Solar Phys (2010) 265: 187–195
DOI 10.1007/s11207-010-9527-2

Remote Sensing of Magnetic-Cloud Topology

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Received: 4 November 2009 / Accepted: 31 January 2010 / Published online: 23 February 2010

Abstract We investigate the topology of magnetic clouds using energetic particles from a variety of sources outside the clouds as probes to remotely sense the interconnections of the magnetic field. We find that only a small percentage of field lines in magnetic clouds are truly closed directly to the Sun, so as to exclude particles from an external source. Field lines that are open to the outer heliosphere must be mixed with closed field lines on a fine spatial scale in the clouds to explain the simultaneous observation of anomalous cosmic rays from the outer heliosphere and of counter-streaming suprathermal electrons from the corona. The results of this paper show that, given sufficient time, particles accelerated at shock waves outside magnetic clouds have access to the interior and to a wide region of solar longitude in interplanetary space surrounding the clouds.

Keywords Solar energetic particles · Shock waves · Magnetic clouds

1. Introduction

Energetic particles from a variety of sources are guided by magnetic fields as they propagate throughout the heliosphere, providing a means of remotely sensing and mapping those fields. The magnetic topology of the inner heliosphere can be quite complex as multiple coronal mass ejections (CMEs), often containing well-organized magnetic clouds (MCs), drive shock waves out into the solar wind. MCs are characterized by strong magnetic fields that are helically wound into a loop-like structure (Burlaga *et al.*, 1981). Observation of counter-streaming suprathermal electrons in MCs is taken as evidence that the field lines are closed, meaning that both ends of the magnetic field lines connect directly back to the corona within the local region of interest (*e.g.* Gosling *et al.*, 1987;

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Guest Editors: M.M. Bisi, and A.R. Breen.

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Shodhan *et al.*, 2000). In some MCs the field lines are reported to be 100% closed (see Shodhan *et al.*, 2000). These electrons are presumably injected onto the field lines from the tail of the thermal electron distribution in the corona. Observations of particles of higher energy from impulsive solar events, for example, also probe these MCs, indicating that at least one end of some of the field lines is rooted at the Sun (Kahler and Reames, 1991).

On the smallest spatial scale, however, turbulence in the circulation of the photospheric plasma produces a random walk of the footpoints of magnetic field lines (Jokipii and Parker, 1969; see also Parker, 1987) that can create an irregular pattern of tangled, perhaps interconnected, magnetic flux tubes. Particles released at one point in this pattern can spread laterally, mainly by diffusing *along* the field lines. Given sufficient time, the particles can reach a distant point laterally after traversing a substantial path length along the field lines. This pattern can be further complicated by subsequent reconnection of the field in regions that may unite closed and open field regions such as the so-called interchange reconnections (Crooker, Gosling, and Kahler, 2002).

In addition to solar energetic particles (SEPs) accelerated by flares and CME-driven shock waves, the inner heliosphere is also bathed in energetic particles from the outer solar system (for a review, see Reames, 1999). For many years galactic cosmic ray (GCR) intensities have been observed to be suppressed by a few percent downstream of interplanetary shock waves (*e.g.* Forbush, 1946), resulting partly from the sweeping action of the shock and partly from exclusion of particles by the MC (*e.g.* Burlaga *et al.*, 1981). If the field lines in MCs are closed directly back to the Sun on both ends, how do $\sim 90\%$ of the GCRs get in? Generally this question was dismissed, perhaps because of the high rigidity of the >1 GeV GCR protons, even though their gyroradii ($\sim 10^{-3}$ AU) are much smaller than the cloud size.

Recently, however, it has been reported (Reames, Kahler, and Tylka, 2009) that low-energy anomalous cosmic rays (ACRs) from the outer heliosphere also penetrate easily into MCs. ACR He^+ at ~ 4 MeV amu^{-1} has a gyroradius of $\sim 2 \times 10^{-4}$ AU near Earth. If ACRs can penetrate MCs so easily, SEPs of similar energy must also be able to penetrate MCs. Are the field lines in MCs open or closed? How can we reconcile the evidence of counter-streaming electrons with that from ACR observations in the same clouds? In this paper we examine ACR and SEP observations and seek answers to these questions.

