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Cosmic ray evidence for magnetic field line disconnection inside interplanetary coronal mass ejections

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Abstract. A characteristic feature of most interplanetary coronal mass ejections (ICMEs) is the presence of bi-directional flows of solar wind electron heat–fluxes. These flows indicate that the magnetic field lines within ICMEs are connected to the Sun at both ends. However, the bi-directional electron flows are frequently observed to be intermittent. It has been suggested that this occurs when field lines inside the ICME reconnect with open field lines of the normal solar wind. Occasionally the heat–flux is entirely absent, indicating a completely open structure. In either case this means that there are open field lines within the ICME along which cosmic rays may gain easy access. We examine cosmic ray intensities inside several ICMEs at 1 AU which have extended periods of unidirectional heat–flux or complete heat–flux 'dropouts' and consider whether there is any evidence that the intensities are related to the characteristics of the heat–fluxes and hence to the field line configuration.

1 Introduction

Interplanetary coronal mass ejections (ICMEs), also sometimes called ejecta, are the manifestations in the solar wind of the material expelled during coronal mass ejections at the Sun (CMEs). CMEs involve the expansion of closed solar magnetic field lines, which may be dragged out into the solar wind to distances of 1 AU or more. Compelling evidence for the presence of looped field lines rooted at the Sun is provided by the observation of intervals of bi-directional solar wind electron heat–fluxes (BDEs) inside many ICMEs (Gosling et al., 1987). An electron heat–flux directed away from the Sun along interplanetary field lines is a pervasive feature of the solar wind. Thus, on looped field lines connected to the Sun at each end, a bi-directional heat–flux may develop. However, observations show that interruptions in these bi-directional flows may occur, with unidirectional or even no heat–fluxes being observed instead. Gosling et al. (1995) suggested that these interruptions indicate previously looped field lines which have reconnected with the ambient interplanetary magnetic field. Unidirectional flows occur when one end of the field line remains connected to the Sun, whereas a heat–flux drop out indicates that the field line is completely disconnected from the Sun, and instead is connected at both ends to the IMF.

Since ICMEs contain closed field lines expelled from the Sun, the cosmic ray population within ICMEs will be initially depleted. Furthermore, cosmic rays can only slowly propagate perpendicular to the closed field lines into the interior of ICMEs as the ICMEs move away from the Sun. Hence, when an ICME passes by an observer, a depression in the cosmic ray intensity is generally observed. (Additional cosmic ray modulation may occur if the ICME is fast enough to drive a strong shock because of scattering in the post-shock plasma (Barnden, 1972).) If the Gosling et al. (1995) interpretation of the interruptions in the BDEs is correct, we might expect cosmic rays to be able to gain easier access to the interior of ICMEs along reconnected field lines, as indicated by the absence of BDEs. Access may be especially efficient when heat–flux drop-outs occur. Hence, we might expect the cosmic ray intensity inside ICMEs to be less depressed at those times when BDEs are absent. Bothmer et al. (1997) found evidence of this pattern during one ICME observed by the Ulysses spacecraft at 32^oS, 4.6 AU. They noted a small cosmic ray increase at the only time inside the ICME when the bi-directional electron heat–flux disappeared. In this paper, we examine whether there is a close relationship between the presence or absence of BDEs and the cosmic ray intensity in a series of ICMEs observed near the Earth in 1995-1998.

We will predominantly use cosmic ray observations made by the anti-coincidence guard of the Goddard experiment on IMP 8, which detects > 60 MeV particles. Cane et al. (1997) made an extensive study of short–term decreases seen in the counting rates of the IMP 8 anti–coincidence guard and similar guards of the University of Kiel experiments on Helios 1 and 2. The guards are very sensitive to depressions in

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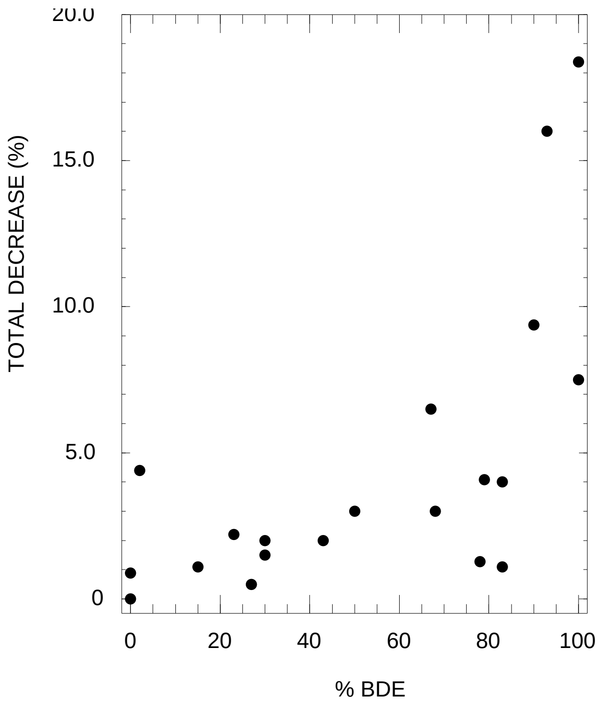

