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A heliospheric simulation-based approach to SEP source and transport modeling

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Abstract

Solar Energetic Particle (SEP) ion flux time profiles, continue to be a subject of interest because of the information they contain about sources and acceleration processes. STEREO and someday the LWS Sentinels missions have increased capabilities for resolving some of the outstanding questions raised by SEP profiles by means of regular multipoint SEP measurements over a wide energy and mass spectrum. Among these is the location and nature of the source(s) and the effects of source properties versus transport in determining the profiles. However, the interpretation of these data will require a more realistic description of the coronal and interplanetary source and transport geometries than previous approaches. In particular, the possibilities for tracing back minimally scattered SEP (>10 MeV) ions to their sources has greatly improved as a result of computational models of the coronal and interplanetary magnetic fields based on solar magnetograms. Here we use a heliospheric MHD simulation of the May 12, 1997 interplanetary coronal mass ejection to illustrate an approach to modeling the associated SEP event. Our approach assumes that the simulated shock is the moving source of the ions, and that a near-Earth spacecraft samples the fluxes on a sequence of field lines connected to that evolving source. It is found that the combination of a relatively simple shock source description and scatter-free propagation can approximate an observed SEP time profile. The approach emphasizes the importance of knowing the observer-connected shock source time history, which is difficult to include in a SEP event model without a realistic underlying model of the heliospheric event.

Keywords: Solar Energetic Particles; Space weather

1. Introduction

The Solar Energetic Particles or SEPs of most interest in space weather studies are ∼10–100 MeV ions, mainly protons. The general behavior of SEPs in the spatial and temporal domains is understood from the observational synthesis of Cane, Reames and von Rosenvinge over a decade ago (Cane et al., 1988; Reames, 1999). Their analysis explained how a longitudinally extended, moving shock source from a Coronal Mass Ejection or CME could produce the main categories of time profiles of proton events observed both at Earth and in distributed multispacecraft investigations. The key to their interpretation, illustrated in Fig. 1, was the time-dependent geometry of the connection between an observer and the moving, spatially-dependent shock source of the particles. Yet much uncertainty still exists over the proper description of the SEP source(s), and their relationships to CMEs and flares. For example Cane et al. (2003) recently argued that evolving ion composition differences in the time profiles of large events required a two-component source population, one from flares and one from the corona/solar wind. These issues must be resolved for successful interpretation and forcasting of SEP events, which are of great interest from both a heliospheric physics perspective and for managing radiation-sensitive satellite resources and human activities in space.

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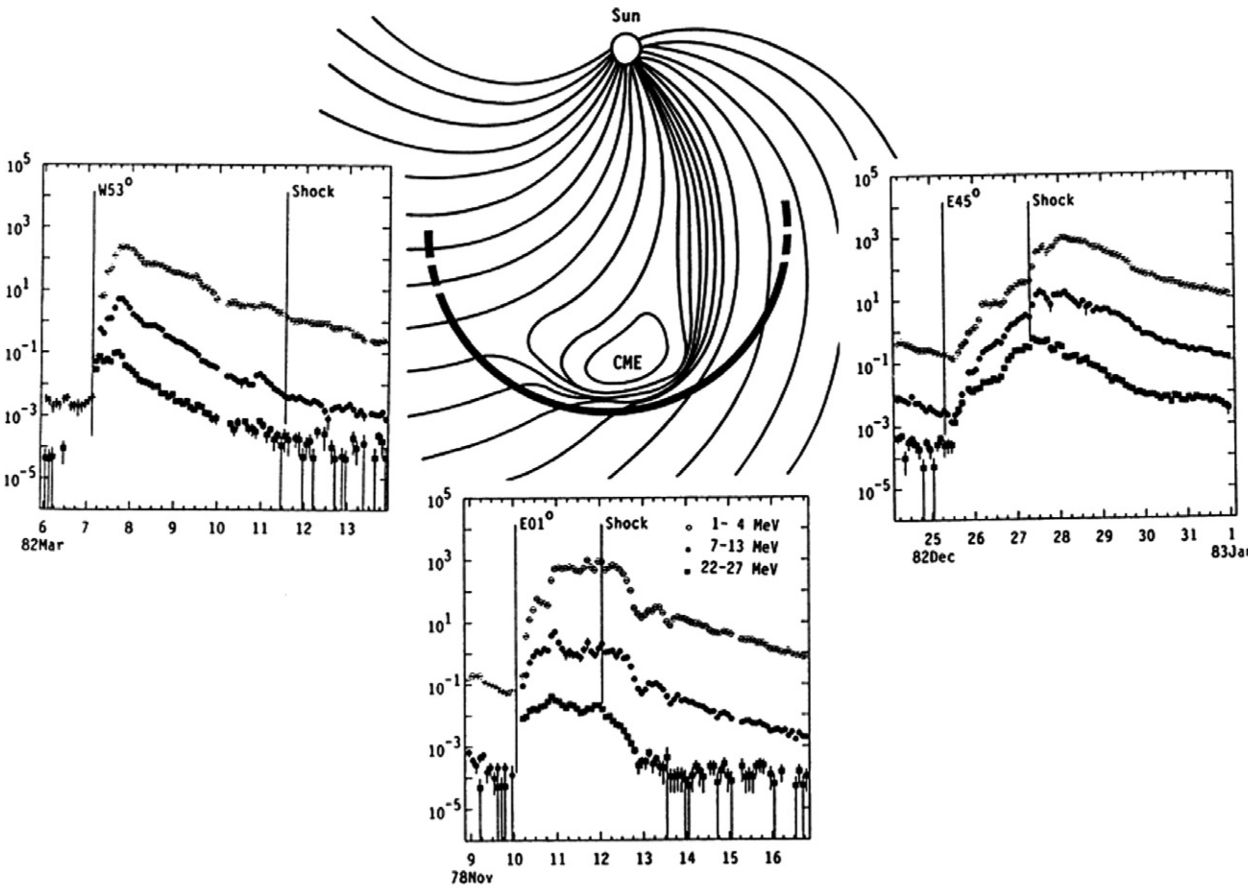

