CORONAL MASS EJECTIONS AND FORBUSH DECREASES

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Abstract. Coronal Mass Ejections (CMEs) are plasma eruptions from the solar atmosphere which involve 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 reach maximum depression within about a day and last typically for about a week, were first observed by Forbush (1937) and Hess and Demmelmair (1937) using ionisation chambers. It was the early 1950's 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. "Recurrent decreases" (Lockwood, 1971) are more gradual and more symmetric in profile, and are well associated with corotating high speed solar wind streams (*e. g.*, Iucci *et al.*, 1979b). "Non-recurrent decreases" are caused by transient interplanetary events which are related to mass ejections from the Sun. 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. In the following, the term Forbush decrease is used for the non-recurrent decreases (*i. e.* those associated with transient solar wind disturbances) 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 (with 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 that is generated behind the shock which this fast ejecta (CME) 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 particle decreases. Since it is

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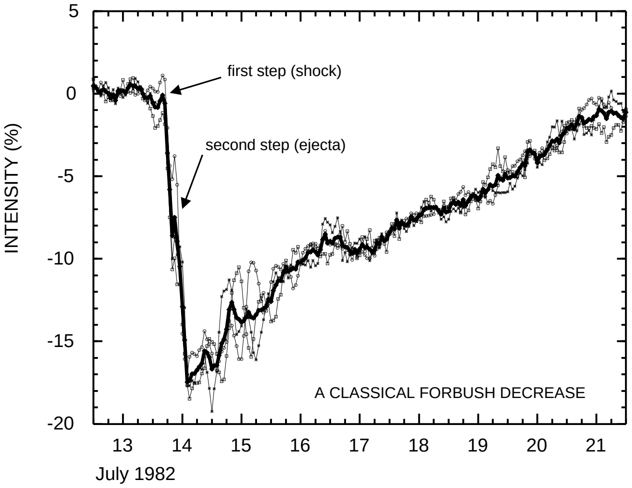


Figure 1. Percentage decrease for three neutron monitor stations spaced about equally in longitude (Deep River, Mt.Wellington, Kerguelen). The heavy line indicates the average of the count rates which is an approximate measure of the isotropic intensity. The two steps are indicated.

important to understand the characteristics of CMEs, 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 they are completely closed. Also of importance is the occurrence rate of CMEs 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 the extent of our knowledge of the characteristics of CMEs has been presented by Hundhausen (1998) with particular emphasis on the s Solar Maximum Mission (SMM) results. CME speeds occur in the approximate range 20–2000 km/sec with the average speed being about 400 km/sec. The extremely fast events tend to occur near solar maximum. Angular sizes occur in the range 5°-120° with the average size slightly less than 50°. (The maximum size just quoted excludes events that are viewed head-on and have sizes of 360°.) The average CME kinetic energy is about 5×10^{30} ergs. Since 1996, our knowledge of CMEs is being greatly enhanced by observations by SOHO and the LASCO coronagraphs. 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 have been seen to occur for 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 as has been sometimes assumed. Flares and prominence eruptions are different phenomena and often occur simultaneously. Usually the flares associated with CMEs are of long duration and also have associated meter wavelength type II and, particularly, type IV radio bursts (Robinson *et al.*, 1986). Type IV emission is believed to occur inside CMEs and is a good flare signature for the more energetic ones. 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. Flares are believed to be generated by the heating resulting from reconnection of field lines blown open by the CME. 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 on-disk phemomena is greatly enhanced by the UV and soft X-ray observations now available from SOHO and Yohkoh respectively.

The pre-SOHO CME rate has been summarised by Webb and Howard (1994). They found a rate of about 0.25 CMEs/day at solar minimum rising to about 2.5–3 CMEs/day at solar maximum (see also Fig. 2). The absolute rates are an underestimate 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 exclusion of minor CMEs from the rates determined from Solwind observations decreased the amplitude but did not substantially affect 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 per day during 3 months in early 1997 *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 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 Fig. 2 which

