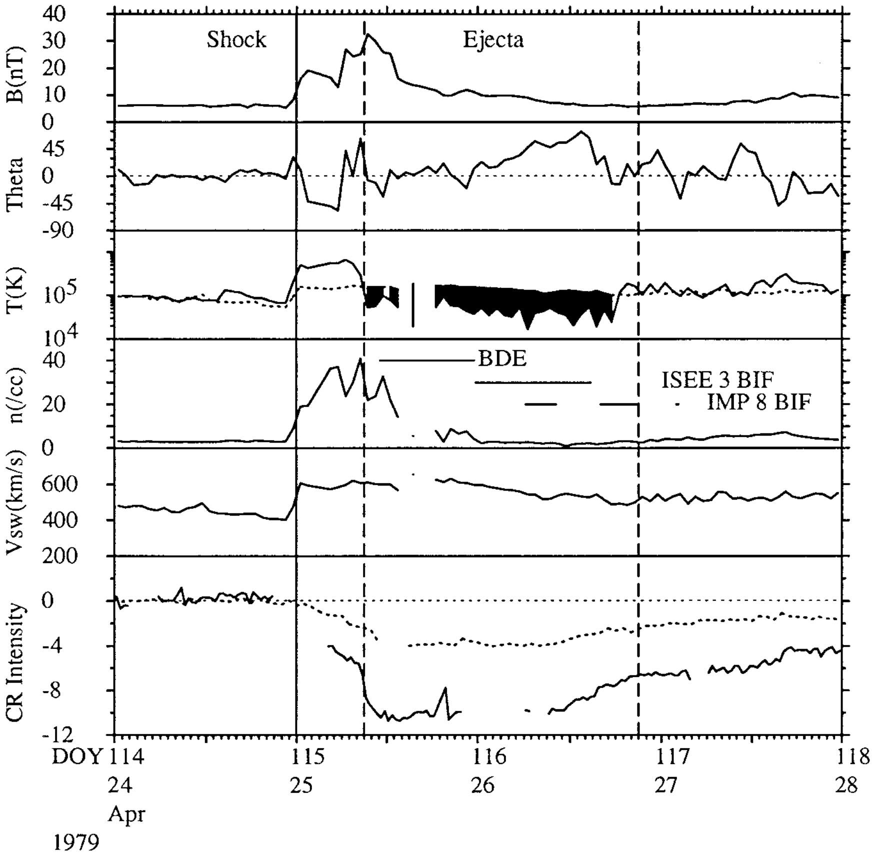

Figure 3. Solar wind data during a period when an ejecta was encountered. The top three panels show the magnetic field and its component out of the ecliptic, the proton temperature, density and speed. The dashed line in the temperature panel shows the expected temperature for normal solar wind expansion. The blackened area is a low temperature region, indicative of an ejecta. The vertical, dashed lines indicate the extent of the ejecta and the solid line indicates the passage of a shock which the ejecta creates. Horizontal lines in the density panel indicate the durations of periods of particle bi-directional (BD) flows, (see the text for more details) another indicator of ejecta material. Note that the BD flows are intermittent and the different measures do not overlap. The bottom panel shows the isotropic cosmic ray intensity as determined by using three well-spaced neutron monitors (*dotted line*) and the anti-coincidence guard on IMP 8 (*solid line*). A sudden decrease in cosmic ray count rate on entry into the ejecta is particularly evident in the IMP 8 data.

Also shown in Figure 3 are measures of the isotropic cosmic ray intensity. The solid line is data obtained from the anti-coincidence guard of the GSFC medium energy experiment on IMP 8. The dotted line shows the isotropic intensity determined from three neutron monitors (as in Figure 1). The solar wind structures discussed above caused a moderately-sized two step decrease. Note the clear particle depression during the passage of the ejecta. Since such a depression is nearly always present, it is to be hoped that in the future a standard technique for identifying the presence of ejecta material will be to look at energetic particle data, especially from neutron monitors.

Of particular interest to theoreticians (because such structures can be easily modelled) are ejecta with the so-called magnetic cloud or magnetic flux rope geometry. These ejecta have a magnetic enhancement which shows a clear rotation in direction and are therefore easy to identify. The conclusion of Gosling (1990), that only one third of ejecta have the magnetic cloud structure is often quoted. However Cane *et al.* (1997) suggest that the ratio might be more like 50% and furthermore that the cloud geometry may be a consequence of intercepting an ejecta near its centre. Cane *et al.* (1997) presented an event seen by two spacecraft in which there was a magnetic cloud at one location but absent at the other. It is important therefore to note that studies limited to magnetic clouds may exclude about 50% of all ejecta. The topology assumed for magnetic clouds is that of a flux rope with both ends attached to the Sun. Lepping *et al.* (1990) and Bothmer and Schwenn (1998) find that the axes of magnetic clouds typically lie east-west and close to the ecliptic. It is unlikely that geometries in which the cloud is completely detached from the Sun (*e.g.*, a spheromak, Vandas *et al.*, 1993) can apply since rapid onsets of solar energetic particle events are seen at spacecraft when inside ejecta, implying field line connection to the Sun (*e.g.*, Farrugia *et al.* 1993). Note that the loop type of geometry implied by Figure 8 of Burlaga *et al.* (1990) in which the ‘legs’ of the ejecta return to the Sun at widely spaced locations is probably misleading since the two separated intersections of an ejecta suggested by the figure have never been recorded. A more likely scenario is that presented in Figure 1 of Crooker *et al.* (1998) in which the trailing leg folds into the back of the leading leg with distortions along the Parker spiral. At the Sun the legs are separated only by a current sheet and reform the streamer configuration. Although the details of these ejecta remain to be worked out, it is expected that such organised field structures may have implications for particle transport.