Fig. 1. Illustration from Reames (1999) of the geometrical organization of observed SEP event time profiles to the CME shock driver and interplanetary shock source. The strongest source region is considered to be located at the nose or leading portion of the shock. The SEPs travel to first order along field lines connecting the shock source and the observer, as the shock moves outward.

Several efforts are underway to develop highly sophisticated, self-consistent space weather simulations of real solar and heliospheric space weather events (e.g. Odstrcil et al., 2002, 2004). These provide an unprecedented opportunity to experiment with the SEP source and propagation problem because they give specific and detailed information about the space and time-dependent interplanetary shock, traditionally considered the primary source of ions in many "gradual events" (Reames, 1999; Kahler, 2001), together with consistent coronal and interplanetary magnetic fields. The study described here uses information obtained from the May 12, 1997 CME-related event MHD simulation described by Odstrcil et al. (2004) to analyze the associated moderate SEP event. It illustrates, by example, an approach to SEP event modeling that can reveal more about SEP sources. The general philosophy of the adopted approach is similar to that explored by Kallenrode (1993, 1995); Lario et al. (1998) and Li et al. (2003) in that the moving shock source is specified and then a transport calculation gives the related time profile of the pre-shock-arrival SEP fluxes sampled by a stationary observer at 1 AU. Lario et al. (1998) and Li et al. (2003) also used an interplanetary shock and field geometry from an MHD model in their analyses. Lario et al., worked backward to infer the injection rate of protons at the shock necessary to produce observed time profiles, while Li et al., assumed shock source properties and applied forward modeling for an idealized shock and interplanetary field model. An advantage of the forward modeling approach, in addition to its generality, is its potential for use as a forecast tool.

Our treatment, which is an element of the CISM (Center for Integrated Space Weather Modeling) framework of coupled numerical simulations, is designed to address the forward-SEP event modeling problem for a specified interplanetary shock and Sun-to-Earth magnetic field environment. In the application described here, the shock parameters and observer-connected magnetic field lines derived from the MHD event simulation are used to characterize the particle injections and field-aligned transport paths, respectively. The present version tests the assumption that all important scattering is effectively confined to the shock source, and that the subsequent transport can be described by conserving the first adiabatic invariant of the shock-injected ions moving in the prevailing 3D coronal and interplanetary fields. The results suggest that this set of assumptions may be appropriate for gradual SEP event modeling when realistic MHD simulation results are available.