2. ACR Observations

Following Reames, Kahler, and Tylka (2009), we reexamine 21 MCs from the list of Shodhan *et al.* (2000) where the magnetic topology of each cloud has been determined from counter-streaming suprathermal electrons. The clouds of interest occurred during solar minimum and were not accompanied by fast shock waves that could accelerate SEPs, since the latter would obscure the presence of the low-intensity ACRs. Clouds with SEPs were eliminated as described below. Figure 1 shows intensity vs. time plots for two MCs that are reported by Shodhan *et al.* (2000) as having 100% bidirectional electron flows. The nature of the ACRs is identified by the unusual relative abundances of He, C, and O (He $\approx$ O, O $\approx 20 \times$ C), as observed by the *Wind* spacecraft, while the 120 – 229 MeV GCR protons shown are measured on IMP-8 (see Reames, Kahler, and Tylka, 2009).

Reames, Kahler, and Tylka (2009) selected MCs for their list with the requirement that $O/C \sim 20$ in order to eliminate MCs in which shock acceleration (with $O/C \sim 2$) has contributed SEP particles. The present paper begins with the same MC list but also requires that $He/O \sim 1$ (*vs.* $He/O \sim 60$ for SEP events) which eliminated from the list two MCs (number one and 15) with substantial He increases in or immediately ahead of the MC.

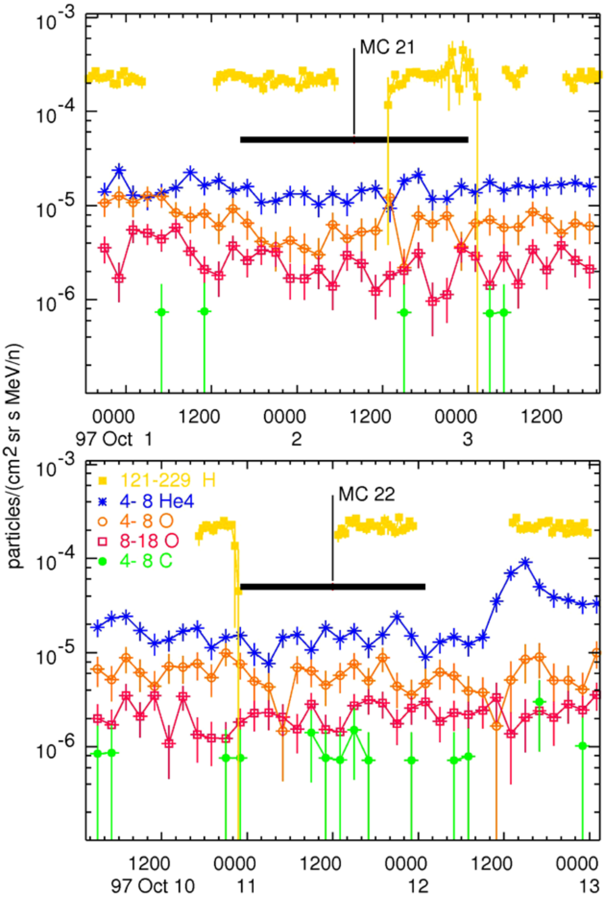

Figure 1 Intensities of energetic particles during two magnetic cloud events with 100% closed field lines. Abundances of He, O, and C identify those as ACRs, while the 121 – 229 MeV protons are GCRs. Neither show significant depression during the MC intervals shown.

Since the errors on the ACR measurements are fairly large, we examine, for each MC, the ratio of the average intensity of the 4 – 8 MeV amu^{-1} He in the MC divided by the corresponding intensity during the 12 hours prior to the MC. These ratios are shown as a histogram in Figure 2. While the ratios for individual MCs vary by $\sim \pm 15\%$, the mean value is $-4.2 \pm 3.2\%$, indicating a small mean suppression of the ACR He intensity by the MCs. Much of the large cloud-to-cloud variation is caused by the varying ACR reference because of the 27-day modulation of the ACR intensities (see Figure 3 of Reames, Kahler, and Tylka, 2009). As noted above, these ACR He ions have a gyroradius that is typically $\sim 2 \times 10^{-4}$ AU, three orders of magnitude smaller than the size of the MCs.

3. Open or Closed Flux Tubes?

In the MCs discussed above and shown in Figure 1, counter-streaming electron data is interpreted as showing that the field lines are 100% closed while ACR observations show that more than $\sim 90\%$ of the field lines are open. How can we reconcile these observations?