Our current picture of the large scale structure of the transient interplanetary shocks created by CMEs differs little from that first proposed by Hundhausen (1972; see Figure 4). (Hundhausen used the term ‘ejecta’ to identify the drivers of interplanetary shocks at a time when CMEs were unknown). One feature of importance is that asymmetries in longitude arise in the effects of interplanetary shocks (modulation and particle acceleration) because ambient solar wind field lines get draped around the ejecta as it propagates away from the Sun. This means that when the shock is beyond the observer, an observer on the western side of an ejecta is connected to the strongest part of its shock.

While the latitudinal extent of CMEs can be inferred from coronagraph observations, it is more difficult to infer the longitudinal extent of ejecta following shocks, though this will certainly be less than that of the associated shock. From a study of ejecta signatures following a group of very energetic shocks, Richardson and Cane (1993) determined that the longitudinal extent of ejecta at 1 AU was at most 100°. In another multi-spacecraft study Cane *et al.* (1997) found that for less energetic events the size extent was probably less than 50°. In contrast, some interpretations of the *Ulysses* results have suggested that ejecta are very large. Part of the apparent size discrepancy may result from the fact that at high latitudes ejecta ‘over expand’ (Gosling *et al.*, 1994).

3. Forbush Decreases

3.1. INTRODUCTION

The most comprehensive article about the characteristics of Forbush decreases remains that of Lockwood (1971). Much of the description there is still appropriate although the understanding of the cause was lacking. Readers interested in early articles about Fds should refer to the Lockwood (1971) paper. Just a year or so after this paper, Barnden applied the Hundhausen shock picture to classic, two-step Forbush decreases in two papers presented at the International Cosmic Ray Conference in Denver (Barnden, 1973a, b). Barnden reasoned that the first step occurs at the shock and the second at the discontinuity marking entry into the ejecta. More recently, a number of researchers (*e.g.*, Iucci *et al.* 1986; Nagashima *et al.*, 1990) have discussed Fds in terms of two components but it would appear that their conception of the causative solar wind is not consistent with the correct structure. For example, Iucci *et al.* (1986) appear to have associated the second step with the magnetic field increase comprised of the post-shock compression region and the ejecta. More importantly, no theoretical models have been proposed that consider the fact that there are two different physical mechanisms which cause Fds, it i.e., the interplanetary shock, if one is generated, and the interplanetary counterpart of the CME, the ejecta. Figure 4 illustrates the large scale structure of an ejecta and associated shock and how the cosmic ray response is related to the path through the ensemble. (No attempt has been made to show the magnetic field structure, it e.g., a flux rope, inside the ejecta.)

If an observer is passed by a shock and its associated ejecta, two-steps are seen as shown for path A. A less energetic ejecta which does not create a shock causes only a short-duration one component/step decrease as the ejecta passes by. Such events are often too small to produce a significant decrease in the records of a single neutron monitor. Since shocks have a greater longitudinal extent than ejecta, it is possible to intercept the shock but not the ejecta as shown by path B. In this case, only the effect due to the shock is evident. Note that the ejecta pushes aside the upstream solar wind, compressing and heating it and that the field lines get draped around the ejecta. This leads to an asymmetrical structure which is responsible for the long established asymmetry in the sizes and presence of Fds as a function of longitude of the associated solar event (Haurwitz *et al.*, 1965).

Thus CME-related cosmic ray decreases are of three basic types; those caused by a shock and ejecta, those caused by a shock only and those caused by an ejecta