2. Background

Observations of SEP events can be organized into three basic event types:

(1) Relatively low flux, short-lived or impulsive events with a clear flare timing association that can be mapped back along the Parker Spiral field from Earth to a source region on the western solar disk, and are characterized by high heavy element abundances and charge states as well as accompanying electron events (e.g. Reames, 1999);
(2) The so-called gradual events that may or may not have a prompt onset. These longer-lived events may also contain significant contributions of heavy elements in their prompt onset phase, where they also exhibit velocity dispersion signatures with timing consistent with a ~5–10 solar radius source location in the corona. Gradual events may last a day or two, are associated with central-to-western disk CMEs (including halo CMEs) and may include superposed flux enhancements (see (3)) of up to orders of magnitude coincident with shock arrival at Earth ~1–4 days after the solar event (e.g. see Reames, 1999; and references therein).
(3) Energetic Storm Particle or ESP events are superposed on some gradual events and are associated with the arrival of the interplanetary shock source at the observer. The ESP event fluxes may be the largest in the gradual event, but usually exhibit a softer energy spectrum than that in the prompt arriving parts of the time profile. Only the very fastest/largest events have significant ESP peaks at energies ~100 MeV and above.

Recently, Odstrcil et al. (2004) numerically simulated the ICME signature following the May 12, 1997 halo CME observed with the LASCO coronagraph on SOHO (Plunkett et al., 1998). Their main results are illustrated in Fig. 2 a and b which, respectively, show the 3D heliospheric disturbance and the comparison with WIND spacecraft in-situ observations. This simulation used a cone model of the ICME (Zhao et al., 2002), together with an ambient solar wind model based on magnetogram-derived synoptic maps, to create the interplanetary shock and the following compressed sheath-like region in realistic surroundings. While the cone model simulations do not include the ejecta driver magnetic fields, they do include the parts of the ICME that result from the solar wind interaction. For the case of the May 12, 1997 event, which appeared at Earth on May 15, the cone model appears to provide a reasonable approximation to the measured disturbance in solar wind density, velocity and magnetic field. These attributes are the main contributing factors in determining the associated SEP event characteristics upstream of the shock. Here we use the cone model results as the basis for a consistent model of the May 12–16, 1997 moderate SEP event, as seen on IMP-8, shown in Fig. 3 (IMP-8 plot courtesy of A. Tylka).

The approach described here of particular importance for SEP data analysis during the upcoming STEREO mission, where routine multipoint SEP event observations with ACE and WIND will be available. These will require interpretation in terms of the prevailing large scale 3D magnetic field topologies that connect various spacecraft to different parts of the same shock source, as well as an understanding of the underlying coronal and interplanetary events.

3. Approach and methodology

3.1. Field model description

A realistic heliospheric field description is necessary for accurately mapping SEP events to and from a presumed SEP source. Impulsive SEP events behave in a manner consistent with a spatially concentrated source near a flaring site on the Sun, followed by nearly scatter-free propagation along the Parker Spiral magnetic field to the observer (e.g. Giacalone et al., 2000). This simplest of SEP transport pictures can also be adopted as a first approximation to the behavior of the energetic prompt particles associated with an ICME shock in the inner heliosphere, where it is expected to be strongest. The velocity dispersions of the energetic ions in the prompt particles indicate that the effective source height is sometimes within the domain of the coronal portion of heliospheric MHD models (e.g. Odstrcil et al., 2002). Whether this innermost portion is available or realistically described for SEP modeling clearly depends on the MHD model used. Depending on the event, the shock source may weaken or strengthen with increasing solar distance. The initially focused (along the interplanetary field) pitch angle distributions of these early arriving particles can be attributed to their transport in the diverging field geometry of the heliosphere.

Models of large-scale heliospheric field structure span the sophistication range from Parker Spiral fields extended directly into the photosphere (e.g. Balch, 1999) to numerical MHD model results including detailed coronal and solar wind structure (e.g. Riley et al., 2001). The former are too simplified to address the level of observations available and expected in the next two years, but the latter are still in the development stage, especially in their inclusion of the transient CME events. Hence it is worthwhile to make use of interim models, such as the cone model, that still contain some of the topological attributes whose effects we wish to study. In particular, the results of Odstrcil et al., include the 3D shock and field line geometry that an observer samples in a sequence as the SEP event evolves.