Let us suppose that at 1 AU the field in an MC is actually a mixture of open and closed flux tubes (see *e.g.* Gosling, Birn, and Hesse, 1995; Owens and Crooker, 2007) on a very

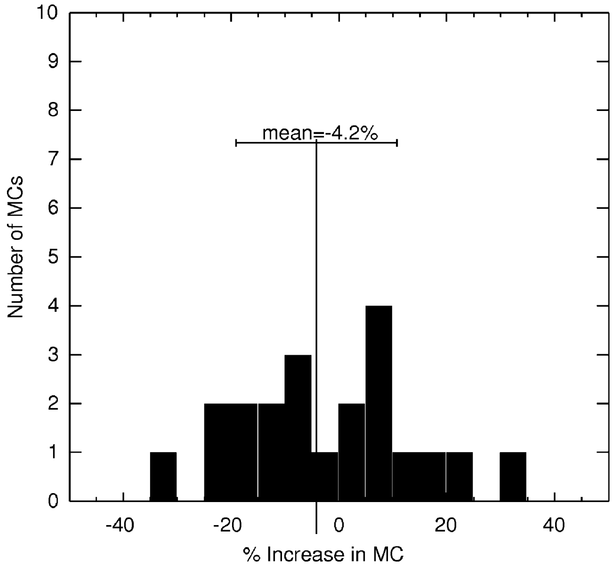

Figure 2 Distribution of % increases of 4 – 8 MeV amu^{-1} He ACRs inside MCs compared with previous 12 hrs. Mean decrease is $-4.2 \pm 3.2\%$.

fine spatial scale that cannot be resolved by spacecraft electron observations. Suppose these tangled flux tubes were formed into a twisted flux rope and ejected from the corona before reconnection occurred over substantial regions, probably near the base of the structure. One end of such a structure is sketched in the upper panel of Figure 3. For this case, the reconnection may have occurred sometime during the $\sim$4-day transit of the MCs to 1 AU. However, the ACRs must have access to open flux tubes in the structure on a typical time scale of $< \sim 8$ hr to keep the MC filled with ACRs as it expands outward.

We assume that the highly mixed elemental flux tubes are reconnected randomly near each end of the loops so a flux tube that is open at one end may be randomly open or closed at the other. An example with 80% reconnection at each end would yield the probabilistic distribution of open and closed lines shown in the lower panel of Figure 3. Note that only $\sim$4% of the flux tubes are closed at both ends, for this case, while $\sim$96% are open at one end, at least, and can be easily filled by ACRs from the outer heliosphere.

Assuming that suprathermal electrons flow upward from each flux tube that is still connected to the corona in our example, 20% of the flux tubes would have electrons flowing from the "right" and 20% from the "left." This is true even though 16% of the right- (or left-) flowing electrons are on open field lines that do not soon return toward the Sun. Thus the electron streaming would be observed to be 100% balanced and "bidirectional." The true structure of the MC could only be determined if the spatial resolution were fine enough to determine that 64% of the flux tubes had no electrons on them at all, and that only 4% had true bidirectional flow.

Of course, both ends of the MC field lines need not have the same reconnection fraction, as it does in our example. If not, the bidirectionality will not be balanced and may even be completely one-sided.

4. Multi-Spacecraft SEP Studies

If ACRs can easily penetrate MCs, given enough time, then SEPs of similar energy can also penetrate them. Multi-spacecraft studies of SEP events frequently show highly uniform