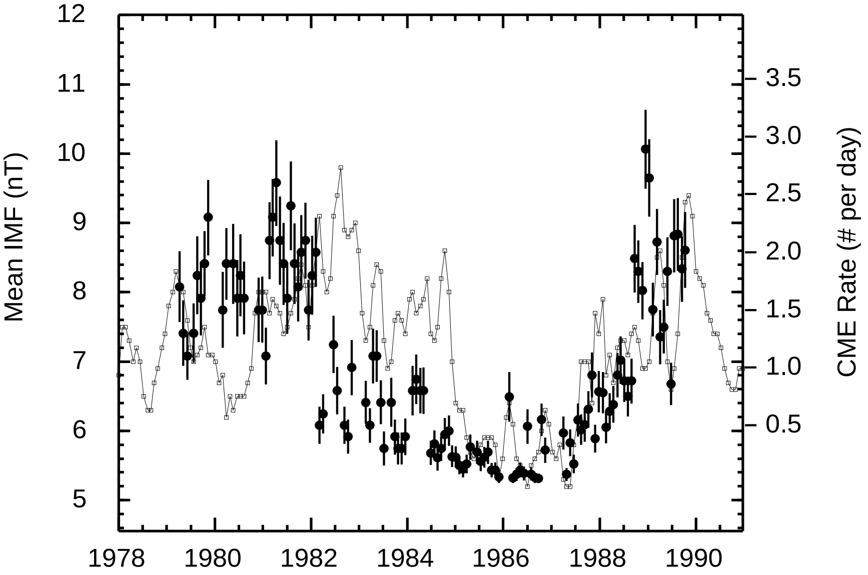


Figure 2. The CME rate (*large, filled circles*) compared with the interplanetary magnetic field (*small, open squares*) (IMF). Carrington rotation averages are used. The IMF has been smoothed using a running mean over 3 rotations. (The CME data were provided by O. C. St. Cyr.)

shows that the CME rate (SMM data Carrington-rotation averaged; St Cyr, private communication) does not track very well the average interplanetary magnetic field strength. Using one technique for identifying them in the interplanetary medium, Smith and Phillips (1997) estimate that CMEs contribute 8% to the interplanetary magnetic field. Webb and Howard (1994) found that CMEs contribute 10% to the solar wind mass flux.

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 a different name should be used 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 *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 all 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

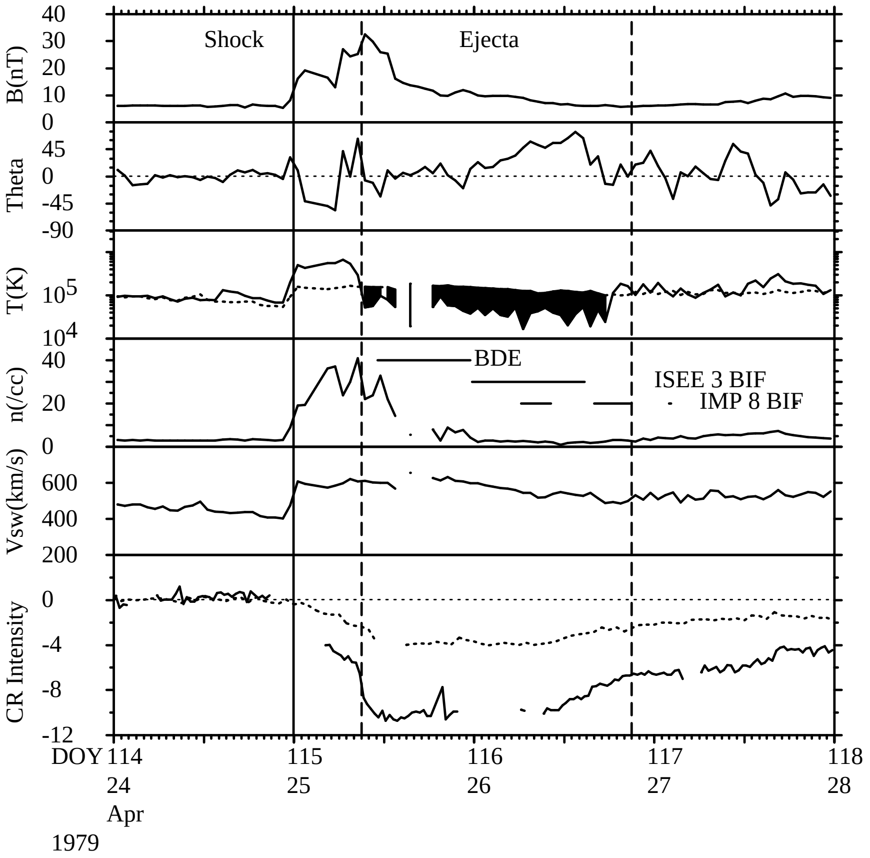


Figure 3. Solar wind data during a period when an ejecta was encountered. The top three panels show the magnetic field and its component out of the ecliptic, the proton temperature, density and speed. The dashed line in the temperature panel shows the expected temperature for normal solar wind expansion. 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