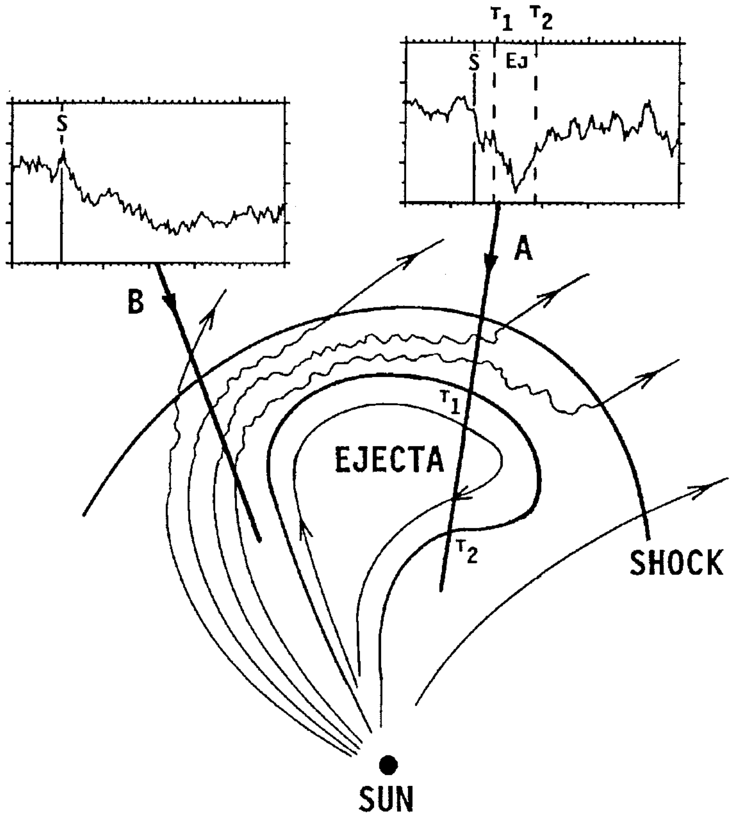

Figure 4. The large-scale structure of a fast ejecta and associated shock. The upstream solar wind is draped around the ejecta and heated and compressed at the front of the ejecta. Two paths through the ensemble are indicated with differing resultant cosmic ray profiles. The time of shock passage is indicated by a vertical line marked S and the start and end times of ejecta passage are marked T1 and T2. Only if the ejecta is intercepted is a two-step decrease be observed.

only. The majority (>80%) of short-term decreases greater than 4% are of the two step (shock plus ejecta) type (Cane *et al.*, 1996). Only very energetic CMEs create shocks which are strong enough on their flanks to cause significant cosmic ray decreases for observers who detect the shocks beyond the azimuthal extent of the ‘driver’ CMEs (it i.e. shock-only decreases). In such cases the shocks also generate major solar energetic particle increases with profiles characteristic of events originating far from central meridian (Cane *et al.*, 1988). The energetic particles allow one to be sure that the cosmic ray decrease was caused by a CME-driven shock intercepted on its flank and not by a co-rotating stream.

These two types of decreases are rather similar in appearance which is not unexpected since the local solar wind conditions are similar. However corotating streams do not produce detectable particle enhancements above $\sim$20 MeV amu^{-1} at 1 AU. In contrast, energetic CMEs are well-associated with solar energetic

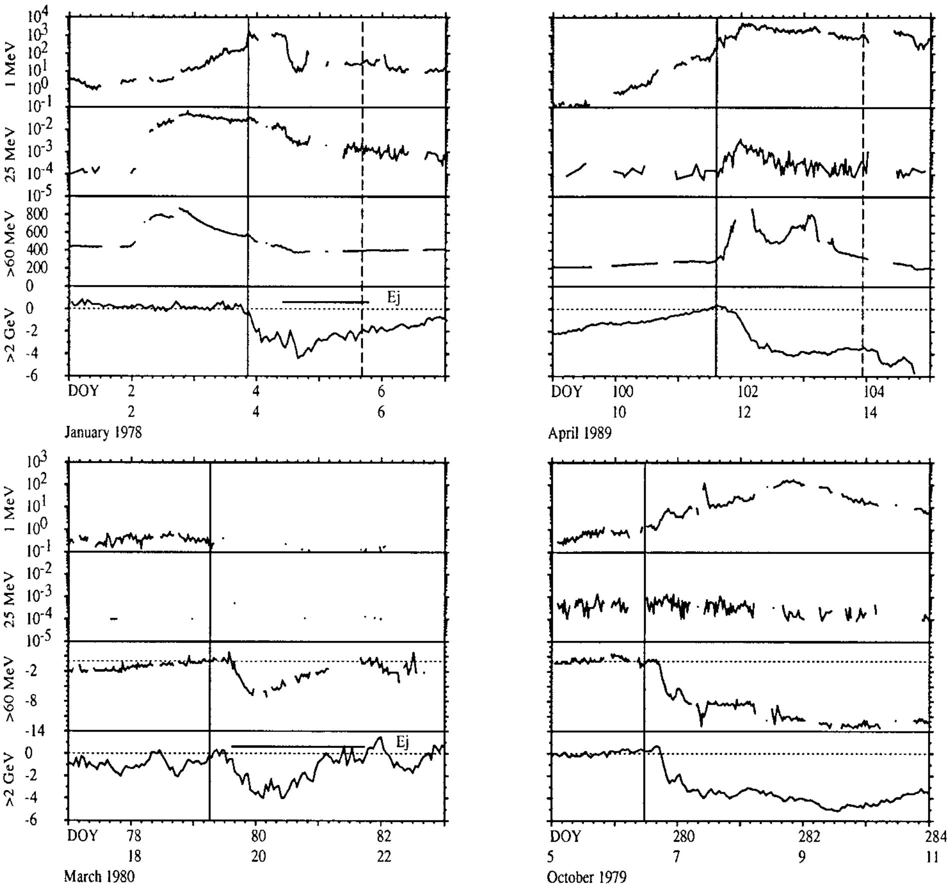

Figure 5. Particle data at four energies for four different types of solar wind flow (*see text*). The vertical lines indicate the times of shocks and the horizontal lines times of ejecta. The cosmic ray decreases in the top left and right panels are representative of paths A and B, respectively, in Figure 4.