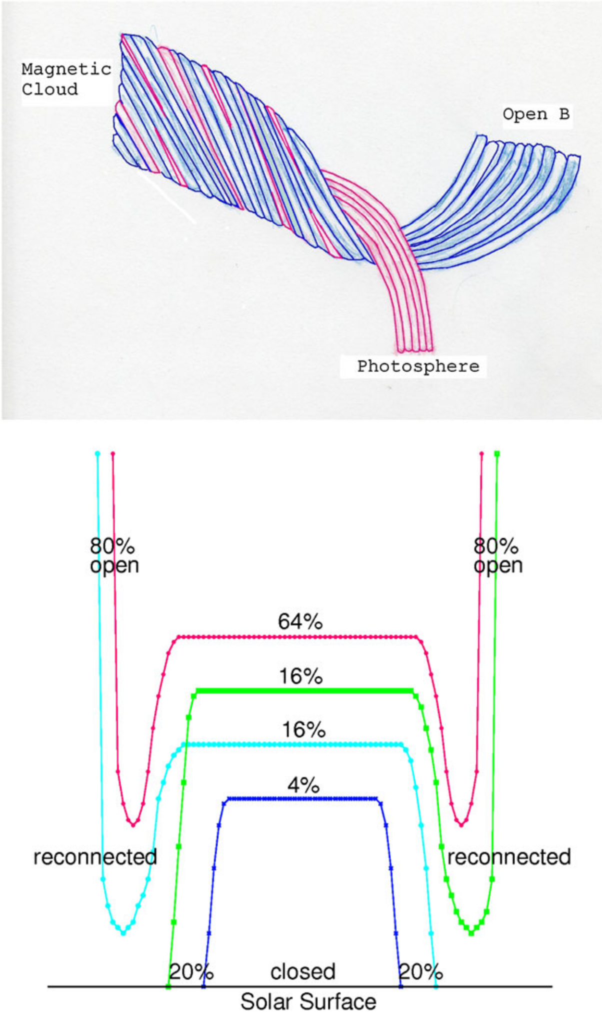

Figure 3 The upper panel sketches one end of a magnetic cloud composed of finely mixed flux tubes that are open (blue) or closed (red) at one end. The lower panel shows the logical composition of a cloud that is 80% reconnected (open) at each end. Statistically, only 4% of the field lines are completely closed and contain no ACRs, yet 20% of the field lines can show suprathermal electron flow to the "left" and 20% to the "right".

spatial distributions of particles, behind the associated shock, in and around the MC (*e.g.* Reames, Kahler, and Ng, 1997). A typical SEP event seen in March 1979 by *Helios 1*, *Helios 2*, and IMP 8 is shown in Figure 4. Initially, at the time labeled A, the intensities (and the complete energy spectra) at the three spacecraft are very different, reflecting the fact that the magnetic flux tubes from each of the spacecraft connect to different points along the shock. Hence, they remotely sense variations of the acceleration around the surface of the shock, with no evidence of cross-field transport upstream of the shock on a short time scale. However, when the spacecraft cross into the region behind the shock they each find intensities (and complete spectra) that are independent of longitude and decrease slowly with time as the volume of the MC, and the region surrounding it, expands. At time B in the figure, the complete particle spectra are identical at all three spacecraft (see Reames, Kahler, and Ng, 1997).

The lower panel in Figure 4 shows the trajectory of the spacecraft through a cartoon that simulates the shock, MC, and surrounding field configuration. (Of course, in reality, the