passage and the dashed lines the boundaries of the ejecta. 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 heat flux (as 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 electrons (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.* (1994) to indicate the presence of open field lines within ejecta.

The ejecta shown in Fig. 3 is reasonably typical. Its average speed is about 600 km/s which is greater than the upstream solar wind speed and therefore a shock is created. 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.

Also shown in Fig. 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 (see McDonald, 2000, this volume). The dotted line shows the isotropic intensity determined from three neutron monitors. This interplanetary event 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 is to look at energetic particle data especially that 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. Such an organised field structure may have implications for particle transport. 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 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 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 Fig. 8 of Burlaga *et al.* (1990) in which the 'legs' of the ejecta return to the Sun at widely spaced locations is misleading. Two separated intersections of an ejecta have never been recorded. A more likely scenario is that presented in Fig. 1 of Crooker *et al.* (1998) in which the following 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.

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 Fig. 4). (Hundhausen used the term “ejecta” to identify the drivers of interplanetary shocks at a time when CMEs were unknown). One feature of importance for understanding the asymmetries in longitude effects of interplanetary shocks (both for modulation and particle acceleration) is the fact that the pre-existing solar wind field lines get draped around the ejecta as it propagates away from the Sun. This means that an observer on the western side of an ejecta is connected to the strongest part of its shock when the shock is beyond the observer.

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 interpretation of the Ulysses results suggests 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. Just a year or so after the Lockwood (1971) paper, two papers by Barnden were presented at the International Cosmic Ray Conference in Denver. In these papers Barnden (1973a, 1973b) applied the Hundhausen shock picture to classic, two-step Forbush decreases. Barnden reasoned that the first step occurs at the shock and the second at the discontinuity marking entry into the ejecta. Unfortunately this work was never published in a refereed journal and thus it is only recently that researchers have stressed (*e. g.*, Wibberenz *et al.*, 1998) that there are two different physical mechanisms which cause Fds *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, *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,

