A TOOL TO MODEL SOLAR ENERGETIC PARTICLE EVENTS.

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ABSTRACT

Gradual solar energetic particle events pose a serious risk to spacecraft components. The origin of these particle events is closely associated with the development of coronal mass ejections and shock waves driven by them. Prediction of fluences observed at different heliospheric positions during these events requires to know the physical processes occurring during their development. We outline the main ingredients of a model that reproduces particle flux and anisotropy profiles of these events. This model includes a simulation of the propagation of the associated CME-driven shocks and a simulation of the injection and transport of shock-accelerated particles. We present an application of this model to produce several "typical" synthetic flux and anisotropy profiles which allows us to delimit the particle effects under different conditions and situations.

Key words: solar proton events; CME; Interplanetary Shocks.

1. INTRODUCTION

Large solar energetic particle (SEP) events, characterized by gradual intensity timescales, are generated at the shock fronts associated with coronal mass ejections (CMEs) (Cane et al., 1988; Kahler et al., 1998). These gradual particle events pose a serious threat to spacecraft components, materials and operations (Turner, 1996). They are characterized by high SEP intensities, rich proton abundances, long time durations (of the order of several days), and may be simultaneously observed over a broad range of heliospheric locations (Reames et al., 1996).

The injection of energetic particles during gradual events starts when a perturbation, originated as a consequence of a CME, generates a shock wave which propagates across the solar corona. If the conditions are appropriate this shock is able to accelerate particles from the ambient plasma and to inject them at the base of the interplanetary magnetic field (IMF) lines. These energetic particles stream out along these lines en route to earth and to the spacecraft located in the interplanetary medium. The perturbation that generated the shock into the corona may also expand through the heliosphere driving a shock wave across the interplanetary medium. The behavior of the shocks close to the Sun and through interplanetary space is quite different (Cane, 1997). While strong shocks may extend up to 300° in longitude near the corona, they extend at most 180° at 1 AU (Cliver et al., 1995).

As the shock goes away from the Sun, it crosses many IMF lines and may be responsible for accelerating particles to energies much higher than the thermal solar wind background (Sanahuja & Domingo [1987] and references therein). These energetic particles propagate along the IMF lines flowing outward from the shock and arriving at the spacecraft positions. These space probes detect particle intensity increases which constitute the SEP events. The particle intensity profiles observed by spacecraft take different forms depending on (1) the heliolongitude of the source region with respect to the observer location, (2) the strength of the shock and its efficiency accelerating particles, (3) the presence of a seed particle population subject of being accelerated, (4) the evolution of the shock (its speed, size and shape), (5) the conditions for the propagation of shock-accelerated particles, and (6) the energy considered (Cane et al., 1988; Lario et al., 1998). Particle flux profiles range from a prompt increase shortly after the CME with a posterior gradual decay, to a sudden increase shortly (a few hours) before the arrival of the interplanetary shock at the spacecraft, passing through gradual and progressing enhancement of the particle intensity from the moment of the CME up to the arrival of the shock (see Figure 15 of Cane et al., 1988).

The simulation of these particle events requires a knowledge of how particles and shocks propagate through the interplanetary medium, and how shocks accelerate and inject particles into interplanetary space. The modeling of particle fluxes and fluences associated with SEP events has to consider (1) the changes in shock characteristics as it travels through the interplanetary medium, (2) the different points of the shock where the observer is connected to, and (3) the conditions under which particles propagate.

2. THE MODEL

We have developed a numerical model (Heras et al., 1992, 1995; Lario et al., 1998) that reproduces SEP events by simulating the propagation of the associated interplanetary shocks and the injection and transport of shock-accelerated particles. In order to derive the injection rate of shock-accelerated particles, it is necessary to deconvolve the effects of the journey of particles from the point of the shock where they are accelerated to the observer's position. During this propagation, energetic particles suffer the effects of the IMF and solar wind, that is, focusing, pitch-angle scattering, solar wind convection and adiabatic deceleration effects. A complete transport equation (to first order in v_{sw}/c, where v_{sw} is the (constant) solar wind velocity) which takes into account these effects is the following (Ruffolo, 1995):