Fig. 1. Decrease in the cosmic ray intensity, as measured by the IMP 8 GME guard, which detects >60 MeV particles, as a function of the percentage duration of the associated magnetic cloud which exhibits bi-directional electron heat–flux flows indicating closed magnetic field lines (Shodhan et al., 2000). The decrease size shows some correlation with the fraction of BDEs, through there are clear exceptions, indicating that other factors are also important.

the cosmic ray intensity associated with ICMEs because of the low energy cut-off (since the depression size decreases with increased energy (Cane et al., 1995)) and because of the good counting statistics. Many of the decreases studied were only about 1% and would not have been detectable by neutron monitors. After first identifying ICMEs using their various characteristic solar wind signatures (see Richardson and Cane, 1995, and references therein), it was found that in essentially all ICMEs, the cosmic ray intensity was reduced. There was no indication of a distinct subset of ejecta showing no decrease which might have suggested that the ejecta field lines were predominantly open. The few events below 1% appeared part of the general distribution. This finding suggested that, at least on the scale size scanned by these cosmic ray particles (Larmor radius of ∼0.005 AU at ∼2GV), magnetic field structures in most ejecta are predominantly closed.

Recently, Shodhan et al. (2000) have examined the presence of BDEs observed by the WIND spacecraft during 34 ICMEs in 1995-98. These were all examples of the subset of ICMEs known as “magnetic clouds” (Burlaga et al., 1981). These are characterized by enhanced magnetic fields (> 10 nT) which rotate smoothly through a large angle and are consistent with a magnetic flux rope configuration, and with low β plasma. They found that BDEs were present during a fraction of the total duration of the ICME ranging from essentially 100% to rare examples with no BDEs. Typically, an ICME had intermittent periods of bi-directional or uni-directional streaming. Intervals of heat–flux drop–outs were observed in a few ejecta. We have examined the cosmic ray intensity-time profiles for these events, in order to assess whether there is any clear evidence of an association with the detection or absence of BDEs and heat–flux drop-outs consistent with the presence of open field lines along which cosmic rays can gain entry into the interior of ICMEs.

2 Results

We have first examined whether the size of the cosmic ray depression is correlated with the fraction of the ICME when BDEs were observed by WIND. Based on the arguments above, we might expect ICMEs with few BDEs to include predominantly open field lines and hence be associated with rather weak cosmic ray depressions. Conversely, those with essentially continuous BDEs should be predominantly closed and have larger cosmic ray depressions. Figure 1 shows the size of the cosmic ray decrease plotted versus the fraction of time when BDEs were observed in the ICME. The largest depressions do indeed appear to be associated with those ICMEs where BDEs are observed for the major fraction of the ICME duration. Furthermore, there was no depression associated with the ICME of January 10, 1997, which is the only example in the Shodhan et al. (2000) study that had extended heat–flux drop–outs suggesting that it was extremely well-connected to the IMF. However, there are exceptions which suggest that the relationship between decrease size and heat–flux observations is more complex. In particular, the ICME of May 15, 1997 included essentially no BDEs yet was associated with a ∼5% cosmic ray depression. Since there are other factors which influence the size of the cosmic ray decrease, this is not completely surprising. For example, the cosmic ray decrease can include contributions from post-shock scattering. The decrease size will also depend on the size (diameter) of the ICME, its speed (cosmic rays will have less time to fill in a fast ICME), and the particle propagation characteristics inside the ICME (Cane et al., 1995). Furthermore, Shodhan et al. (2000) found that the fraction of ICMEs where BDEs are observed is correlated with the diameter of the ICME inferred from a fit to a flux-rope model (see their Figure 5). Thus, it is unlikely that the dependence in Figure 1 can be solely ascribed to the fraction of open field lines within ICMEs.

