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Cone model-based SEP event calculations for applications to multipoint observations

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Abstract

The problem of modeling solar energetic particle (SEP) events is important to both space weather research and forecasting, and yet it has seen relatively little progress. Most important SEP events are associated with coronal mass ejections (CMEs) that drive coronal and interplanetary shocks. These shocks can continuously produce accelerated particles from the ambient medium to well beyond 1 AU. This paper describes an effort to model real SEP events using a Center for Integrated Space weather Modeling (CISM) MHD solar wind simulation including a cone model of CMEs to initiate the related shocks. In addition to providing observation-inspired shock geometry and characteristics, this MHD simulation describes the time-dependent observer field line connections to the shock source. As a first approximation, we assume a shock jump-parameterized source strength and spectrum, and that scatter-free transport occurs outside of the shock source, thus emphasizing the role the shock evolution plays in determining the modeled SEP event profile. Three halo CME events on May 12, 1997, November 4, 1997 and December 13, 2006 are used to test the modeling approach. While challenges arise in the identification and characterization of the shocks in the MHD model results, this approach illustrates the importance to SEP event modeling of globally simulating the underlying heliospheric event. The results also suggest the potential utility of such a model for forcasting and for interpretation of separated multipoint measurements such as those expected from the STEREO mission.
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Keywords: Solar energetic particle events; Shock acceleration of particles; Space weather

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1. Introduction

Several decades of solar energetic particle (SEP) event observations have led to important conceptual pictures of the relationships between the ion flux time profiles and their associated solar and interplanetary events (Cane et al., 1988; Reames, 1999; Tylka, 2001; Klecker et al., 2006). The great majority of SEP ions are protons which reach energies up to the GeV range on occasion. Significant events involve a moving, evolving shock source that may survive well past 1 AU. These SEP events are often referred to as gradual events due to their long duration (up to several days) compared to the smaller impulsive events commonly associated with small-to-modest flares. Gradual events observed at the Lagrangian upstream location (L1) typically start around the time of a Coronal Mass Ejection (CME) that is headed toward Earth, and therefore appears as a 'halo' around the solar disk in coronagraph images (e.g. Kahler, 2007). Radio bursts accompanying these CMEs are thought to signify the early formation of a shock wave that evolves as the coronal plasma and magnetic field making up the CME ejecta moves outward and expands.

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The first SEP particles may arrive when the shock is still close to the Sun, at which time the observer may see a beamed or anisotropic distribution of particles focused along the interplanetary magnetic field (e.g. Reames et al., 2001). The highest energies arrive first, as the fastest particles emitted by the early shock win the race to reach the observer. Interplanetary shocks produced by CMEs have been inferred to either accelerate and then decelerate in the case of modest CME velocities (∼<600 km/s), or to decelerate continuously for CMEs that start with very high speeds (up to ∼2500 km/s) close to the Sun. If the shock crosses the 1 AU observer's location, the beamlike nature of the SEP pitch angle distribution broadens and the flux at lower (< a few MeV) energies may be enhanced as if these particles are temporarily trapped in its vicinity. This so-called ESP or Energetic Storm Particles event is a special part of gradual SEP events that provides a look inside the shock source itself. The CME ejecta may also be detected in the post-shock plasma and magnetic field data, and is often associated with a reduction in the SEP event intensity, as if its magnetic fields form a barrier to their entry into that structure (e.g. Cane, 2000). The complete in-situ structure of shock and ejecta, usually referred to as an ICME or Interplanetary CME, thus provides important complementary information when interpreting a measured SEP event profile.

Theoretical work related to the acceleration and transport of shock-generated SEPs has similarly developed over decades (e.g. Lee, 1983, 2005; Ng and Reames, 1994; Giacalone and Kota, 2006). The generally held paradigm involves diffusive acceleration and scattering by waves, both ambient and self-generated, as primary factors in describing what is observed (e.g. as treated analytically by Lee, 2005). Various assumptions, usually involving the solution of some form of Boltzmann equation in a spherical geometry, have been introduced to obtain both analytical and numerical descriptions of gradual SEP event time profiles, including ion composition variations (e.g. Ng and Reames, 1994; Ng et al., 1999). In particular, these theoretical treatments suggest the extent to which the particles can be viewed as moving through a prescribed background magnetic field, with scattering from ambient field fluctuations, versus generating their own scattering centers through anisotropy-related instabilities (e.g. see the discussion by Tylka, 2001). However, the ability to include realistic background coronal and solar wind structure, and to simulate real events that consistently combine the ICME and SEP events, has remained elusive.

Realistic SEP event models are a highly desired part of space weather simulations, due to both their fundamental interest as an astrophysical research tool and the practical need for related hazard predictions (e.g. Balch, 1999; Mewaldt, 2006). A successful SEP event model relies on the successful description of the background heliospheric plasma and magnetic field, both ambient and disturbed, as well as the SEP source(s) and transport. Compounding these challenges, SEP sources include both flare and CME/ICME shock contributions, with a possible role for background suprathermal ion seed populations (e.g. Cane et al., 2003). In spite of these difficulties, a few attempts have been made to numerically model the shock-accelerated component of SEP time profiles, both semi-empirically (see Heras et al., 1992; Kallenrode and Wibberenz, 1997; Lario et al., 1998; Aran et al., 2006, 2007, 2008) and using MHD models of an interplanetary shock together with the assumption of diffusive acceleration and transport (Li et al., 2003; Kota et al., 2005; Kocharov et al., 2009). All of these methods rely on various simplifying assumptions to either make the problem more mathematically or computationally tractable, or to fill in for poorly constrained parameters. These include adopted descriptions of the scattering magnetic field fluctuations and/or diffusion coefficients, and of the underlying large scale plasma and magnetic field geometry including the moving shock. In general, the issue of how much of a gradual SEP event time profile is determined by the evolving shock properties and observer connection details, versus the diffusive aspects of shock acceleration and particle transport, is rarely emphasized and not yet resolved. Diffusive processes, or their 'focused diffusion' variants (e.g. Ruffolo et al., 1998), are generally presumed to dominate. Yet the shock source evolution is an essential factor in the physics of the problem and in defining real event profiles (e.g. see Heras et al., 1992, 1994; Kallenrode and Wibberenz, 1997).

The approach described by Luhmann et al. (2007), for ∼10–100 MeV protons, provides another alternative that emphasizes and tests for the shock evolution importance in SEP event profiles. In this case both the shock and SEP transport information are derived from an MHD model of an ICME that is initiated using a cone model description of a CME derived from coronagraph images (Howard et al., 1982; Fisher and Munro, 1984; Zhao et al., 2002). The realistic ambient solar wind MHD simulation is based on photospheric magnetograms, while the ICMEs are created by the cone model-based injection(s) of high speed, high density 'gusts' at the inner boundary of the solar wind model (Odstrcil et al., 2004, 2005). We use a particular version of this combined CME cone model and MHD solar wind model called CORHEL, developed and tested as part of the Sun-to-Earth space weather simulation of the Center for Integrated Space Weather Modeling – CISM (Luhmann et al., 2004). This simplified approach to ICME modeling provides a first-order 3D, time-dependent description of an interplanetary shock and the interplanetary conditions resulting from a particular observed CME, similar to the earlier models of Dryer (1996) and Fry et al. (2003) (also see Smith et al., 2009). Our method then treats the SEP source as a shock strength-parameterized 'black box', similar to the semiempirical models of Heras, Kallenrode, Lario and their coauthors. The SEP protons are injected onto a sequence of the observer-connected model field lines intersecting the moving shock location, after which they adiabatically propa-