Our concept of the SEP event simulation problem is illustrated in Fig. 4, together with other concepts that are sometimes adopted. The idea of a source fixed at the Sun followed by diffusive propagation is shown in the left panel, while the central panel shows the modern view that the primary source is the moving shock. Existing models based on this view typically make use of an analytical or idealized numerical descriptions of the heliospheric field and of

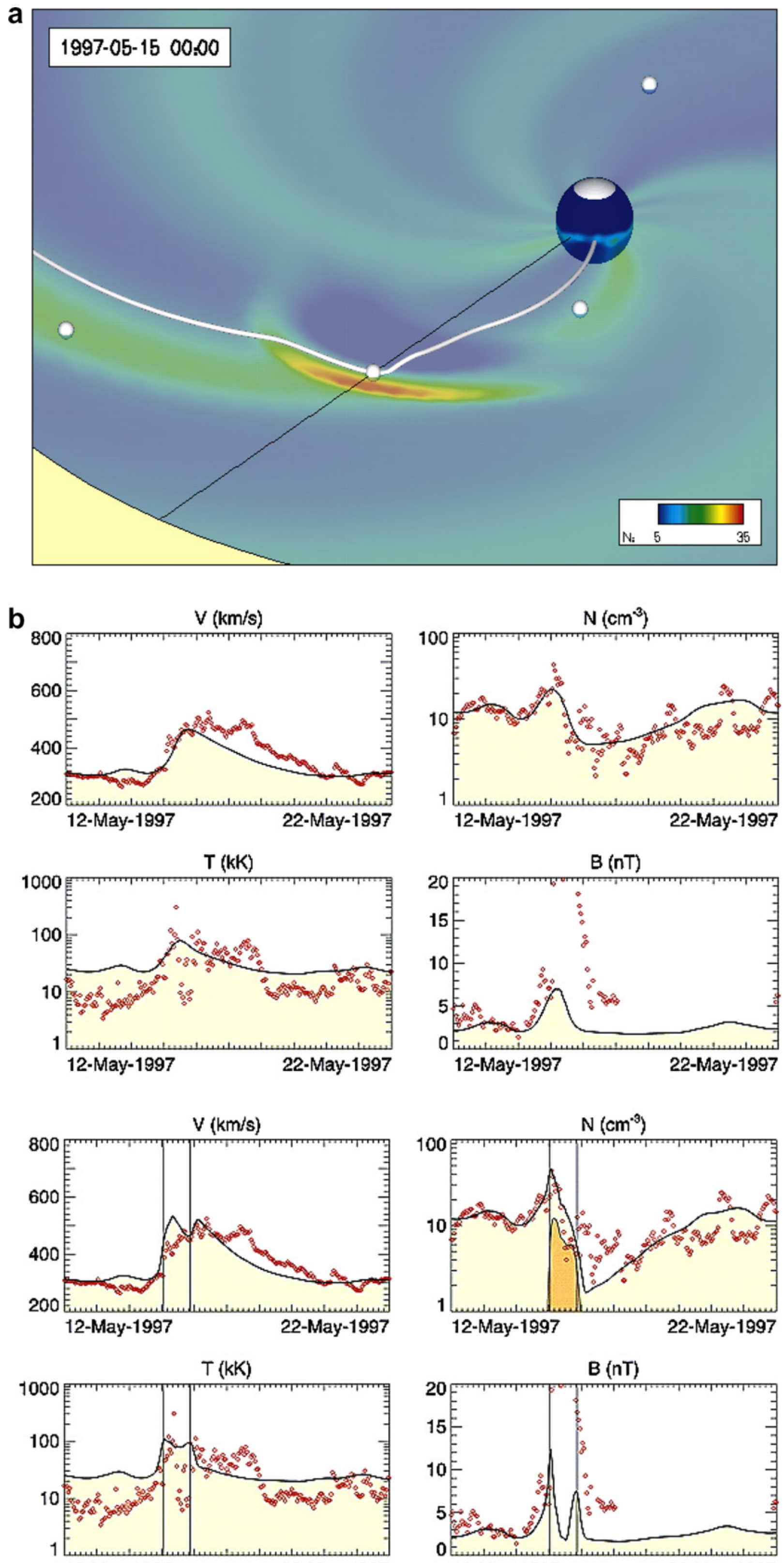

Fig. 2. Results of a cone model simulation of the May 12, 1997 CME/ICME event from Odstrcil et al. (2004). (a) Heliospheric density snapshot, showing the shock and an Earth-connected magnetic field line. (b) Simulated time series of the solar wind parameters during the ICME passage without (top) and with (bottom) the cone model CME injection included. The red dots show the corresponding WIND spacecraft data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