particle events (Kahler *et al.*, 1987) and the start of the particle event usually occurs within an hour or so of the associated flare. When high energy particles ($>\sim$50 MeV) are present with a cosmic ray decrease one can be sure that a solar flare will have accompanied the CME when it left the Sun. Conversely when such particles are absent the CME is less energetic and the more likely solar signature of CME departure is a disappearing filament with perhaps a weak flare. However some of these small two-step decreases will have no Hα solar association.

Figure 5 illustrates the relationships between cosmic ray decreases and lower energy particle increases at four energies ($\sim$1, $\sim$25, $>$60 MeV, and $>$2 GeV) and how they can be used to infer interplanetary and solar associations. The lower energy data come from the GSFC experiment on IMP 8 and the $>$2 GeV data are the average of the three neutron monitor stations referred to previously. The vertical lines indicate times of sudden commencement geomagnetic storms, indicative of shock passage. The dashed lines are for weaker shocks. The two particle increases at the top of the figure both extend to above 60 MeV and are associated with flares. The January 1 1978 flare occurred at E06° and not surprisingly, in view of its central location, an ejecta was detected near Earth. In this example the ejecta decrease is clearly visible in the 1 MeV data at the same time as the minimum in the cosmic ray decrease on January 4. The April 9 1989 flare occurred at E28° although the particle profile, with most of the increase after shock passage, is more characteristic of an event located further from central meridian. The double hump in the >60 MeV profile is unusual and it is not clear whether this a second solar event or not. No ejecta was detected at Earth and the cosmic ray decrease has a rather smooth gradual profile. The short decrease after the second weak shock is caused by an ejecta almost definitely related to a separate solar event.

In the absence of particles accelerated to above a few MeV, the two cosmic ray decreases at the bottom of Figure 5 are also seen in the >60 MeV data and are about a factor of 2 larger than in the >2 GeV data. The lower left panel illustrates the particle response to a slow ejecta in March 1980. At 1 AU the ejecta speed was near 400 km s^{-1}. The associated shock did not generate a detectable particle increase above 1 MeV nor a cosmic ray decrease. (Note that it is the low particle intensity at this time that is primarily responsible for the absence of 1 and 25 MeV data.) The cosmic ray decrease was produced only by the ejecta. Note that the decrease recovered as soon as the ejecta had passed on March 21. The lower right panel shows, for comparative purposes, a decrease caused by a co-rotating stream. It looks quite similar to the Fd in the panel above but note that the particle increase, caused by acceleration at the corotating reverse shock in the outer heliosphere, does not extend above 20 MeV. Furthermore, the particles peak several days after shock passage instead of within a few hours of shock passage.

3.2. GENERAL CHARACTERISTICS

The characteristics of the two parts composing Fds need to be considered separately and such a comprehensive study has yet to be done. For a recent summary of Fds in terms of the two steps see Wibberenz *et al.* (1998). Below the characteristics of entire decreases are summarised.

Magnitudes of Fds. The largest Fds have magnitudes in the range 10–25% for neutron monitors. Note that because of anisotropies present in neutron monitor data, the size reported for an Fd will vary from one station to another. Also the sizes will be smaller if daily averages are used rather than hourly averages. For a 30-year period from 1964–1994 Cane *et al.* (1996) list 10 events $>10\%$ for neutron monitors (it e.g. Mt. Wellington) with a cut-off rigidity of ~ 2.0 GV. At the lower rigidities accessible via spacecraft observations, Fds are larger. Lockwood *et al.* (1986) and Cane *et al.* (1993) found that the ratio of the magnitudes of decreases as seen by IMP 8 (median rigidity of ~ 2 GV) relative to Mt. Wellington/Mt. Washington was typically about 2 for those events in which there were no accelerated particles.

Rigidity dependence. The rigidity (P) dependence of the amplitude of Fds is approximately equal to $P^{-\gamma}$ where γ ranges from about 0.4–1.2. A number of researchers have examined whether the rigidity dependence of Fds varies with the Sun’s polarity and all groups have concluded that it does not (see, it e.g., Morishita *et al.*, 1990).

Precursory increase. Many Fds show a precursory increase. Such an increase can result from reflection of particles from the shock or acceleration at the shock. Few neutron monitor researchers seem to consider the latter as likely even for very large energetic shocks despite the fact that at the energies accessible from spacecraft there appears to be a continuum from low to high energies of the shock-accelerated population. Two events in which this was the case are the August 4 1972 and October 20 1989 shocks. Precursory decreases are discussed in Section 3.3.

