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Local and non-local geometry of Interplanetary Coronal Mass Ejections (ICMEs): GCR short-period variations, and magnetic field modeling

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We examine measurements of the integral GCR fluence ($\geq$100 MeV) from the CEPPAD instrument aboard the Polar spacecraft along with IMF and plasma data from ACE and NEAR during the October 28, 2003 and July 14, 2000 solar energetic particle events. The Polar instrument, designed to measure radiation-belt electrons, makes clean measurements of the integral GCR fluence when Polar is outside of the radiation belts. The GCR measurements show variability on timescales including the frequency range of 0.1 mHz - 1.0 mHz. This variability is also found in neutron monitor data and might indicate a change in magnetic scattering power, the passage of a shock discontinuity, the passage of a large-scale magnetic rope or tangential discontinuity in the solar wind plasma. Using a non-force-free magnetic flux rope model in conjunction with particle data allows us to investigate the local geometry of Interplanetary Coronal Mass Ejections (ICMEs), associated with these short-period GCR variations. Modeling solar wind magnetic field observations upstream of these particle events indicate rates of decrease, recovery, and particle anisotropy are different for magnetic cloud topologies than for non-cloud ICME drivers. Analysis of multi-spacecraft observations reveals these different rates are due to the non-local, three-dimensional characteristics of ICME shock, sheath, and envelope regions.

1. Introduction

Energetic particles are a primary source of the highest particle intensities observed at Earth and serve as useful probes of the solar wind structures through which they propagate. Analysis and modeling of these solar energetic particles (SEPs) provides vital information on particle scattering and transport in the interplanetary medium. Although once believed to be accelerated in solar flares, it is now understood that significant acceleration of SEPs occur at shocks driven by coronal mass ejections (CMEs). Thus it is the focus of this paper to study the solar wind structures ahead of energetic particle events and understand how solar wind topology influences observations made by ground stations and Earth orbiting spacecraft.

In Section 2, we analyze the well-known Halloween SEP occuring on October 28, 2003 and briefly describe the non-force-free flux rope model used to invert the upstream solar wind ICME structures. In Section 3, we perform a multispacecraft analysis of the Bastille day July 14, 2000 event observed at the ACE and NEAR spacecraft. In Section 4, we briefly discuss the implications of our work and summarize our conclusions.

2. October 28, 2003 SEP event

At 11:02 UT on October 28, 2003 a Radio Type II burst reaches Earth from the third most powerful solar X-ray flare ever recorded (category 4B/X17.2), erupting from sunspot 10486 located at S16 E08. Shortly thereafter, a bimodal distribution of energetic protons begin arriving at Earth, having both a prompt impulsive component (hard spectra) arriving from the antisunward direction and a delayed component (softer spectra) arriving from the sunward direction. The left panel of Figure 1 shows several neutron monitor ground station responses to the particle event. Note the pre-existing Forbush decrease at the time of the particle injection. Solar neutrons detected by the Tsumeb NM ground station (not shown) begin at ∼11:04 UT. At ∼11:12 UT there is a fast impulse-like response at Norilsk (No) and Moscow (Mo). Later, beginning at ∼11:40 UT delayed responses are observed at McMurdo (McM) and Cape Shmidt (CS). The right panel of Figure 1 shows Polar low energy

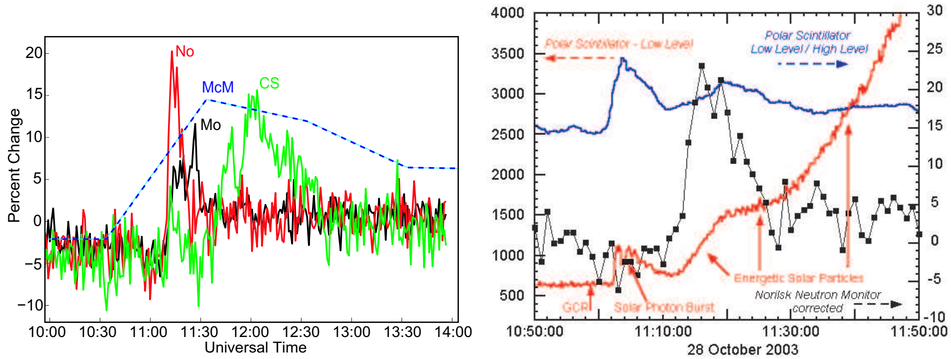

Figure 1. Neutron monitor (left) and Polar spacecraft (right) observations of the October 28, 2003 particle event.

and low/high energy scintillator data (red and blue lines, respectively). Norilsk ground station data (black dots) are shown again for comparison. Note Polar observes gamma rays at 11:06 UT and then a rise in energetic protons just before the Norilsk proton observations. The changes in slope in the low/high energy scintillator data indicate at least 3 distinct proton populations within the event. The location of Polar, coincident with the SEP arrival, is similar to the Norilsk viewing cone, pointing nearly sunward at -222° longitude in GSE coordinates (∼6 Re tailward, ∼5 Re duskward, and ∼2 Re southward).