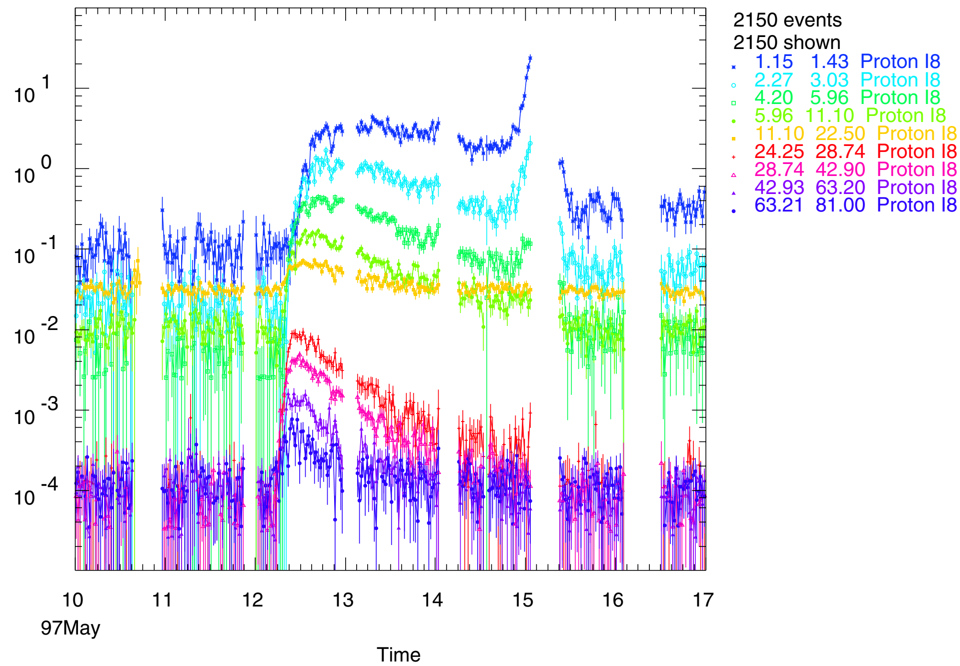

Fig. 3. IMP-8 observations of the SEP event associated with the May 12, 1997 halo CME (courtesy of A. J. Tylka). The numbers in the legend are the energy ranges in MeV.