Recovery characteristics. In isolated single Fds the recovery can be described as exponential with an average recovery time of ~5 days but ranging from ~3 to ~10 days (Lockwood *et al.,* 1986). The recovery time is dependent on the longitude of the solar source region (Barnden, 1973a; Iucci *et al.*, 1979b; Cane *et al.*, 1994). Lockwood *et al.* (1986) found that the recovery time was independent of rigidity in the range ~2 to ~5 GV and with no dependence on solar polarity or time in the solar cycle. In contrast Mulder and Moraal (1986) found that the recoveries were longer for the $A < 0$ epoch in the 1960s compared with the $A > 0$ epoch in the 1970s. These authors did not fit recoveries to individual events but rather compared recoveries when the event minima were normalised.

Anisotropies. Fds display anisotropies both in, and perpendicular to, the ecliptic plane and these are related to the structure of the associated solar wind. Anisotropies are most marked near shock passage and inside ejecta. There are also periods of enhanced diurnal waves in the recovery phases of Fds. For a summary of early work see Duggal and Pomerantz (1978). For a more detailed discussion and a summary of recent work see Section 3.3.

Solar associations. Large Fds are caused by fast CMEs and their associated interplanetary shocks which can be associated with specific solar flares. Note again that the flare does not produce the CME (see also Gosling, 1993) but nevertheless is a useful diagnostic for determining the longitude on the Sun at which the CMEs and interplanetary shocks causing Fds originate. In some less energetic CME/Fd events it is also possible to deduce a ‘source longitude’ by noting the occurrence of a disappearing filament without a flare. It is of historical interest that Gosling, in a private communication referred to by Duggal and Pomerantz (1978), suggested that mass ejections without associated solar flares might cause some Fds. Previously Duggal and Pomerantz (1977) had suggested that flares could not be the causes of Fds based on a superposed epoch analysis between flares and cosmic ray variations.

Cane *et al.* (1996) have studied all $\geq$4% Forbush decreases for a 30 year period (1964–1994) and determined which are flare related based on the presence of associated energetic particle events. Two-step Fds were divided into two classes depending on whether they were associated with a significant flare or not. The point is that the flare-associated events are in general caused by more energetic CMEs. The division has no meaning in terms of the physics of the particle effects although there is some suggestion (it e.g., Sheeley *et al.*, 1999) that there are two classes of CMEs. Cane *et al.* (1996) determined that of 92 ‘classic, two step’ $>$ 4% decreases, slightly more than half (55%) can be associated with significant flare events. These flares occur within 50° of central meridian, consistent with the high probability of detecting the radially propagating ejecta. That large Fds originate near central meridian has been known for many years (Yoshida and Akasofu, 1965) and Barnden (1973b) supplied the explanation in terms of the large scale structure of solar ejecta in the interplanetary medium as discussed above. Nevertheless many subsequent workers have attributed two-step decreases to flares occurring far from central meridian. For example, Iucci *et al.* (1979b) used long-lasting type IV emission to make flare associations. This is a reasonable way to determine those flares associated with a CME. However not all of the CMEs will intercept the Earth. The distribution of two-step Fd source regions shown by Iucci *et al.* (1986) extends over the entire visible disk of the Sun. Given that quite a few CMEs have no associated flare or filament disappearance one should expect that there will also be Fds with no such associated solar event. Thus studies attributing interplanetary events to flare activity alone (it e.g., Iucci *et al.*, 1979b) or even including disappearing filaments (Belov and Ivanov, 1997) are likely to have some incorrect associations. Including energetic particle information on event times, location and energetics allows one to be sure of events that can be associated with a specific flare.

Occurrence rates. Fds are most common near solar maximum but occur throughout the solar cycle. There are fewer than 10 Fds greater than 10% per cycle and they occur around sunspot maximum but notably not in the year or so just after solar maximum (Cane *et al.*, 1996). To estimate whether the Fd rate is consistent with the CME rate, as observed in coronagraph data, note that the CME rate at solar minimum is approximately 0.7 per day (see Section 2.1). If we assume that all CMEs are in the ecliptic (which is reasonable at minimum conditions), that a typical CME is 40° in angular extent and that LASCO can detect CMEs over a 240° range (it i.e., from the visible disk and 30° beyond each limb) we might expect something like 0.1 ejecta per day at Earth or 36 per year. Belov (private communication) reports over 100 ‘Forbush effects’ in the year 1995 but based on the above estimate it is unlikely that the majority of these events are caused by CMEs. From an examination of the solar wind data it appears that many are caused by small co-rotating high speed streams. One might question the ability of the LASCO coronagraphs to detect all CMEs on the disk. However the study of Richardson *et al.* (1999) finds a good, almost 1:1 correspondence, between Earth-directed CMEs seen by LASCO and cosmic ray depressions seen in the IMP 8 guard data. This suggests that there is not a major class of small CMEs, undetected by LASCO which cause cosmic ray decreases. This also suggests that cosmic ray decreases are a reliable signature of CMEs in the interplanetary medium.