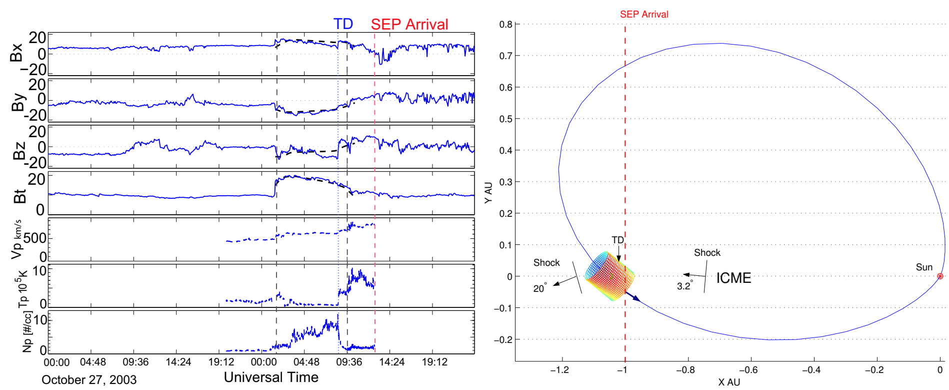

Figure 2. ACE solar wind data (left) and flux rope fit geometry in ecliptic plane (right) during October 28, 2003.

From the ACE magnetic field and plasma data in Figure 2 (left panel) it is obvious the pre-existing Forbush decrease is caused by ICME passing Earth at ∼09:30 UT just prior to SEP arrival. The SEP is marked by a red dashed line, the shock and ICME/ flux rope fit boundaries by black dashed lines. Note the large-scale tangential discontinuity (TD) at the end of the ICME. The non-force-free flux rope model used to to obtain the geometry and properties of flux rope ICMEs is inverted with the magnetic field data. The model has an axial magnetic field component that falls off with an exponential form from the axis of the rope. The azimuthal or poloidal field increases as 1 minus an exponential dependence so that it maximizes at the rope edge. The model flux rope is fit to the data using a downhill simplex inversion technique that varies the fitting parameters in an orderly manner. Further details of the model can be found in Mulligan and Russell, [2001]. Inverting the data with the model gives a flux rope fit axis pointing sunward and slightly westward. The right panel of Figure 2 shows the local geometry and orientation of the October 28, 2003 flux rope ICME in GSE coordinates in the ecliptic plane. Note the rope has travelled beyond the Earth with its axis pointing sunward and westward at the time of SEP arrival at Earth. The shock ahead of the flux rope points 20° west of Earth-Sun line. A tangential discontinuity within the flux rope ICME passes Earth ∼2.5 hrs prior to SEP arrival and its boundary normal is angled ∼100° from the flux rope axis. The flare associated shock at the Sun is nearly radial with a normal ∼3.2° eastward of Earth-Sun line.

3. July 14, 2000 SEP event

On July 14, 2000 a solar flare is observed at 10:24 UT in NOAA active region 9077 located at N22° W07°. It is classified as an X5.7 class eruption in soft X-rays by the NOAA GOES-8 satellite and spawns a full-halo coronal mass ejection (CME) observed with the C2 coronagraph on board the Solar and Heliospheric Observatory (SOHO) spacecraft. The flare erupts at a location where there is expected to be good magnetic connectivity to Earth. Although the solar proton spectra is relatively soft, the SEP population observed contains very high energy particles up to 6-7 GeV.

