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Comparing proton fluxes of central meridian SEP events with those predicted by SOLPENCO

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Abstract

We have developed an operational code, SOLPENCO, that can be used for space weather prediction schemes of solar energetic particle (SEP) events. SOLPENCO provides proton differential flux and cumulated fluence profiles from the onset of the event up to the arrival of the associated traveling interplanetary shock at the observer's position (either 1.0 or 0.4 AU). SOLPENCO considers a variety of interplanetary scenarios where the SEP events develop. These scenarios include solar longitudes of the parent solar event ranging from E75 to W90, transit speeds of the associated shock ranging from 400 to 1700 km s^{-1}, proton energies ranging from 0.125 to 64 MeV, and interplanetary conditions for the energetic particle transport characterized by specific mean free paths. We compare the results of SOLPENCO with flux measurements of a set of SEP events observed at 1 AU that fulfill the following four conditions: (1) the association between the interplanetary shock observed at 1 AU and the parent solar event is well established; (2) the heliolongitude of the active region site is within 30° of the Sun–Earth line; (3) the event shows a significant proton flux increase at energies below 96 MeV; (4) the pre-event intensity background is low. The results are discussed in terms of the transit velocity of the shock and the proton energy. We draw conclusions about both the use of SOLPENCO as a prediction tool and the required improvements to make it useful for space weather purposes.

Keywords: Space weather; Solar energetic particle events; Shocks; Coronal mass ejections

1. Introduction

The existing codes for forecasting solar energetic particle (SEP) events are not reliable when predicting basic features of these events such as duration, peak fluxes, fluences and energy spectra (Baker et al., 2006). The main responsible for this situation is the failure to include the effects of traveling interplanetary (IP) shocks as particle accelerators while propagating out from the solar corona. The limited number of proton flux observations out of 1 AU makes the analysis of the radial dependence of SEP fluxes difficult. From the analysis of 72 SEP events observed by Helios 1 and 2 (at heliocentric radial distances ranging from 0.3 to 0.98 AU) and IMP-8 (at 1 AU), Lario et al. (2006) concluded that the main factor that determines the peak flux and fluences of SEP events is the longitudinal separation between the footpoint of the magnetic field line connecting the observer with the Sun and the site of the associated solar event, whereas the heliocentric radial distance of the observer is of secondary importance. The effects that IP shocks have on particle intensities as they propagate out of the Sun prevent us from using a simple radial power-law to extrapolate particle peak fluxes and fluences measured at 1 AU to other heliocentric distances (Smart and Shea, 2003). Therefore, a more complete physical approach in modeling solar particle generation and propagation

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through the interplanetary medium is necessary, and this approach must be translated into an operational code. That will allow us to predict SEP intensities at different points in interplanetary space.

We have developed the first version of an engineering tool that takes into account the contribution of shock-accelerated protons in the flux of large SEP events associated with IP shocks. A complete description of this code, SOLPENCO (SOLar Particle ENgineering COde), can be found in Aran et al. (2004, 2005a, 2006). SOLPENCO is based on the compound shock and energetic particle model developed by Lario et al. (1998). This compound model assumes that the injection of shock-accelerated particles takes place at the point on the front of the traveling IP shock that magnetically connects with the observer (this point is also known as cobpoint after Heras et al., 1995). As the shock propagates in the interplanetary medium, the cobpoint changes its location along the shock front, resulting in temporal and spatial variations of the shock parameters scanned by this point. The propagation of the IP shock is modeled by means of the MHD model developed by Wu et al. (1983). The propagation of the energetic particles injected from the cobpoint is modeled via the transport equation developed by Ruffolo (1995) that takes into account the effects of streaming, adiabatic focusing, pitch-angle scattering, convection and adiabatic deceleration (Lario et al., 1998). The resulting set of coupled particle transport equations for different energies has two main parameters: the injection rate of shock-accelerated particles, Q, and their mean free path. These parameters are derived by comparing the output flux and first order anisotropy profiles at all the energies considered in the model with the corresponding profiles observed before the arrival of the shock at a given spacecraft (for more details, see Lario et al., 1998). Thus, it is possible to compare the evolution of the MHD variables at the cobpoint with the evolution of Q derived from the transport model.