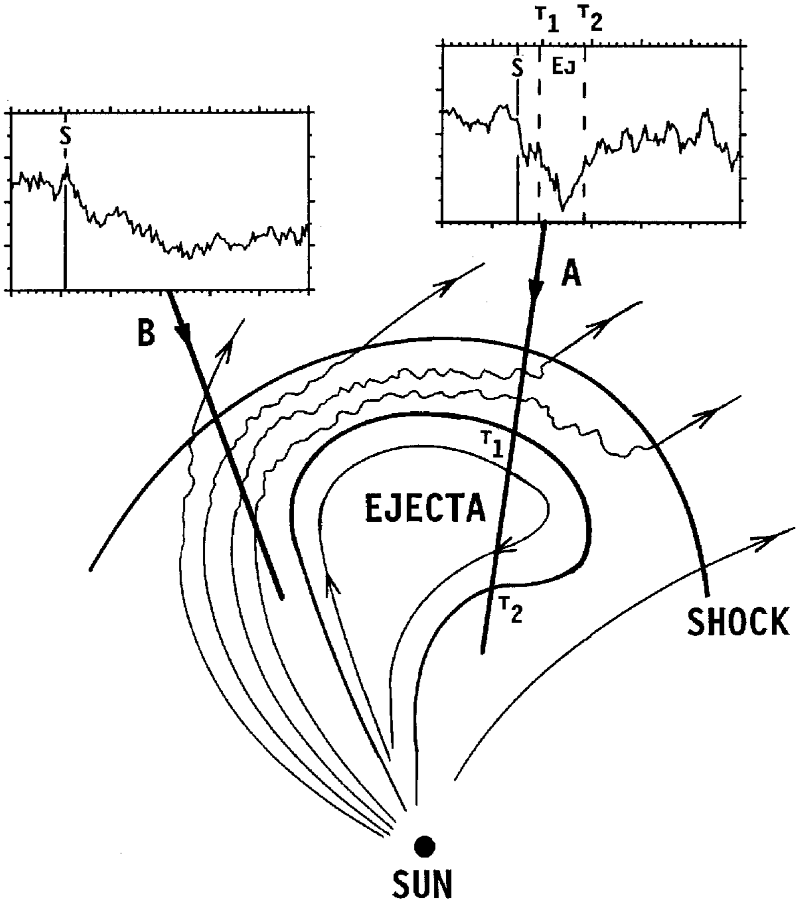


Figure 4. The large-scale structure of a fast ejecta and associated shock. The upstream solar wind is draped around the ejecta and heated and compressed at the front of the ejecta. Two paths through the ensemble are indicated with differing resultant cosmic ray profiles. The time of shock passage is 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.

it is possible to intercept the shock but not the ejecta as shown by path B. 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 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 can create shocks which are strong enough on their flanks to cause cosmic rays 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.

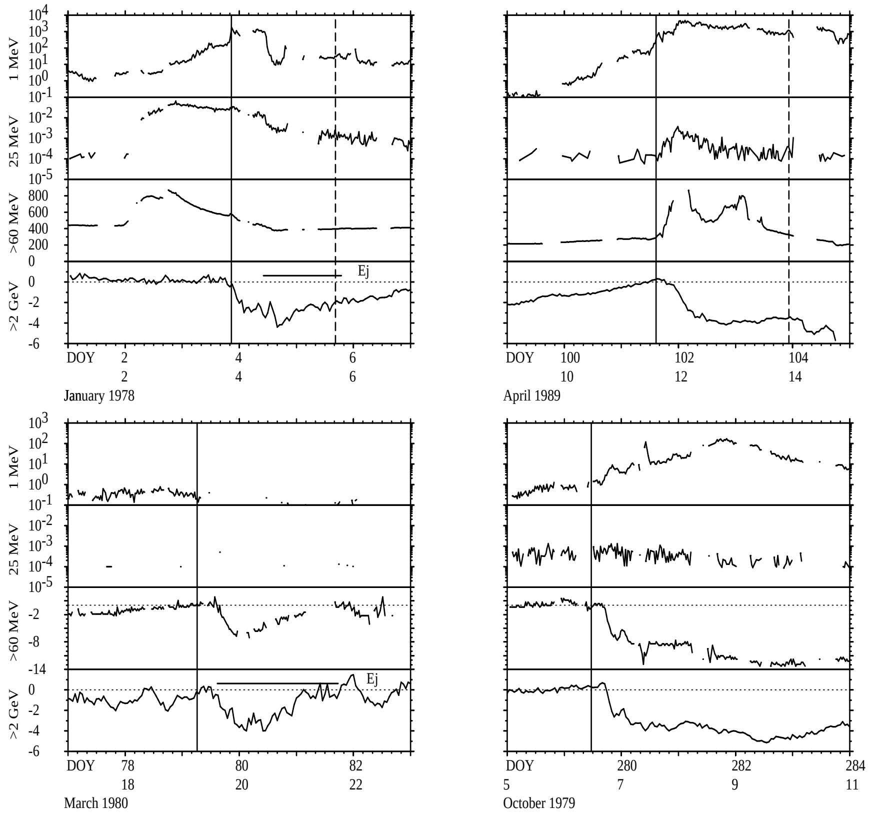


Figure 5. Particle data at four energies for four different types of solar wind flow (*see text*). The vertical lines indicate the times of shocks and the horizontal lines times of ejecta. The cosmic ray decreases in the top left and right panels are representative of paths A and B, respectively, in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

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 particle enhancements above a few MeV at 1 AU. Energetic CMEs are well-associated with solar energetic 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, $>\sim$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 stations referred to previously. The vertical lines indicate times of sudden commencement geomagnetic storms, indicative of shock passage. The dashed lines are for weaker events. 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 if 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 accelerated particles the two cosmic ray decreases at the bottom of Fig. 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. The associated shock did not generate a detectable particle increase above 1 MeV nor a cosmic ray decrease. 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 shock in the outer heliosphere, does not extend above 20 MeV and furthermore that 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 (*e. g.* Mt. Wellington) with a cut-off rigidity of $\sim$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 $\sim$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 dependence 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 *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.