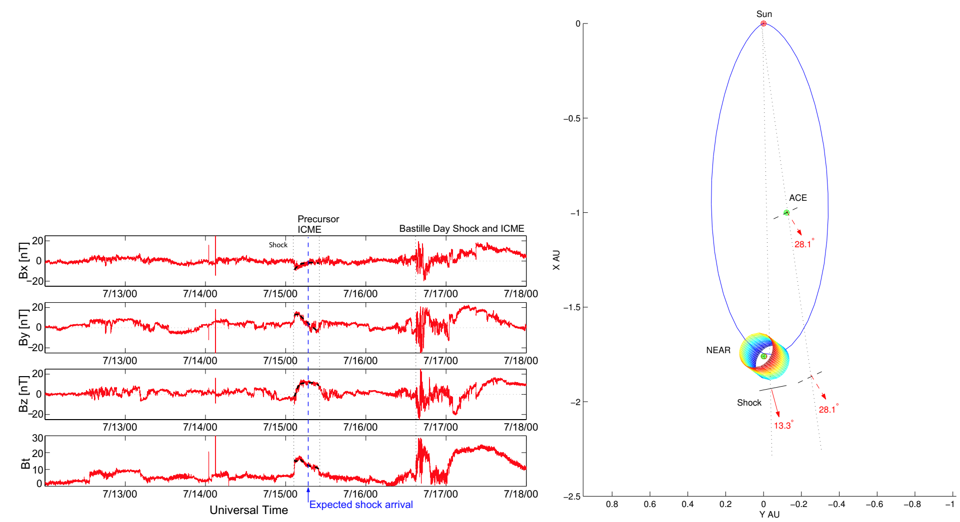

Figure 3. NEAR spacecraft magnetic field data (left) and flux rope fit geometry (right) during the Bastille Day SEP event.

Neutron monitor ground stations observe the energetic particle onset on July 14 at ∼10:40 UT while in a pre-existing Forbush decrease. Initially a high north-south anisotropy exists, which decreases rapidly through the event. Bieber et al., [2001] show the anisotropy and its rapid decline to be inconsistent with particle mean free paths in a Parker spiral field and conclude that a magnetic bottleneck located at ∼1.3 AU must exist to produce the particle signature seen at the Earth. ACE magnetic field and plasma data indeed show the pre-existing Forbush decrease is caused by a shock and hot ICME plasma structure transiting Earth just prior to the SEP arrival. However, it is unclear if ACE observes a flux rope ICME or a disturbed solar wind region adjacent to an ICME. At this time, NEAR was in orbit around 433 Eros, located less than 2° east of the Earth-Sun line and at 1.76 AU heliospheric distance. The left panel of Figure 3 shows the magnetic field data observed by the NEAR spacecraft during the Bastille Day event. Unlike the ACE observations, NEAR sees a clear flux rope ICME signature. Note the arrival of the ICME shock at NEAR is slightly earlier than expected from the calculated shock speed at ACE. The right panel of Figure 3 shows the geometry of the event in the GSE ecliptic plane, consistent with ACE passing just outside of the ICME boundary. When the abberated solar wind direction is taken into account, the flux rope is calculated to pass less than 0.02 AU to the east of Earth. Calculated shock normals are also consistent with ACE passing further to the west of the ICME than NEAR and the apparent acceleration of the shock at NEAR is explained by the curvature of the shock front around the ICME obstacle. Although there is no plasma instrument aboard NEAR, we can determine the average speed of the ICME using the transit time from ACE to NEAR. Along with the energetic particle speed at ACE, we calculate the ICME would be located at $\sim$1.37 AU radially when the energetic particles encounter the flux rope. This is result is reasonably consistent with the conclusions of Bieber et al.,[2001]. Note, bidirectional streaming electron signatures in the ACE suprathermal plasma indicate Earth passes though field lines that are magnetically connected to the Sun. This is also suggestive that Earth passes extremely close to the ICME boundary [Gosling et al., 1987], which may explain the rapid decline of the north-south anisotropy in the solar proton distribution observed by the neutron monitors.

4. Conclusions

During the October 28, 2003 SEP event, three or more distinct energetic particle populations exist ranging from an initial impulsive injection arriving from the antisunward direction to more gradual injections arriving from the sunward direction. The initial antisunward source direction is consistent with neutron decay near the Earth and then adiabatic mirroring of the decay protons back to Earth along magnetic field lines. Observations are consistent with the flux rope field geometry and tangential discontinuity in the upstream solar wind providing the large-scale magnetic bottleneck required to reflect protons towards Earth.

In the July 14, 2000 SEP event, Earth observations indicate an initially high north-south anisotropy that decreases rapidly. Multispacecraft analysis of the upstream solar wind structures during this event shows a grazing incidence of an ICME at the Earth. Modeling the flux rope ICME signature seen at NEAR and propagating it outward, we find the energetic particle population should reach the ICME magnetic boundary at $\sim$1.37 AU, consistent with the conclusions of Bieber et al., [2001]. A short duration bidirectional streaming electron signature in the ACE suprathermal plasma data indicate Earth passes through field lines that are magnetically connected to the Sun. This further suggests Earth passes extremely close to the ICME boundary [Gosling et al., 1987], which may explain the rapid decline of the north-south particle anisotropy upon the SEP encounter.

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