3.3. ANISOTROPIES

It is remarkable that Barnden (1973b) interpreted the anisotropy information obtained from neutron monitor data in terms of the particle flow patterns related to the ejecta and its shock. Since that study relied on relating each Fd to a solar flare it is likely that a number of the associations were incorrect and so the actual patterns he identified, in terms of large-scale structure, need to be verified. For the next 15 years or so the relationship between observed anisotropies and solar wind structures was largely ignored. In fact, since there can be large anisotropies inside ejecta this was the reason work in the late 1980's and early 1990's failed to identify a clear decrease in ejecta that had a magnetic cloud signature. Many of the studies used superposed epoch analyses and thus removed much of the ejecta decrease. Following the first papers about magnetic clouds (it e.g., Zhang and Burlaga, 1988) it was obvious that cosmic rays should show some signatures of these closed structures with a regular magnetic field rotation. However when Zhang and Burlaga (1988) looked at the count rate from a single neutron monitor they concluded that the response of cosmic rays to clouds was essentially negligible and that the only cause for Fds was the post-shock turbulence. Also Lockwood *et al.* (1991) found that magnetic clouds did not have a significant effect on cosmic rays. In contrast, Badruddin *et al.* (1986) and Sanderson *et al.* (1990) concluded that magnetic clouds make an important contribution to Fds. Note that the events studied by Lockwood *et al.* (1991) were relatively minor. The causes of the confusion are that (a) the conclusions depend on the particular events studied and (b) it is difficult to relate the cosmic ray variations to solar wind structures using only a single neutron monitor. The unambiguous depressions caused by magnetic clouds were first illustrated by Cane (1993) using the anti-coincidence guard on IMP 8 which provides a direct measure of the isotropic intensity.

Other workers (Nagashima *et al.*, 1990; Iucci *et al.*, 1989) started with periods of large cosmic ray anisotropies and tried to relate them to interplanetary magnetic field conditions. These researchers recognised the importance of the two components to an Fd but unfortunately did not have good methods for isolating the ejecta component. Their results are very interesting and these techniques should eventually provide details about the internal structure of ejecta. For example, Nagashima *et al.* (1990) isolated regions of low cosmic ray density in which the field

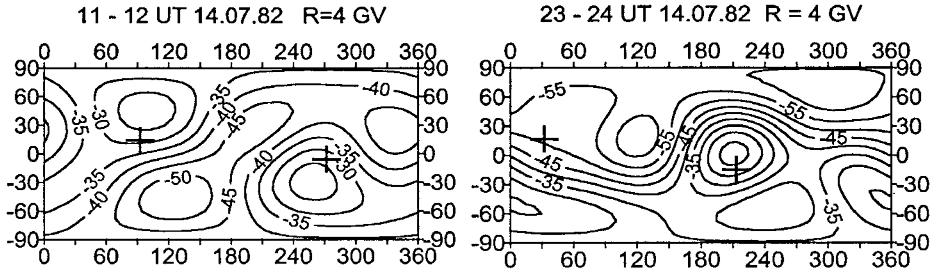

Figure 6. Particle flow directions as determined by Dvornikov and Sdobnov.

has specific characteristics and in which the cosmic rays are supposedly trapped. These regions had a median duration of about 8 hrs which is less than half the duration of a typical ejecta. The peaks discussed by Nagashima *et al.* (1990) may be related to open field lines within ejecta. Note however, that Cane *et al.* (1997) find that extended regions of open field geometry are rare inside ejecta, at least on the ~0.005 AU scale sizes probed by ~2 GV cosmic rays.

More recently Bieber *et al.* (1999) deduce for one event, based on anisotropy data, that the ejecta passed south of the Earth. Hofer and Flückiger (2000) have studied a single large event (in March 1991) in detail. The cosmic ray anisotropy vectors were found to exhibit a rotational behaviour at the onset of the ejecta decrease where the modulation was greatest. Hofer and Flückiger (2000) suggest the presence of a magnetic cloud-like structure. Unfortunately, solar wind data were not available to confirm this because IMP 8, the only spacecraft making near-Earth observations, was in the magnetosphere at the time.

Belov *et al.* (it e.g., 1995; 1997) have determined the isotropic density and 3D-anisotropies of cosmic rays for long periods of time (years) using the ‘global survey method’ (Belov *et al.*, 1995). They have also illustrated the large variability between Fds. In a number of cases the phase of the in-ecliptic anisotropy shows an anti-sunward flow in the ejecta and then a clear swing back to the normal co-rotation flow from approximately the east near the rear of the ejecta. It remains to be determined how often these and other patterns occur. This will provide the information necessary to determine how and where particles enter ejecta.