From modeling different SEP events (i.e., Lario et al., 1998; Aran et al., 2004), we have been able to derive an empirical relation between the injection rate of shock-accelerated particles, Q, and the normalized downstream to upstream ratio of the radial plasma velocity, VR, computed at the cobpoint. This Q(VR)-relation reads as follows:

$$\log Q(t,E) = \log Q_0(E) + k\mathrm{VR}(t). \quad (1)$$

The values of k and Q_0 change from event to event and with the energy of the particles. The factors that determine these values are described in the aforementioned papers and in Aran et al. (2007). To generate the synthetic proton flux profiles contained in the data base of SOLPENCO, we adopted average values of k (=0.5) and Q_0. Q_0 is scaled with the energy as a power-law, $Q_0(E) \propto E^{-\gamma}$ with the spectral index $\gamma = 2$ for $E < 2$ MeV, and $\gamma = 3$ for $E \geqslant 2$ MeV as discussed in Aran et al. (2004), whereas k is kept constant at all energies.

SOLPENCO provides time profiles of upstream proton intensities and fluences, as well as the transit time and speed of the associated shock for a large set of scenarios where SEP events develop. These scenarios are characterized by the following parameters (to be chosen by the user): (1) 10 proton energy channels from 0.125 MeV up to 64 MeV; (2) the heliolongitude of the associated solar event site from E75 to W90 for observers located either at 1 AU or at 0.4 AU; (3) the initial speed of the shock at 18 $R_\odot$ from 750 km s^{-1} up to 1800 km s^{-1}; (4) four different transport conditions described by (4.1) the parallel mean free path of 0.5 MeV protons (either 0.2 or 0.8 AU), scaled to different energies as $\propto P^{0.5}$ where P is the proton rigidity; (4.2) the existence or the absence of a turbulent foreshock region able to keep particles confined around the shock. The range of initial shock speeds at 18 $R_\odot$ translates into transit times of the associated IP shocks (defined as the time elapsed from the onset of the event up to the shock arrival at the spacecraft) that range from ~25 to ~100 h for observers located at 1 AU and from ~9.5 to ~49 h for observers located at 0.4 AU, depending on the heliolongitude of the solar event. These result in transit speeds (defined as the radial distance from the Sun traveled by the shock over its transit time) of the associated IP shocks that vary from ~400 to ~1700 km s^{-1}.

The Q(VR)-relation was derived from modeling individual SEP events and then fitting a regression line to the inferred values of Q and VR. High regression coefficients were obtained with an average value over the modeled events of $\xi = 0.89$. These regression coefficients show slight differences depending on the type of event and the energy considered (see details in Lario et al., 1998 and Aran et al., 2004, 2007). It is important to note that SOLPENCO uses the same average values for the Q(VR)-relation for any type of SEP event. Therefore, one should expect that the synthetic flux profiles may show differences with the observed flux profiles for specific events and at given energy channels. It is clear that two fixed values of k and Q_0 cannot cover all the possible situations and scenarios where SEP events develop (slow/fast shocks, eastern/central meridian/western events, low/high energies, different heliocentric radial distances, etc.). An example of such differences with the energy is discussed in Aran et al. (2006).

We extend the work performed in Aran et al. (2006) to a number of SEP events observed at 1 AU between January 1998 and October 2001 associated with central meridian solar events (i.e., events associated with solar flares occurring at heliolongitudes ranging from E30 to W30). We also extend the study to proton energies higher than those considered in this previous work. In Section 2 we describe the data used in the present study and the criteria established to select the SEP events. In Section 3 we present the comparison of both the observed proton peak fluxes and energy spectra with those predicted by SOLPENCO. Finally in Section 4 we discuss the results and give the conclusions.