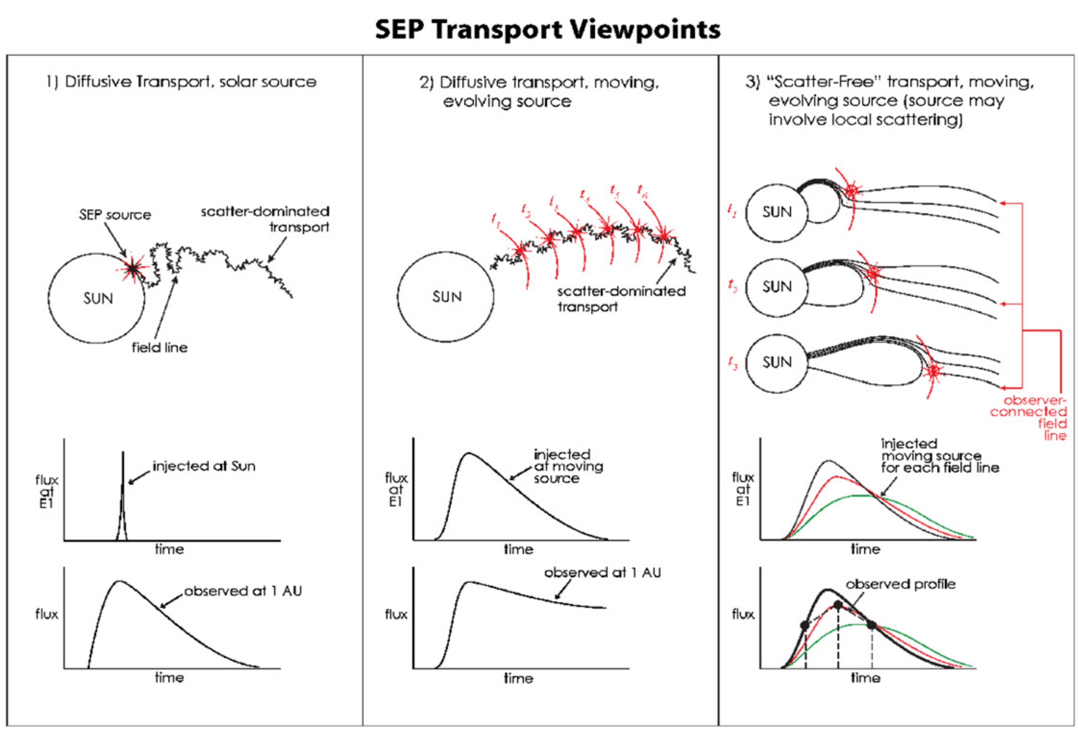

Fig. 4. Illustration of various views of SEP event sources and transport. The left hand column illustrates a source on the Sun followed by diffusive propagation though fluctuating magnetic fields. The center column illustrates a moving shock source with diffusive propagation. The right column illustrates the concept adopted in our model, which initially involves sampling the events on a sequence of connected field lines to get the observed profile, and scatter-free motion outside of the shock source on the field lines. In effect, the final profile emerges from a sequence of snapshots of injected fluxes on individual field lines.

shock shape and strength, and use a cosmic ray transport equation to calculate the SEP time profile at an observer's location. In actuality the observer samples a sequence of field lines, each with their own time profile reflecting the shock history on that field line, assuming the particles stay roughly in the flux tube into which they are injected at the shock. The observer then effectively samples each field line's SEP profile at the time it connects to the field line. The observed profile is thus made up of a sequence of sampled profiles as Fig. 4 suggests. Using the archived results from the MHD model illustrated in Fig. 2, we obtain a sequence of observer-connected field line descriptions and the shock description that goes with them. To make the problem computationally practical, we use observer-connected field line data saved at a roughly 5 min cadence. We further assume the SEPs on each field line can be approximated by an impulsive injection from the shock on that field line at the time of connection, which are then integrated to produce the observer's overall SEP profile. It should be noted that the cone model shock by definition exists only in the solar wind portion of the simulation beyond about 30 solar radii, which we use as the inner boundary for our calculations at this time. However, there is no barrier to extending the method into the coronal domain for future more complete CME/ICME simulations.

4. SEP source description and transport

Even though a flare occurred in association with the halo CME observed on SOHO, we assume that the only significant source of the SEP ions in the May 12, 1997 event is the CME ejecta-driven interplanetary shock. Interplanetary shock sources in our model are described as point sources moving along those field lines of the MHD model affected by the shock. In the present case these are open coronal field lines mapping from the Earth-based observer to the region affected by the cone model transient. First, the shock location and jump in solar wind dynamic pressure, as well as density and velocity is determined on the connected field lines. Fig. 5 shows the moderate jumps determined for the sequence of connected field lines for the May 12, 1997 event cone model used here, with smoothing applied to eliminate clearly incorrect values The shock normals are then determined from the locations of the shock on several adjacent field lines. However, the jumps used in these initial calculations are the jumps along the connected field lines, which underestimate the true jumps. (We are in the process of constructing code to determine the jumps along the shock normals.) Ions are then launched from the MHD model shock site on a field line with a prescribed energy distribution, a power law that depends on the MHD model shock compression ratio, and another factor that depends on the shock normal angle according to an empirical result by Lario et al. (1998). The spectral index is related to the shock compression ratio using the formula: index $= -0.5*(r+2)/(r-1)$, where r is the density jump (see Jones and Ellison, 1991; for a