$$
\begin{aligned}
\frac{\partial F(t,\mu,r,p)}{\partial t} &= -\cos\psi\frac{\partial}{\partial r}\left\{v\mu F\right\}- \\
&-\cos\psi\frac{\partial}{\partial r}\left\{\left(1-\mu^2\frac{v^2}{c^2}\right)v_{sw}\sec\psi F\right\}- \\
&-\frac{\partial}{\partial\mu}\left\{\frac{v}{2L(r)}\left[1+\mu\frac{v_{sw}}{v}\sec\psi-\mu\frac{v_{sw}v}{c^2}\sec\psi\right](1-\mu^2)F\right\}+ \\
&+\frac{\partial}{\partial\mu}\left\{v_{sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)F\right\}+ \\
&+\frac{\partial}{\partial\mu}\left\{\varphi(\mu)\frac{\partial}{\partial\mu}\left\{\left(1-\mu\frac{v_{sw}v}{c^2}\sec\psi\right)F\right\}\right\}+ \\
&+\frac{\partial}{\partial p}\left\{pv_{sw}\left[\frac{\sec\psi}{2L(r)}(1-\mu^2)+\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu^2\right]F\right\}+ \\
&+Q(t,\mu,r,p)A(r)
\end{aligned}
$$

where $F(t,\mu,r,p) = \frac{d^3N}{dr\,d\mu\,dp}$ is the density of particles in a given magnetic flux tube as a function of four independent variables: t (time), μ (pitch-angle cosine in the solar wind frame), r (heliocentric radial distance), and p (momentum in the solar wind frame). Also v is the particle speed, $\psi(r)$ is the angle between the IMF and the radial direction, $L(r)$ is the focusing length $-B/(dB/dz)$, z is the distance along the magnetic field line ($dr = dz\cos\psi$), and $\varphi(\mu)$ is the pitch-angle diffusion coefficient. $A(r)$ represents the area of the flux tube at a distance r, and Q the injection rate of particles accelerated at the shock at a given energy. In the upstream region of the shock, the IMF can be described by a Parker spiral in a solar wind steady regime. Pitch-angle diffusion coefficient is parameterized following the quasi-linear theory (Jokipii, 1971).

The injection of particles is considered to take place at the cobpoint (Heras et al., 1995), that is the foot point at the shock front of the IMF line connecting with the observer. All particles injected from the cobpoint are considered to fill the same flux tube where they propagate. As the shock expands, the cobpoint moves along the shock front. The instantaneous position of the cobpoint is given by the intersection between the instantaneous position of the shock and the flux tube where the observer is located.

In order to describe the evolution of shocks through the interplanetary medium a magnetohydrodynamic (MHD) model is required. Interplanetary shocks are usually detected through *in situ* observations of solar wind plasma and magnetic field. These measurements, made at the location of space probes, can only give us a few insights about the global shape of the shock topology, but nothing about the evolution of its large-scale structure during its journey from the Sun to the spacecraft. We use the $2\frac{1}{2}$-D MHD, self-consistent, time-dependent code developed by Wu et al. (1983) as a suitable tool for studying the evolution of shocks in the ecliptic plane (Dryer, 1994). This code gives a dynamical description of the propagation of an interplanetary shock between 18 $R_\odot$ and 220 $R_\odot$ from the Sun. An initial input shock is considered at 18 $R_\odot$ which represents the interplanetary shock at this distance, and which allows us to reproduce the arrival times, plasma and magnetic field data, as well as the shock parameters supplied by several spacecraft located at different positions in the heliosphere. A model describing quantitatively the formation of a shock wave in the corona from reasonable physical parameters related to observations, and its evolution to the interplanetary medium, does not exist yet. That is because, at present, it is not possible to infer quantitative information concerning the initial conditions of a shock at the corona and its transition to interplanetary space from the observations made at the onset of CMEs (Cane, 1997). Then, what happens below 18 $R_\odot$ remains masked to our simulation. Injection of particles from the solar corona or below 18 $R_\odot$ (accelerated by a different evolving coronal shock) is represented by the model by a Reid-Axford profile from the root of the IMF line connecting the observer with the Sun. Once the shock described by the MHD model establishes magnetic connection with the observer, the injection of particles is considered from the cobpoint (see discussion in Lario et al., 1998).

3. APPLICATION OF THE MODEL TO THE SPACE WEATHER

Prediction of particle fluxes at different heliospheric locations during gradual SEP events requires to know the characteristics of the evolving shocks and their effects on particle population. There is a wide variety of SEP events and associated shocks (Cane et al., 1988). The contribution of a shock to the energetic particle population evolves as it moves from the Sun to 1 AU and beyond. In principle, its efficiency as an accelerator of particles is different at different parts of its front and for different energies. The strongest parts of a shock (near its central region) are presumably more efficient accelerating particles than its weak flanks. When shocks are close to the Sun, they are able to accelerate particles to high energies (up to energies as high as 1 GeV; Kahler, 1994) but only to lower energies when they are arriving at 1 AU. That leads to a softening of the shock-accelerated particle energy spectrum while the shock propagates between the Sun to farther in the interplanetary medium.