Recovery Characteristics In isolated single Fds the recovery can be described as exponential with an average recovery time of $\sim$5 days but ranging from $\sim$3 to $\sim$10 days (Lockwood *et al.*, 1986). These authors found that the recovery time was independent of rigidity in the range $\sim$2 to $\sim$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 1960's compared with the $A>0$ epoch in the 1970's. 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 Sect. 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 determined 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 division has no meaning in terms of the physics of the particle effects. The only point is that the flare-associated events are in general caused by more energetic 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 (1973a) 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.* (1979a) 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 (*e. g.* Iucci *et al.*, 1979a) or even including disappearing filaments (Belov and Ivanov, 1997b) 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.

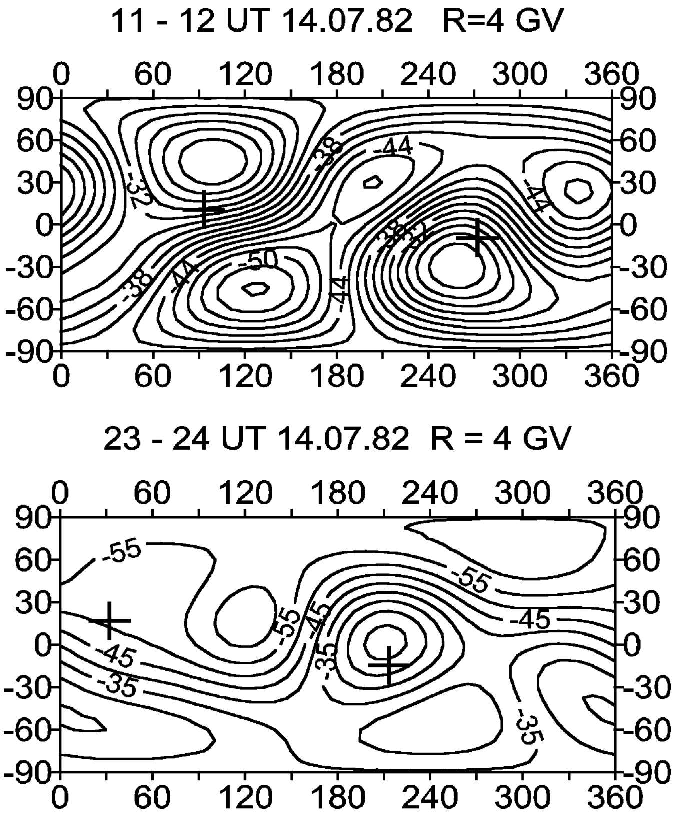
Occurrence Rates Fds are most common near solar maximum but occur throughout the solar cycle. There are fewer than 10 Fds greater than 10% per cycle and they occur around sunspot maximum but not in the year or so just after solar maximum (Cane *et al.*, 1996). To estimate whether the Fd rate is consistent with the CME rate, note that the CME rate at solar minimum is approximately 0.7 per day (see Sect. 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, we might expect something like 0.1 per day at Earth or 36 per year. Belov (private communication) reports over 100 “Forbush effects” in the year 1995 and based on the above estimate it is unlikely that the majority of these events are caused by CMEs. Many are probably 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 front-side 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 (*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 cause of the confusion is that a) it depends 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 has specific characteristics and in which the cosmic rays are supposedly trapped. These regions had a median duration of about 8 hours 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.

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 (1999) 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 (1999) 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.



11 - 12 UT 14.07.82 R=4 GV

23 - 24 UT 14.07.82 R = 4 GV

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

Belov *et al.* (*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 (*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 (*e.g.*, Belov *et al.*, 1995; Bieber and Evenson, 1998; Bieber *et al.*, 1999).

All of the work described above has only considered the first-order anisotropy of cosmic ray flows. Dvornikov and coworkers (*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 Fig. 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 bidirectional flows (Richardson, private communication). 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. EVOLUTION 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 occur on the backside of the Sun that can be the cause of events 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.