Another way to examine whether there is such a relationship is to examine individual ICMEs. Figure 2 shows an example of an ICME observed near Earth in October 1995. This event is of interest because, other than the January 1997 ICME, it includes the largest fraction of heat–flux dropouts among the events discussed by Shodhan et al. (2000), while BDEs were observed for much of the rest of the time within the ICME. Hence, if variations in the cosmic ray intensity within an ICME really reflect the field line topology as indicated by the electron heat–fluxes, we might expect these to be particularly clear in this event. The panels in Figure 2 show (from top) the solar wind magnetic field strength, polar and azimuthal angles, the proton temperature, density and speed, from the WIND spacecraft. The ICME, delineated by the vertical dashed lines, is characterized by the enhanced, slowly rotating magnetic field characteristic of a magnetic cloud, and by intervals of abnormally low-temperature plasma (shaded), which are identified by the criterion $T_p < 0.5T_{ex}$ where T_{ex} is the temperature for normally expanding solar wind calculated from the solar wind speed (see Richardson and Cane, 1995 for details) indicated by the dashed line in the T_p panel. Note that, although the magnetic field signature suggests a homogeneous structure, the plasma temperature data indicate that the ICME consists of two regions of cool plasma near the edges with a region of more normal temperature near the center. The upper horizontal bars in the solar wind speed panel indicate periods of bi-directional heat–fluxes, while the lower indicate heat–flux drop-outs (Shodhan et al., 2000). Other periods have unidirectional heat–fluxes. Based on the discussion above, we might expect cosmic rays to have restricted access to the regions where BDEs are observed (indicating looped field lines), but be able to enter regions with heat–flux dropouts more readily. The bottom panels of Figure 1 show several measures of the cosmic ray intensity, specifically the intensity of 10 GV cosmic rays inferred from analysis of data from the worldwide NM network (Dvornikov and Sdobnov, 1997) (dashed line), an average of the count rates of several neutron monitors with ~ 2 GV cutoffs (solid line), and from the IMP 8 guard. The cosmic ray intensity begins to decline following passage of a shock generated ahead of the ICME (at 1041 UT, October 18). There is then a more abrupt decrease (most evident in the guard data) as the leading edge of the ICME arrives. Hence this is an example of a "two-step" Forbush decrease (Barnden, 1972; Cane et al., 1994). Of particular interest here is the tendency for the cosmic ray intensity to recover from around 06 UT on October 19 at the time when the BDEs cease and heat–flux drop-outs begin to occur. Thus, the behaviour of the cosmic rays during this ICME appears to be consistent with the expectation from the electron heat–fluxes that the leading part of the ICME includes closed field lines whereas the trailing part contains field lines well connected to the IMF. We have examined the cosmic ray anisotropies at 4 GV inferred from the NM network, but these are weak and we do not find any clear pattern such as bi-directional flows during the BDE intervals (c.f., Richardson et al., 2000) and unidirectional flows during the heat–flux drop-outs.

A preliminary examination of the other events of Shodhan et al. (2000) suggests that there is generally no clear temporal relationship between the cosmic ray intensity and the presence or absence of BDEs. Certainly, as noted above, those ICMEs almost completely filled by BDEs also tend to have large cosmic ray depressions, whereas weak depressions are associated with the heat–flux drop-outs in two ICMEs. In other events where there are intermittent intervals of uni- and bi-directional heat–fluxes, there is generally no consistent pattern of lower cosmic ray intensities when BDEs are observed, and temporary recoveries when BDEs cease such as in the Ulysses example reported by Bothmer et al. (1997). A possible explanation is that the location at which field line reconnection occurs may also be important. For example, suppose that reconnection of a looped ICME field line occurs very close to the Sun. Though the field line is disconnected from the Sun and a unidirectional heat–flux is detected on this field line within the ICME, this change in field-line connection at the footpoints of the ICME will cause essentially no change in the overall structure of the ICME stretching far out (~ 1 AU or more) into the solar wind, to which the cosmic rays respond. (In fact, Shodhan et al. (2000) also conclude from the fact that magnetic clouds are coherent magnetic structures, yet the changes in heat–flux occur intermittently and are not related to local plasma structures, that reconnection must occur far from the observer.) On the other hand, if reconnection occurs far out in the solar wind and closer to the observer, then there is a greater chance that cosmic rays entering the ICME along these field lines will be detected. Perhaps it is significant that the event discussed by Bothmer et al. (1997) occured far from the Sun since presumably there will be a greater possibility of reconnection with the solar wind magnetic field in such extended structures.

