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ANOMALOUS COSMIC RAYS AS PROBES OF MAGNETIC CLOUDS

D. V. Reames[1], S. W. Kahler[2], and A. J. Tylka[3]
[1] Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA; dvreames@umd.edu
[2] Air Force Research Laboratory, RVBXS, 29 Randolph Rd., Hanscom AFB, MA 01731, USA
[3] Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA
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ABSTRACT

We report, for the first time, the observation near the Earth of anomalous cosmic ray (ACR) particles throughout the interiors of interplanetary magnetic clouds (MCs) at the same intensity as outside the MCs. ACRs, accelerated in the outer heliosphere, have unique elemental abundances making their identity unambiguous as they probe these clouds from the outside. Thus, MCs, carried out from the Sun by coronal mass ejections (CMEs), are seen to contain no structures that are magnetically closed to the penetration of ions with energies above a few MeV amu^{-1}. As the MCs expand outward, they must fill their increasing volume with ACRs dynamically, to the same degree as neighboring "open" field lines. These observations cast doubt on conventional ideas about the closed field topologies of MCs and the cross-field transport of energetic particles. The ACR observations conflict with some reports of significant exclusion from MCs of solar energetic particles (SEPs) of comparable energy and rigidity. A process that allows cross-field transport of ACRs may also allow similar transport of SEPs late in events, causing the large spatial extent and uniformity of SEPs in "invariant spectral regions" extending far behind CME-driven shock waves.

Key words: cosmic rays – interplanetary medium – shock waves – Sun: coronal mass ejections (CMEs)

1. INTRODUCTION

Magnetic clouds (MCs) are interplanetary loop structures with strong helical magnetic fields that are ejected from the Sun in coronal mass ejections (CMEs; e.g., Burlaga et al. 1981). MCs are believed to evolve from the expansion of magnetic flux ropes in streamers near the Sun (Wu et al. 1999). Observation of bidirectional flows of solar wind heat flux electrons from the tail of the thermal distribution at the Sun (Gosling et al. 1987) has led to the suggestion that some or all of the flux loops in the MCs are magnetically "closed" (Shodhan et al. 2000) in the sense that both ends of the loop connect directly back to the solar surface (see review by Wimmer-Schweingruber et al. 2006). The twisting of the field about the axis of the MC loop can produce long field-line lengths of up to ~3 AU that can be measured by the timing of impulsive electron injection at the solar foot points (e.g., Larson et al. 1997). In a study of Forbush decreases in the intensity of galactic cosmic rays (GCRs) at MCs, Zhang & Burlaga (1988) noted that these decreases were much smaller (0.5% versus 2.5%) when MCs were not preceded by interplanetary shock waves, suggesting that the depressions were mainly caused by the sweeping action of the turbulent sheath behind the shock. However, there is sometimes surprise at the presence of MeV solar energetic particles (SEPs) inside the presumably "closed" fields of MCs, even suggestions of possible new reconnection mechanisms to accelerate ions into the sunward end of MCs, while there are other reports of 70%–90% exclusion of SEPs from MCs (see reviews by Gazis et al. 2006; Klecker et al. 2006; Wimmer-Schweingruber et al. 2006). Are the ions in MCs greatly suppressed or are they enhanced by novel acceleration?

Studies of the energetic particles of ~10–50 MeV amu^{-1} during solar quiet times led to the discovery of the anomalous cosmic rays (ACRs), so named because of their unusual spectra and element abundances, e.g., O/C > 20 and He/O ~ 1 (Garcia-Munoz et al. 1973, 1975; McDonald et al. 1974). ACRs were observed to be modulated like GCRs during the solar cycle (e.g., Reames & McDonald 2003). ACRs were explained as interstellar neutral elements (with high first ionization potentials) that entered the heliosphere, were photoionized by the Sun, carried out by the solar wind, and accelerated at the heliospheric termination shock (Fisk et al. 1974; Pesses et al. 1981). After acceleration, ACRs are modulated as they propagate back in to 1 AU against the flow of the solar wind plasma. The abundances, spectra, and temporal behavior of the ACRs at 1 AU have been well described since the last solar minimum using data from the Low-Energy Matrix Telescope (LEMT) on the *Wind* spacecraft (Reames 1999a; Reames & McDonald 2003). All ACR measurements used in this Letter come from LEMT as described in those references. ACRs have been previously overlooked as possible probes of MCs.