Probably the best data sets from which to infer how Fds evolve with time and radial distance are those from the anti-coincidence guard on the Helios spacecraft (Univ. of Kiel experiment) 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 showed 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

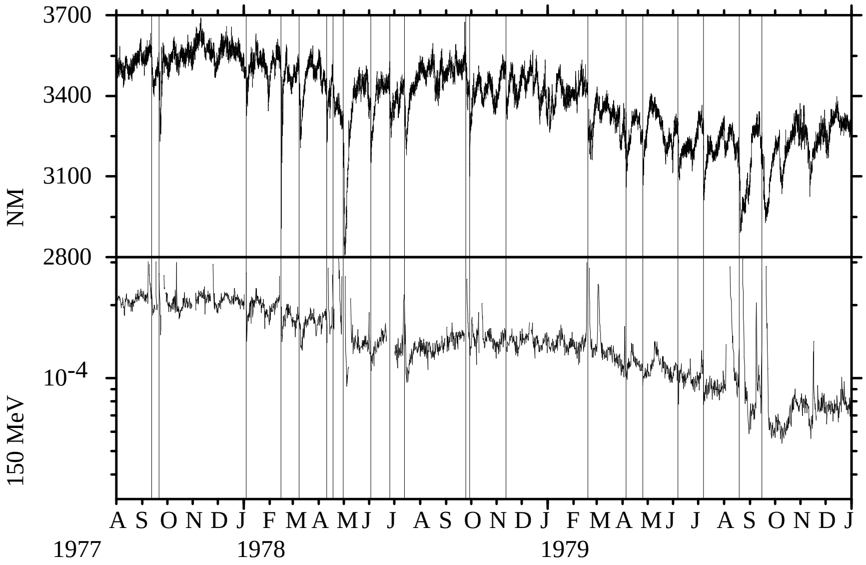


Figure 7. The cosmic ray variation in the period mid-1977-end 1979 when two “steps" occurred; one beginning late 1977 and the other near the start of 1979. The top panel shows the Mt. Wellington neutron monitor data and the bottom panel shows the 120-230 MeV differential intensity measured by the GFSC experiment on IMP 8. Vertical lines indicate the times of major CME-related Fds. The Fds are clearly superimposed on the gradual decline in intensity.

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.

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) formed by the merging of CMEs and corotating flows in the heliosphere beyond 10 AU. Recently Cane *et al.* (1999) have proposed an alternative explanation which is that the ‘steps’ 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 Fds, produced by CMEs/ejecta, are rather short on the time-scale of medium-term modulation events and at 1 AU appear superimposed on the steps as may be seen in the Fig. 7. In this figure the Mt. Wellington neutron monitor data are shown along with the IMP 8 120–230 MeV proton differential intensity for the steps in 1978 and 1979. Vertical lines indicate the times of $>4\%$ CME-related decreases which can be seen to be superimposed on the longer, downward trend of the data. Cliver *et al.* (1993) have also 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) and suggested that maybe it is the more common, less energetic, CMEs that are responsible. However based on our work showing that there is a good correspondence between ejecta (interplanetary

CMEs) and particle decreases (Cane *et al.*, 1997; Richardson *et al.*, 1999), it can be deduced that the majority of CMEs, even small ones, produce a signal in the 1 AU cosmic ray record. Thus the long-held idea (Lockwood, 1960) that the 11-year modulation is caused by the accumulated effect of many Fds should finally be put to rest.

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 correct part of the decrease is considered for 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),

$$\Phi = \int (V/3K)dr \tag{1}$$

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

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

C is the Compton-Getting factor. $\Delta\Phi$ represents the difference between the undisturbed and the disturbed conditions, and the integral in Eq. 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 (where V' and K' are the speed and diffusion coefficient behind the shock) and a box-like depression over a spatial region L Wibberenz *et al.* (1998) obtains the size of the depression as $\Delta U/U_o = CV'L/K'$. 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

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

where $\Delta U/U_o$ is the maximum depression, r the distance of the observer from the Sun, a and V the radius and speed of the cloud, $K_\perp$ the perpendicular diffusion coefficient. The function F is a monotonically decreasing function of the variables. If one also inserts $K_\perp \propto 1/B$, one sees therefore that $\Delta U/U_o$ increases monotonically with the product Ba^2V. Thus the size of the depression gets smaller when B, a or V are reduced. Thus there is a lower limit to the size of an ejecta which will produce a detectable decrease.

5. Summary

CMEs cause depressions in the cosmic 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. 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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