A separate line of research has been undertaken by Nagashima and colleagues (it e.g., Nagashima *et al.*, 1992). They have studied anisotropies related to particle effects at shocks and in particular decreases and increases caused by density gradient flows across the shock. The decreases which are sometimes visible prior to shock arrival may have some application in Space Weather forecasting (it e.g., Belov *et al.*, 1995; Bieber and Evenson, 1998; Bieber *et al.*, 1999). Note that the largest geomagnetic storms are caused by CMEs and the surrounding solar wind with which they interact. This is why Fds and major geomagnetic storms are well associated as noted first by Forbush (1938).

Most of the work described above has only considered the first-order anisotropy of cosmic ray flows. Dvornikov and coworkers (it e.g., Dvornikov *et al.*, 1983) have also calculated the second-order anisotropy. Figure 6 shows the particle density as a function of GSE longitude and latitude for two periods during the ejecta responsible for the July 1982 decrease illustrated in Figure 1. Strong second-order anisotropy in the top panel corresponds to bidirectional flows parallel and anti-parallel to the IMF (+). Such flows occur at times when particles at lower energies also show bi-directional flows (Richardson *et al.*, 2000). The bottom panel shows an interval of unidirectional flow within the ejecta. It remains to be determined what features of individual ejecta lead to particularly well-ordered flows.

3.4. FDS IN THE HELIOSPHERE

There have been a number of studies comparing Fds seen near Earth with ‘Forbush-like’ decreases at greater distances. However, the results of such work must be considered with great caution for the following reasons. First, even at 1 AU the situation can be very complicated with multiple transient events occurring closely spaced in time. Second, decreases related to corotating streams are, without additional information, sometimes difficult to differentiate from transient events. Third, disturbances may merge as they move out through the heliosphere so that the merged region in the outer heliosphere bears little resemblance to its constituent parts near the Sun. Fourth, events on the backside of the Sun relative to Earth can be the cause of depressions seen at distant spacecraft. Webber *et al.* (1986) discuss about 20 events seen at 1 AU and 2–30 AU. Even the three ‘events’ they illustrate have problems in that at 1 AU one is a corotating decrease and the others are multiple events. Similarly the work of Van Allen (1993) has been criticised Cliver and Cane, 1996) because he attributes events seen at huge longitudinal separations as having the same single solar origin. In fact, it is the rather limited longitudinal extent of Forbush decreases that makes multi-spacecraft observations so rare.

Probably the best data sets from which to infer how Fds evolve with time and radial distance are those from the anti-coincidence guards of the University of Kiel experiments on the *Helios 1* and *2* spacecraft when combined with similar data from IMP 8 and neutron monitor data. Cane *et al.* (1994) investigated decrease sizes as a function of longitude and radius by comparing data from the spacecraft anti-coincidence guards which detect $>$60 MeV particles. This study considered 8 large events responsible for Fds seen in neutron monitor data in the period 1976–1979. The response at 3 locations clearly confirmed that decreases are caused by a shock effect and also an ejecta effect for spacecraft close to the radial from the source location. The easternmost observer sees the earliest recovery since corotation means that connection to the shock becomes poorer with time.

There were two events in which IMP 8 and *Helios 2* were radially aligned and the ejecta decrease was seen to become smaller at the more distant spacecraft. This suggests that the decrease is caused by the initial exclusion of particles from the ejecta which then fill it in as a function of time. In a subsequent paper Cane *et al.* (1997) examined smaller decreases as seen by the Helios spacecraft and provided evidence that probably all ejecta cause a particle decrease.

The 250−2000 MeV proton chanel on the Kiel experiment on Ulysses has detected particle decreases in three high latitude ejecta (Bothmer *et al.*, 1997). The sizes of the decreases were surprisingly large leading Wibberenz *et al.* (1998) to suggest that the over expansion in these high latitude ejecta might result in efficient adiabatic cooling. Unfortunately this experiment does not have sufficiently high counting rates to study events in detail and few events have been detected.

3.5. CMEs/FDs AND LONG TERM MODULATION

It has been suggested (Burlaga *et al.*, 1993) that long-term modulation precedes in a series of steps caused primarily by global merged interaction regions (GMIRs). GMIRs are phenomenologically described as shell-like structures with intense magnetic fields, convected outward with the solar wind. Their origin is thought to be related to the merging of systems of transient flows (generated by CMEs) with other streams and interaction regions beyond 10 AU. Cliver *et al.* (1993) have argued that the cosmic ray steps are not well-correlated with large, energetic CMEs (as indicated by fast shocks and high intensities of energetic particles) (see also Cane *et al.*, 1999a) and suggested that maybe it is the more common, less energetic, CMEs that are responsible. Recently Cane *et al.* (1999b) have proposed an alternative explanation which is that the ‘steps’ (or ‘medium-term events’) in the long-term cosmic ray modulation profile are caused by episodes of enhanced magnetic flux emission from the Sun. One argument against the GMIR model is the fact that the steps are seen at 1 AU before merging can have taken place further out. Note also that CMEs are not a significant component of the IMF and the large increase in the IMF in 1982 (for example), and associated cosmic ray modulation event, was not matched by an increase in the CME rate (see Section 2.1). Cane *et al.* (1997) (see also Richardson *et al.* (1999) have found that there is a good correspondence between ejecta (interplanetary CMEs) and particle decreases such that the majority of CMEs, even small ones, produce a signal in the 1 AU cosmic ray record. These too are absent at the onset of medium-term modulation events making doubtful the Cliver *et al.* (1993) suggestion that the more common, less energetic, CMEs are responsible.