3 Summary

From examining the relationship between depressions of the cosmic ray intensity within ICMEs and the field line topology as indicated by the solar wind electron heat–fluxes, we find that there is a tendency for ICMEs in which extended bi-directional heat–fluxes are observed (suggesting the presence of looped field lines rooted at the Sun) to be associated with larger cosmic ray depressions. However, there are clear exceptions to this pattern. Furthermore, there are other possibilities which may help to explain this dependence. For example, ICMEs with larger fractions of BDEs are on average larger and hence would be filled less rapidly by cosmic rays. While these results suggest some support for the expectation that cosmic rays are excluded from closed field regions within ICMEs and can gain easier access along field lines connected to the IMF, a preliminary examination of the ICMEs discussed by Shodhan et al. (2000) suggests that there is no clear relationship between the cosmic ray intensity and the presence or absence of BDEs in individual ICMEs, in contrast to the one example discussed by Bothmer et al. (1997). A possible explanation is that reconnection occurs far from the observer (for example close to the Sun) and does not affect the overall configuration of the ICME to which the cosmic rays respond. There is evidence from the few events such as the January 1997 ICME, which include an unusually large fraction of heat–flux drop-outs (suggesting field lines totally connected to the IMF), that heat–flux drop-outs may be associated with generally weaker depressions.

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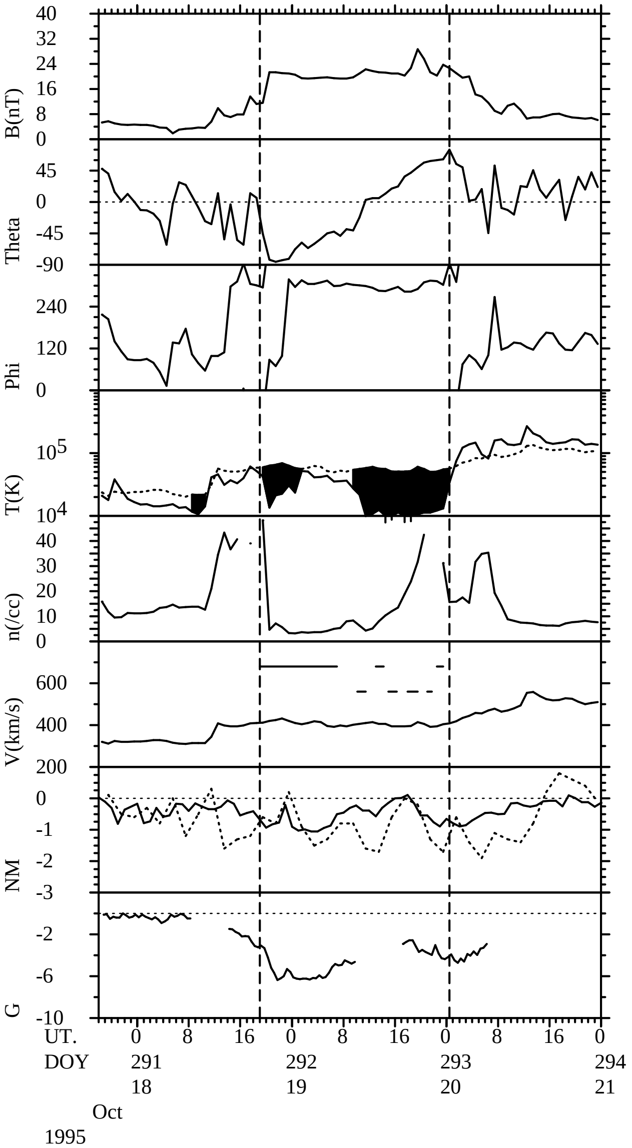

Fig. 2. Solar wind characteristics of a magnetic cloud (upper panels) and the associated response in cosmic rays (bottom two panels). The magnetic cloud is delineated by the vertical dashed lines. The horizontal dashes in the solar wind speed panel indicate periods of bi-directional solar wind electron heat–fluxes (upper) and heat–flux drop–outs (lower) (Shodhan et al., 2000) which indicate closed field lines and field lines totally open to the IMF, respectively. Note that the cosmic ray intensity shows evidence of a partial recovery in the region where heat–flux drop–outs are observed, suggestive of the possibility of cosmic rays entering along open field lines.

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