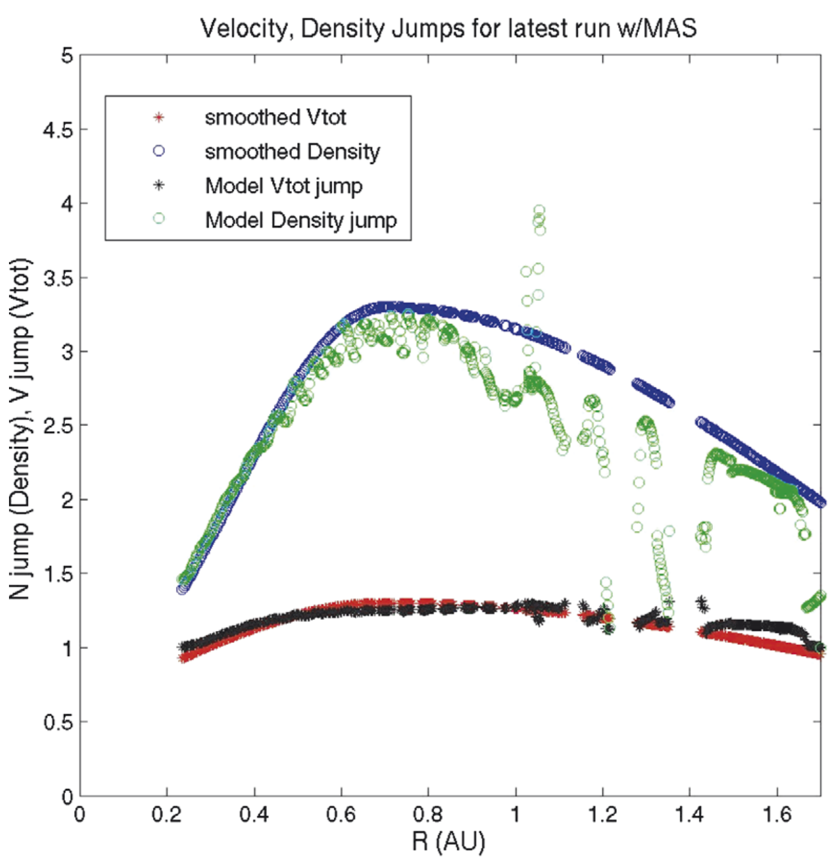

Fig. 5. Shock jumps calculated from the May 12, 1997 cone model event simulation, sampled along the observer-connected field lines. These underestimate the actual jumps because the field lines lie at oblique angles to the shock (see Fig. 2a).

discussion of the basis for a relationship of this nature), while the shock normal angle factor has practically negligible effect, following the nearly flat curves of its inferred variations found by Lario. The injected pitch angle distribution is assumed isotropic.

As mentioned above, each injection is an impulse initiated at the time of the observer's connection to the field line. The intensity of the injection is weighted by a factor of ten raised to a power equal to the normalized velocity jump. This assumption was based on the Lario et al. (1998) empirically derived linear dependence of the log of the apparent shock source strength on the normalized velocity jump. An additional r^{-2} factor is used to mimic an expected dilution of injected flux density with heliocentric distance as the ambient density decreases. This source description is still in flux and will ultimately depend on real event comparisons with the model. The ions' first adiabatic invariants are conserved as each particle is followed along a field line assuming guiding center motion. For each injected burst the time profile of particle numbers and their statistical energy and pitch angle information are recorded upon reaching the observer at 1 AU. The summed results from the transported sequence of impulses, in this case totaling $\sim 10^4$ particles, give the modeled event history. The addition of a flare source is possible within the framework of this model, but is not included here in part because the model field lines used extend inward to only 30 solar radii.

The use of guiding center motion to describe the transport of the particles means that the transport is inherently parallel to the observer-connected field lines. Note that the 3D geometry of the MHD simulation field lines allows the particles that are injected from the shock toward the Sun to mirror and return, adding to their velocity dispersion paths. At this writing we do not assume any special interaction on their return to the shock, and simply allow them to interact with the shocked fields of the MHD simulation in whichever way those fields and field gradients dictate for parallel motion. Special shock reflection and transmission treatments can be easily added to the transport description.

The effects of pitch angle scattering can also be included by introducing pitch angle changes with a specified probability distribution. However, because the scattering mean free path for protons of >10 s of MeV is inferred to be significant fractions of an AU, our initial model assumes all of the important scattering occurs within the shock source and that scatter-free conditions exist otherwise. The extent to which this assumption, and that of parallel propagation, can be generally applied remains to be seen.

An important aspect of our approach is that it takes into account both the temporal and spatial variations of the source and transport. The observed time profile in a SEP event is strongly influenced by the time history and radial evolution of the shock source on the field lines encountering the observer. Without the information provided by the MHD event simulation one could not distinguish between time profile characteristics caused by scattering versus those attributable to the shock source sampling. This point is often understated, in part because of the difficulty of assuming shock source evolution and connection without full 3D MHD simulation information.

5. Results and discussion

The calculated time profile for the May 1997 event case is shown in Fig. 6 for protons with energies consistent with IMP-8 measurements shown in Fig. 3. Considering the approximate description of the ICME provided by the cone model, the assumption of impulsive injections on each connected field line parameterized by the simulated shock properties at the time of observer connection, and the use of first adiabatic invariant-conserving scatter-free transport of the particles, the results produce a reasonable facsimile of the SEP event. The model does not yet include a sufficient description of the ESP peak around the shock source, and so a shock arrival peak is not expected in this initial version. The shock source fluxes used in our model are the ones leaving a hypothetical domain around the shock within which the ions presumably scatter and become energized. The peak flux inside such a domain (that corresponds to the ESP event) is necessarily much larger than the flux at its scatter-free boundary, which produces only the modest low-energy enhancement at arrival on day four, in Fig. 6. Similarly, the modeled profile is not expected to have the notable drop in flux following the ESP peak in Fig. 3 because the cone model does not include the magnetic cloud/flux rope portion of the ICME. Any exclusion of the protons from that structure (observed as a drop in flux) cannot be modeled until a more complete CME/ICME description of the magnetic fields becomes available. Future versions of this model will include the coronal portion of the shock as well as ICME ejecta fields. Once these improvements are available the shock source description will be tuned to provide the best data comparison, and then be used as a baseline source description for other SEP events.