During times near solar minimum, CMEs with MCs are often emitted at speeds comparable with the ambient solar wind speed, nominally ~400 km s^{-1}. These CMEs are too slow to drive strong shock waves in the interplanetary medium hence they rarely accelerate SEPs (see the review by Reames 1999b). This allows us to observe the physics of "pure" MCs as probed by low-intensity nonsolar ACR test particles at MeV energies, as Zhang & Burlaga (1988) did with GCRs at GeV energies. During these MC periods, ACRs are the only particles of ~2–20 MeV amu^{-1} observed by the *Wind* spacecraft to be present in the vicinity of the Earth. At higher energies, GCRs, also near solar maximum intensity, are observed from the *IMP-8* spacecraft.

2. ANOMALOUS AND GALACTIC COSMIC RAYS IN MAGNETIC CLOUDS

For our study, we have used the list of MCs from Shodhan et al. (2000) identified using data from the *Wind* spacecraft between 1995 and 1998. These MCs were identified according to criteria described by Lepping et al. (1990). We have removed 7 MC periods for which abundances, intensities, and spectra do not reflect the dominance of ACRs. In the MCs we removed, the ACRs were usually swamped by the presence of more numerous SEPs accelerated by an associated shock wave.

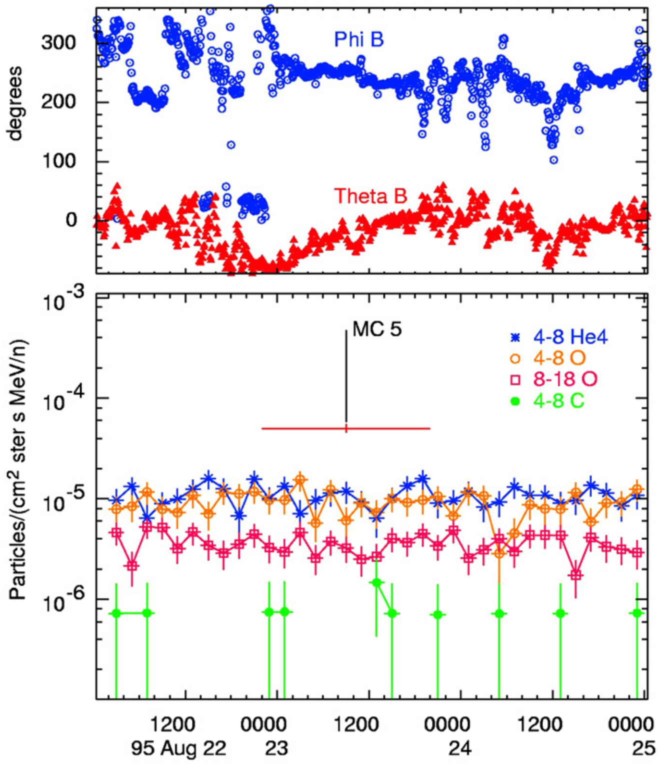

Figure 1. The upper panel shows the polar and azimuthal angles of the magnetic field direction at *Wind*, in GSE coordinates, showing the uniform rotation during the magnetic cloud indicated as MC 5. The lower panel shows intensities of ACR He, C, and O ions.