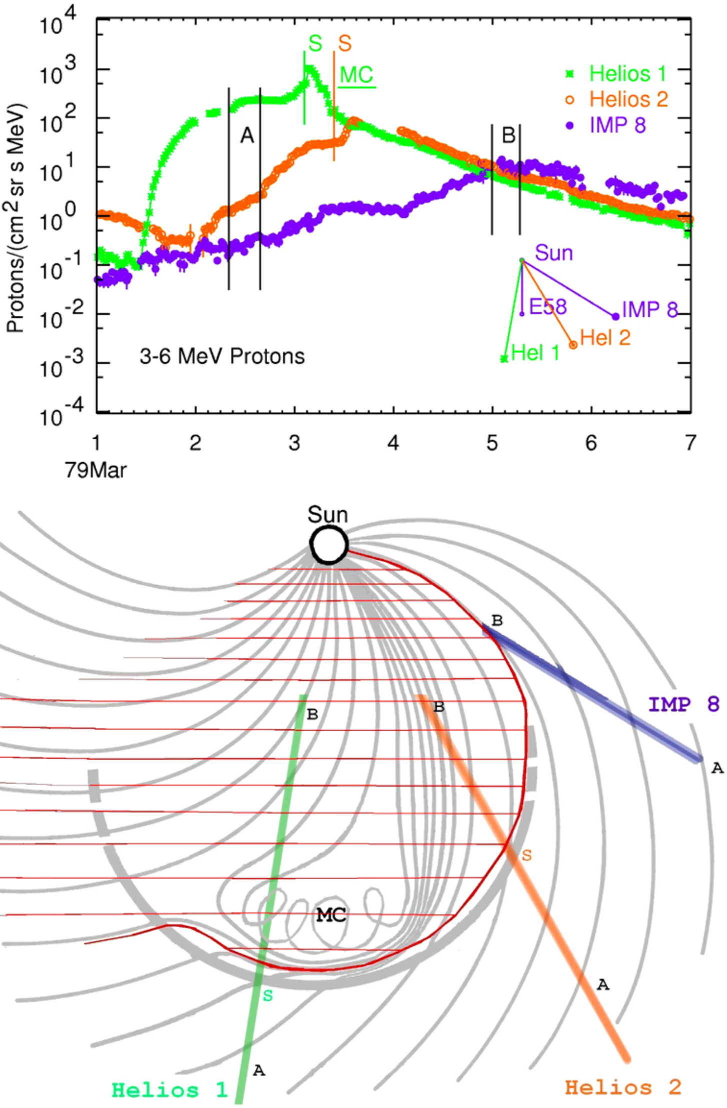

Figure 4 The upper panel shows intensity *vs*. time for 3 – 6 MeV protons observed by *Helios 1*, *Helios 2*, and IMP 8 in the spatial configuration shown in the inset relative to the source longitude of E58 as seen from Earth. The location of shock passage at *Helios 1* and *2* is shown by S; the shock is not seen at IMP 8. The probable spacecraft trajectories across the expanding shock and CME are shown in the lower panel; only *Helios 1* encounters the MC. Particle intensities are uniform throughout the red shaded region when the spacecraft traverse it.

shock and MC expand outward past the spacecraft.) The red shaded region to the left of the red curve in the figure contains SEPs at a nearly constant intensity that decreases with time as the volume of the region expands nearly adiabatically. This region is identified as the "invariant spectral region." Some SEP events show that the invariant region can extend out ahead of the shock on the East flank.

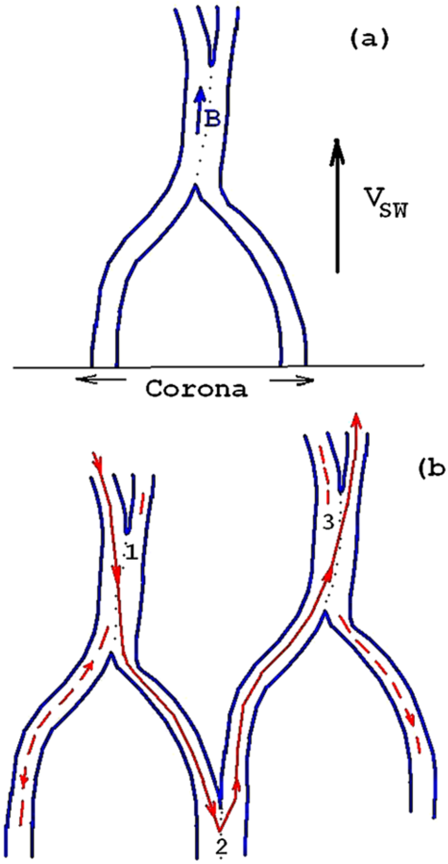

Figure 5 The upper panel (a) shows the possible evolution of flux tubes under the footpoint motion described by Parker (1987). At an earlier time two flux tubes of interest were adjacent. As this region was carried upward by the solar wind plasma, the footpoints drifted apart causing an archway to develop. The lower panel (b) shows a slightly more complicated structure with multiple footpoints. The structure has been produced by wandering footpoints, sometimes moving together, sometimes apart. The red trajectory represents a possible flow path for particles through this structure. At points 1, 2, and 3 the particles must cross into a different flux tube, a more time-consuming process (see text).

The shock is only seen at *Helios 1* and *2* (Reames, Barbier, and Ng, 1996), and the MC is only encountered at *Helios 1* (Cane, Richardson, and Wibberenz, 1997). The intensity peak at the time of shock crossing at *Helios 1* shows that the shock is continuing to accelerate protons of this energy at that time, *i.e.* that the shock is the likely source of all these particles.

5. Meandering Flux-Tubes

The upper panel in Figure 5 shows a possible evolution of flux tubes, with fields all initially directed upward, under the footpoint motion described by Parker (1987). At an earlier time two flux tubes of interest were adjacent, as this region was carried upward by the solar wind plasma, their footpoints drifted apart causing an archway to develop. Note that the field polarity in all cases is generally upward in the figure, there are no oppositely directed fields; no reconnection has been necessary, only footpoint motion.