4. Modelling

Until recently no models have ever included more than a single mechanism. As pointed out by Wibberenz *et al.* (1998) (see also Cane *et al.*, 1994) it is extremely important to separate out the different components of a Forbush decrease because, as discussed above, two separate physical effects are responsible for them. Thus much existing theoretical work on Forbush decreases needs to be revised such that only the appropriate part of the observed decrease is compared with models involving one mechanism.

An excellent summary of the earlier theoretical investigations is provided by Chih and Lee (1986). Furthermore this paper provides an analytical solution to the simple diffusion-convection equation. A similar equation was obtained by le Roux and Potgieter (1991). The basic idea of a ‘propagating diffusive barrier’ has been explored most recently by Wibberenz *et al.* (1997) and Wibberenz *et al.* (1998). In this work the barrier is assumed responsible for the ‘shock effect’ and has been applied to data where the ‘ejecta effect’ has been removed.

In terms of simple models valid for conditions near 1 AU, short term cosmic ray decreases are driven by variations in the interplanetary plasma and magnetic field parameters, leading to changes in the particle diffusion and convection properties. In the case of the shock effect the maximum depression can be approximately related to the modulation parameter obtained in the force-field solution (Gleeson and Axford, 1968),

$$\Phi = \int (V/3K)\,\mathrm{d}r, \tag{1}$$

where V is the solar wind speed and K the radial diffusion coefficient. Then,

$$\frac{\Delta U}{U_0} = -3C\Delta\Phi, \tag{2}$$

C is the Compton–Getting factor. $\Delta\Phi$ represents the difference between the undisturbed and the disturbed conditions, and the integral in Equation (1) is taken over the region in space in which the solar wind parameters deviate from the ambient conditions. For derivation of this approximate solution under various circumstances see Richardson *et al.* (1996) and Wibberenz *et al.* (1998). For a large drop in the ratio V/K at a shock front and a box-like depression over a spatial region L, Wibberenz *et al.* (1998) obtains the size of the depression as $\Delta U/U_o = CV'L/K'$ (where V' and K' are the speed and diffusion coefficient behind the shock). For a typical set of parameters he obtains a value of the order of 8% at neutron monitor energies. It is important to note that the exact value of the depression as well as the temporal shape of the onset of the decrease behind the shock depend on the way in which the disturbance varies with the distance behind the shock.

Cane *et al.* (1995) have discussed the ‘ejecta effect’ in terms of a simple model in which particles gain entry to the ejecta via perpendicular diffusion. The ejecta effect and the model were investigated more fully by Vanhoefer (1996). In the model the size of the depression is a function of the magnetic cloud parameters, with the result

$$\frac{\Delta U}{U_0} = F\left(\frac{K_\perp r}{Va^2}\right), \tag{3}$$

where $\Delta U/U_0$ is the maximum depression, r the distance of the observer from the Sun, a and V the radius and speed of the cloud, and $K_\perp$ is the perpendicular diffusion coefficient. The function F decreases monotonically. Under the simplifying assumption $K_\perp \propto 1/B$, the depression $\Delta U/U_0$ decreases monotonically with the product Ba^2V. This explains why the size of the depression gets smaller when B, a or V are reduced. One expects that the size of the depression will get below detection threshold for larger distances r from the Sun.

5. Summary

CMEs cause depressions in the cosmic ray intensity both locally when an observer is inside the interplanetary structure (ejecta) and remotely if the ejecta is energetic enough to create an interplanetary shock to which the observer is magnetically connected. After the shock and ejecta have passed the intensity gradually recovers as particles diffuse in around the shock. Although the local decrease inside an ejecta can be of the order of 20% in neutron monitor data it does not appear, based on a number of arguments, that CMEs play a major role in long-term modulation. Nevertheless the study of these decreases is important in order to understand which physical processes are most important for particle transport.

In terms of understanding the internal magnetic topology of CMEs in the interplanetary medium, cosmic ray anisotropies should provide valuable information which cannot be obtained by any other type of in situ measurement. Detailed analysis of anisotropy data is only just beginning in earnest. One of the reasons why progress has been slow, despite the availability of methods of analysing the cosmic ray data, has been the inability, until recently, to clearly distinguish the two components of Forbush decreases and their relationship with solar wind structures.

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Address for Offprints: Hilary V. Cane, School of Physics, University of Tasmania, GPO Box 252-21, Hobart, Tasmania 7001, Australia; hilary.cane@utas.edu.au