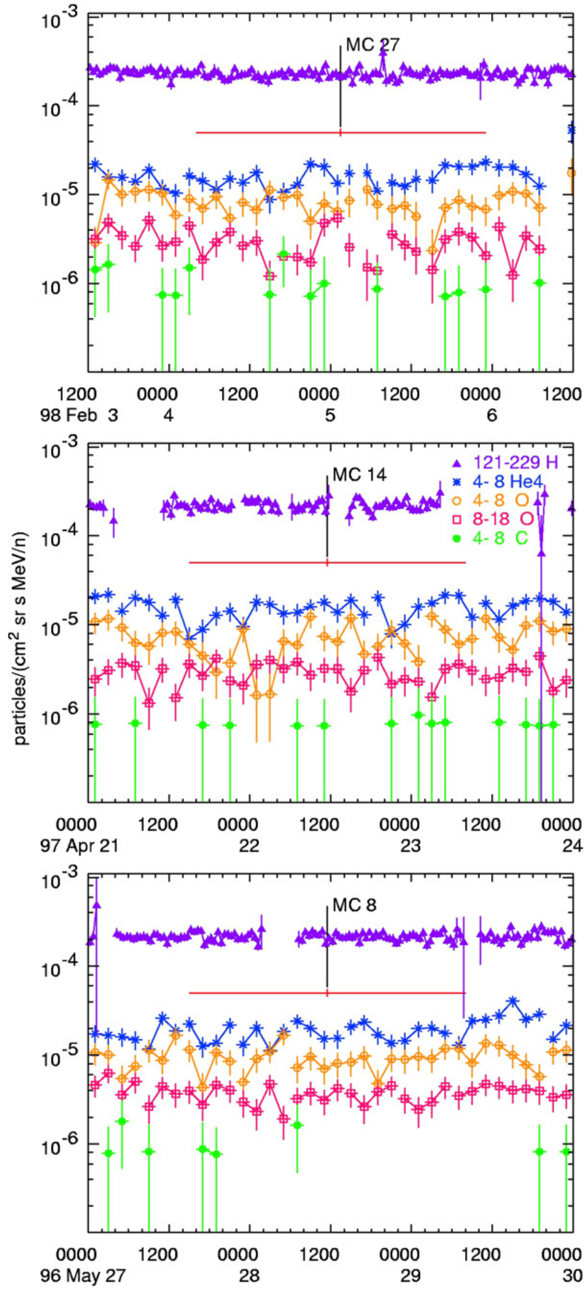

Figure 2. The panels show the intensities of ACR He, C, and O and GCR H in three long duration MC periods.

The lower panel of Figure 1 shows the intensities of ACR ions He, C, and O from the *Wind* spacecraft during one of the MC periods (MC 5). The upper panel of the figure shows angles defining the direction of the magnetic field at *Wind*, which undergoes a characteristic rotation during the MC period. Note from the 4–8 MeV amu^{-1} data that the intensity of He is nearly equal to that of O, and that C/O is very small for the entire period shown. Figure 2 shows the ACR intensities, as well as the intensity of the GCR protons from *IMP-8* for three spatially wide (long duration) MCs for which ACR intensity gradients might be more evident, if they existed. We have retained the cloud numbers from the Shodhan et al. (2000) paper which reports MCs 8, 14, and 27 to have 78%, 83%, and 68% closed field lines, respectively (see below). No exclusion of ACRs or GCRs from these MCs is apparent.

Table 1 lists properties of the 23 MCs in our study including the original cloud number, onset time and duration of each cloud, the intensity of the 4–8 MeV amu^{-1} O, and the He/O and C/O ratios. The last column in the table gives the percentage of time during the MC for which bidirectional electron (BDE) flows are observed; according to Shodhan et al. (2000) this equates to the percentage of closed field lines. However, none of the field lines appear to be closed to the entry of ACRs during any of these MCs. All 23 of the MCs are uniformly full of ACRs, independently of the BDE percentage. BDEs are generally taken as evidence of closed field lines with electrons injected at the Sun on each end. However, it is also possible to produce BDEs by injecting electrons at one end and reflecting them at the other, although angular distributions may distinguish this case.