The lower panel in Figure 5 shows a slightly more complicated structure with multiple footpoints. Again, the magnetic field in all of the flux tubes is directed upward, the structure has been produced by wandering footpoints, sometimes moving together, sometimes apart, but there has been no need for "reconnection." The red trajectory represents a possible flow path for particles through this structure. The particles can easily flow back and forth along the field, but cannot easily scatter across the region of adjacent flux tubes labeled 1, 2 and 3 in the figure, since this may involve more than pitch-angle scattering. Remember, however, that we are considering particles that travel 16 AU day^{-1}, which is many tens of mean free paths for pitch-angle scattering (<1 AU) along the field by the time we see the spatially invariant particle spectra late in an SEP event. Furthermore, if there is braiding of field lines (Parker, 1987) *within* the regions 1, 2, and 3, the transport will be more efficient. Thus substantial "cross-field" transport can be achieved in a time scale of days and it is likely that all of the flux tubes drawn in Figure 5(b) will be filled with particles in that time.

6. Discussion and Conclusions

In the forgoing we have not considered gradient and curvature drifts as a mechanism for cross-field transport. Krittinatham and Ruffolo (2009) have calculated drifts of GCRs in MCs and have found a typical drift time as short as 2.3 hours. While this causes significant transport for GCRs, the drift time depends upon the square of the particle velocity. This means that the drift times for ACRs or SEPs of 4 MeV amu^{-1} would be $\sim$100 times longer than for relativistic GCRs. Hence these drifts have a negligible effect on the cross-field transport of low-energy particles.

We should emphasize that all of our observations of energetic particles in MCs are made from $\sim$0.4 to $\sim$2.0 AU, using data from *Helios*, IMP-8, *Wind*, and *Voyager*, and most of them, especially the ACR observations on *Wind*, were made near 1 AU. These clouds had several days to evolve and reconnect in transit prior to the observations. ACRs or SEPs at 4 MeV amu^{-1} travel 16 AU in a day and can thus probe a wide region of space following tangled magnetic flux tubes. Given enough time, these particles will uniformly fill every nook and cranny that is accessible to them. Note, however, that particles of substantially lower speed may not be able to traverse the long path lengths necessary to fill the MCs and contribute to invariant spectral regions in a few days. Cross-field transport rates for particles with different speeds could provide a test of the physics involved (see Giacalone and Jokipii, 1999).

We can reconcile the observations near 1 AU of the uniformity of GGRs, ACRs, and SEPs across MCs with the simultaneous observations of counter-streaming suprathermal electrons, only if the MCs are composed of a mixture of both open and closed flux tubes on a fine spatial scale. The open field lines in the MCs may result in either of two ways: *i*) reconnection as the MC rises, as implied in Figure 3(a), or *ii*) incorporation of already-open field lines, as shown in Figure 5(b), into the MC as it is formed.

The fine-scale filamentary structure of the magnetic field that we propose is not without precedent. For example, models involving a multithreaded magnetic substructure of coronal loops, substantially below the observable resolution, are used to explain the heating implied by EUV observation from the *Transition Region and Coronal Explorer* (TRACE) (*e.g.* Aschwanden, Nightingale, and Alexander, 2000) and more recent observations on *Hinode* (Warren *et al.*, 2008).

We emphasize that SEPs are unable to find their way across field lines on short time scales. For example, Mazur *et al.* (2000) show dramatic cross-field gradients that come and go in neighboring flux tubes early in impulsive SEP events, indicating that the particles are not easily transported laterally. This is also true even in the turbulent region near a strong shock wave. We have only observed significant cross-field transport for particles that have had time to propagate many AU, perhaps propagating toward the Sun and back many times. Thus, cross-field transport must be slow enough to maintain strong latitudinal gradients early in SEP events (Figure 4) but fast enough to keep an expanding MC filled with ACRs. This suggests a time scale for cross-field transport of ~ 8 hr, or a mean free path of ~ 5 AU, at ~ 4 MeV amu^{-1}.

Acknowledgements I thank Len Burlaga, Jack Gosling, Frank McDonald, Chee Ng, and Allan Tylka for helpful comments on this manuscript. The work was funded in part by NASA grant NNX08AQ02G.

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