While the May 12, 1997 CME/ICME event was particularly attractive because interplanetary conditions were quiet during the surrounding period, and the active region spawning the event was practically the only significant region on the visible disk, the approach used here is general enough to test on virtually any event for which heliospheric conditions are well-simulated by an MHD code. Generalizations that are required for more complicated scenarios include the need to specify the particles' behavior when multiple shocks are present on the same field line, to bookkeep the fluxes from those multiple shock sources, to take into account the existence of closed field structures in the shock drivers, to consider contributions from flare sources at the Sun, and the need to reconsider scattering processes in certain situations such as quasiparallel shock crossings. However, these adjustments are not in themselves difficult within the model framework. For example, Scholer and Morfill (1975) used a Monte Carlo approach to scattering and shock reflection and transmission coefficients based on the

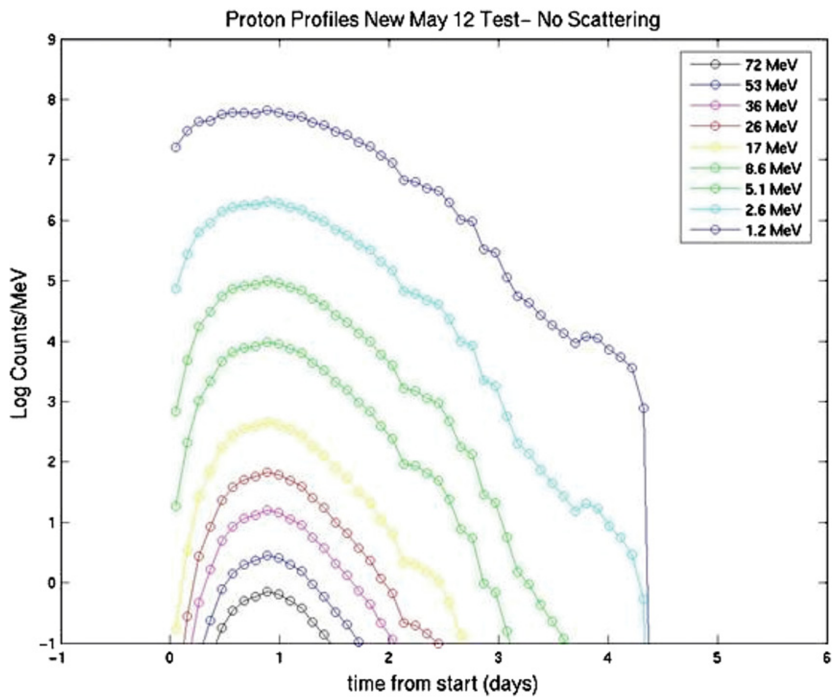

Fig. 6. Modeled SEP event for the May 12, 1997 cone model event simulation-based on a simplified shock source parameterization and scatter-free transport. No attempt has been made to model the ESP peak at shock arrival or the effects of CME ejecta fields which are not included in the cone model simulation. The energy bins correspond to the IMP-8 energy channels displayed in Fig. 3.

shock normals. Eventually we will use hybrid code shock simulations to study the details of the transmission and reflection of ions at shocks over a range of shock parameter space, as well as to develop a more physics-based description of the shock source than is currently used.

In summary, we have developed an approach to SEP event modeling that is generally consistent with numerical simulations of CME/ICME events. The approach is flexible enough to accommodate any complexity of underlying event, a variety of source descriptions, and a range of assumptions about the scattering environment during transport. Future generations will include the realistic coronal portion of the ICME as well as the option of flare-produced additional sources. They will also provide the possibility of simulating a role of seed particle populations that may be present. The potential for applications and further development of this approach in the upcoming era of STEREO mission multipoint SEP event measurements is great, but will also depend on the ability of the coronal and heliospheric modelers to realistically initiate and propagate the observed CMEs. Without accurate underlying heliospheric magnetic fields and shocks, SEP event modeling will by its nature remain limited.

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