The cloud-to-cloud variations in O intensity seen in Table 1 are placed in the context of overall ACR temporal behavior in Figure 3. In the figure, the intensities during MCs are shown as open circles against the background of the continuous ACR variation including the well-known 27 day modulation of the intensities (e.g., Reames & Ng 2001). Figure 3 also explains why it is difficult to establish a long-term-averaged reference of ACR intensity for comparison with ACRs inside MCs. To the extent we can measure it, the ACRs intensity in the clouds fluctuates above and below the precloud level by ∼10%.

3. DISCUSSION

Before proceeding, we should point out that we *cannot* firmly establish the method by which the ACRs penetrate the MCs. They could (1) enter along the field lines that are originally open that thread through all regions of the MCs, they could (2) drift or scatter transversely across both open and closed field lines after a sufficient amount of time or path length is traversed,

Table 1
Properties of Magnetic Clouds

MC	Onset (UT)	Duration (hr)	4–8 MeV/amu O (m^2 sr s MeV/amu)$^{-1}$	He/O	C/O	%BDE
1	1995 Feb 8 0300	20	0.070 ± 0.008	3.92 ± 0.54	0.0149 ± 0.015	65
3	1995 Apr 6 0700	12	0.065 ± 0.010	1.62 ± 0.34	<0.026	29
4	1995 May 13 1000	7	0.088 ± 0.016	1.59 ± 0.38	0.0333 ± 0.034	17
5	1995 Aug 22 2200	22	0.094 ± 0.008	1.15 ± 0.13	0.0350 ± 0.016	92
6	1995 Oct 18 1900	30	0.064 ± 0.006	1.35 ± 0.16	0.1200 ± 0.032	48
7	1995 Dec 16 0500	18	0.069 ± 0.007	1.68 ± 0.23	0.0476 ± 0.024	50
8	1996 May 27 1500	41	0.090 ± 0.006	1.90 ± 0.15	0.0172 ± 0.009	78
9	1996 Jul 1 1700	17	0.088 ± 0.009	2.31 ± 0.29	0.0106 ± 0.011	0
10	1996 Aug 7 1300	22	0.131 ± 0.010	1.43 ± 0.14	0.0055 ± 0.0055	5
12	1997 Jan 10 0500	22	0.076 ± 0.007	1.70 ± 0.20	0.0175 ± 0.012	27
13	1997 Feb 10 0300	16	0.073 ± 0.008	1.38 ± 0.21	0.0256 ± 0.018	83
14	1997 Apr 21 1500	41	0.065 ± 0.005	2.26 ± 0.21	0.0465 ± 0.017	83
15	1997 May 15 0900	17	0.062 ± 0.008	2.40 ± 0.36	0.0317 ± 0.023	2
16	1997 Jun 9 0200	22	0.110 ± 0.009	1.67 ± 0.17	0.0124 ± 0.0088	6
17	1997 Jul 15 0600	20	0.080 ± 0.008	2.02 ± 0.24	0.0185 ± 0.013	30
18	1997 Aug 3 1400	12	0.100 ± 0.011	1.85 ± 0.26	<0.012	50
21	1997 Oct 1 1600	32	0.054 ± 0.005	2.52 ± 0.28	0.008 ± 0.008	100
22	1997 Oct 10 2300	26	0.052 ± 0.005	2.76 ± 0.34	0.0870 ± 0.032	100
25	1998 Jan 7 0300	32	0.082 ± 0.006	1.63 ± 0.16	0.0275 ± 0.012	79
26	1998 Jan 8 1400	9	0.076 ± 0.011	1.93 ± 0.35	0.0217 ± 0.020	5
27	1998 Feb 4 0400	43	0.077 ± 0.005	2.02 ± 0.18	0.0446 ± 0.015	68
28	1998 Mar 4 1400	41	0.073 ± 0.005	1.93 ± 0.17	0.0239 ± 0.011	15
30	1998 Jun 2 1000	6	0.049 ± 0.011	1.76 ± 0.51	0.0526 ± 0.054	0

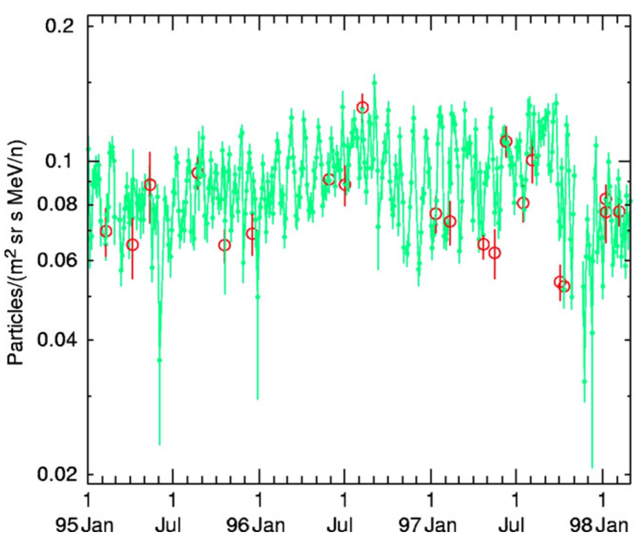

Figure 3. Intensities of 4–8 MeV amu^{-1} O are shown in MC periods as open circles superposed on the background intensity which is undergoing 27-day variations.

or they could (3) enter through progressively opened field lines following continual reconnection of MC closed field lines with ambient open field lines of the solar wind. These alternatives are not mutually exclusive.

There is abundant evidence that, on short timescales, particles from impulsive injections from compact sources at the Sun do not cross onto neighboring flux tubes. Mazur et al. (2000) observed dropouts in MeV ion intensities as the spacecraft crossed magnetic flux tubes that were, or were not, connected to their solar impulsive source. Larson et al. (1997) had observed similar behavior for electrons. Multispacecraft observations of large SEP events show strong spatial gradients early in the events (Reames et al. 1997). These ions and electrons have traversed a distance of 1–3 AU when they were observed. ACRs at 4 MeV amu^{-1} travel ∼16 AU day^{-1}. Hence, if the field lines in MCs are not initially open, we estimate that a scattering mean free path for cross-field transport of ∼5 AU might be required to maintain uniformity of the ACRs, adding to the MCs' content on a timescale of ∼8 hr as they expand. This estimate of ∼5 AU or 8 hr is a compromise between the 1–3 AU, for which ions do not seem to cross flux tubes (e.g., Mazur et al. 2000), and the need to fill the MCs in a small fraction of their transit time out to 1 AU. However, the ACRs show no evidence of spatial gradients within the MCs that might be expected from cross-field drift or diffusion. Reconnection and mixing of field lines on a similar timescale might also maintain the ACR intensities.

By studying MCs that drive only weak shock waves, we can separate possible magnetic exclusion by the MC from the sweeping effect of the turbulent sheath of the shock and its downstream compression region that dominates the Forbush decreases in GCR intensity (e.g., Zhang & Burlaga 1988). However, our interest lies with particles of much lower energy and rigidity.

Using SEP data from Cane et al. (1995), a review by Richardson (1997) found that "At lower rigidities (less than 0.5 GV, $E_{\text{proton}} < 100$ MeV) the depression can be greater than 70%. These observations suggest that ejecta are predominately closed magnetic structures." This percentage implies a factor of 3 or more intensity decrease inside MCs. Our ACR He at 4 MeV amu^{-1} has a rigidity of 0.347 GV and is not suppressed by more than a ∼10%, if at all, in 23 MCs. This appears to be a major difference in behavior. A depression of the ACR intensity by a factor of 3 or more would be quite obvious in Figures 1 and 2 and in all of the similar MCs in Table 1. The statistics of the ACR measurements, while imperfect, are quite adequate to show a lack of extreme suppression below 0.5 GV. Perhaps the large spatial gradients in SEP intensities, attributed to the MC itself, actually occur outside the MC.

If BDEs signify the percentage of closed field lines and if closed field lines excluded ACRs, then we would expect that those MCs with >50% BDEs (Table 1) would also show suppression inside the MCs by factors of >2. The MCs plotted in Figures 1 and 2 have BDE percentages of >68% and should show large ACR suppression. MC 5 in Figure 1 has a BDE percentage of 92% and should show a factor of 10 suppression of ACRs inside the cloud. None of the 23 MCs show *any* significant suppression of ACR intensities, independently of the BDE percentage. Mazur et al. (2000) showed intensity dropouts in an impulsive SEP event as the spacecraft crossed filled and empty flux tubes; no such intensity dropouts of ACRs are seen as *Wind* crosses supposedly closed and open field lines in the MCs.

At the other extreme, if ACRs and SEPs easily penetrate MCs, it seems unnecessary to suggest any new acceleration mechanisms to supply the SEPs found inside (Richardson 1997; Klecker et al. 2006). Thus, "particles accelerated at the time of the CME lift-off at the Sun" and unrelated to the shock (see p. 241 of Klecker et al. 2006) are not required to populate the inside of the MC.

Being singly ionized, the ACRs have a higher rigidity and gyroradius (typically $\sim 2 \times 10^{-4}$ AU for He at 4 MeV amu^{-1}) than partially ionized SEPs or other ions of the same velocity or energy nucleon^{-1}. However, for He especially, this only amounts to a factor of 2 rigidity difference, which cannot have a major qualitative effect on the cross-field transport. Furthermore, the ACR spectrum actually extends below $\sim$2 MeV amu^{-1}. Thus, it seems likely that SEPs can go anywhere ACRs can go, with nearly equal facility. This suggests that SEPs accelerated at a CME-driven shock wave could continually fill the MC behind that shock as do ACRs; SEPs in an MC need not be accelerated by some new mechanism at the sunward end of the cloud.

Multispacecraft observations (e.g., Reames et al. 1997) have shown that large spatial regions extending far behind the shock wave in large SEP events are filled with SEPs at highly uniform intensities that decrease slowly with time. Particle spectra in these regions are presumably maintained by adiabatic deceleration in the expanding volume. Production of these "invariant spectral regions" suggests that extensive cross-field transport, up to $\sim 120^\circ$ in solar longitude and several AU in radius, must occur late in events from cross-field scattering or from field-line mixing and reconnection.

4. CONCLUSIONS

Most MCs during the 1995–1998 study period surrounding solar minimum are "pure" in that they are not accompanied by strong shock waves or locally accelerated particles that could obscure ACRs. The MCs we observe during this period are uniformly populated with ACRs and GCRs. These clouds must continue to fill with ACRs and GCRs dynamically as they expand. These observations argue against the existence of any dominant structures in the clouds that are magnetically closed to energetic ions above a few MeV amu^{-1}. Intrinsically open fields, subsequent field-line reconnection, or cross-field transport with an estimated timescale of $\sim$8 hr or mean free path of $\sim$5 AU could explain the observations. Whatever the mechanism, ions of more than a few MeV amu^{-1} cannot be excluded from the clouds and SEPs undoubtedly propagate into the MCs with equal facility as the ACRs and need not be accelerated in the magnetic regions where they are found. Slow cross-field transport, perhaps by field-line mixing and reconnection might also explain the uniformity and extent of invariant spectral regions late in SEP events.

The rare and enigmatic ACRs provide a new, long-overlooked, tool to study particle penetration into MCs. They do not provide decisive information on the physical mechanism of penetration, but they do raise many significant new questions about the validity of contemporary views of particle transport and the topology of MCs.

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