In order to discern the effect of the different factors that determine the particle flux of SEP events, the simulation of a large number of particle events is required. The present state-of-the-art of SEP-event simulation is rather reduced (see Sanahuja & Lario [1998] for a review). In Lario et al. (1998), we

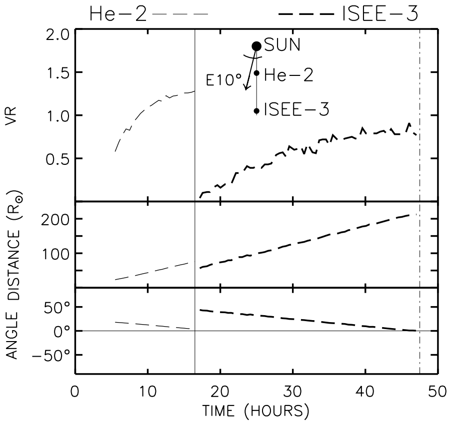

Figure 1. Two bottom panels: Evolution of the cobpoint coordinates (heliocentric radial distance and angle with respect to the Sun-spacecraft line) for Helios-2 and ISEE-3. Top panel: Evolution of VR *at both cobpoints. The origin of time is set at the occurrence of the solar event. Each line extends from the moment where the simulated shock and spacecraft establish magnetic connection up to the arrival of the shock (vertical lines) at both spacecraft.*

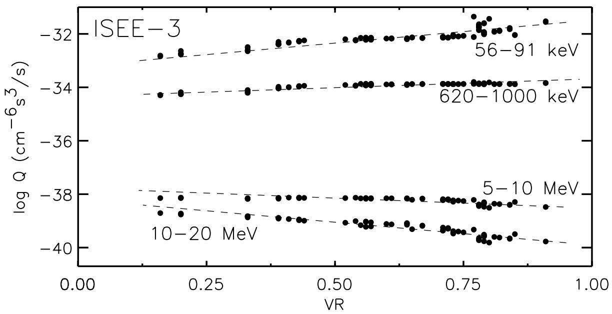

Figure 2. Dependence of the injection rate Q on VR at different energies for the SEP event on 24 April 1979 after a simulation of ISEE-3 observations.

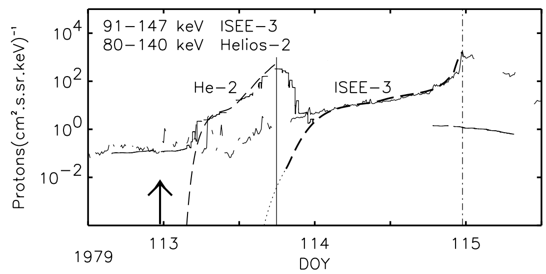

Figure 3. Low-energy flux profile derived for Helios-2 assuming $\log Q \propto$VR. *Thin lines show the flux profiles measured by ISEE-3 and Helios-2. Thick dashed line shows the fit for ISEE-3. The thin dashed line shows the flux profile predicted by the model for Helios-2, under the assumptions commented on in the text. Vertical lines represent the shock passage, and the arrow indicates the time of the solar activity.*

have reproduced the 50 kev-10 MeV [1] proton flux and anisotropy profile of four SEP events associated with interplanetary shocks observed by the ISEE-3 spacecraft. These simulations allow us to relate the temporal evolution of the MHD properties of shocks to the injection rate of shock-accelerated particles. From the MHD simulation of the shock propagation, it is possible to estimate the MHD strength at each point of its front, and particularly at the cobpoint. The strength of the shock is characterized by the downstream to upstream normalized velocity ratio, VR=$[V_r(d) - V_r(u)]/V_r(u)$, where V_r is the radial plasma velocity and u and d stand for the values upstream and downstream of the front, respectively, as measured from a fixed frame at the Sun. We have found a functional dependence of the injection rate Q with VR for the different events we have simulated (Lario et al., 1998). Once the properties of a shock (in particular VR) are known, this dependence allows us to infer the contribution of the shock to the particle population as it travels to 1 AU.

Let us study an application of such a dependence. The two bottom panels of Figure 1 show the evolution of the cobpoint position as given by the MHD simulation of the shock associated with the SEP event on 24 April 1979 (see Lario et al., 1998). This shock was observed by the ISEE-3 and Helios-2 spacecraft (Sanahuja et al., 1983). The location of both spacecraft with respect to the parent solar activity is indicated by the inset on the top panel of Figure 1. Each spacecraft has different cobpoints. In the lowest panel we show the angle between the Sun-cobpoint and Sun-spacecraft lines, and in the top panel the evolution of VR at the cobpoint for both spacecraft. As the cobpoint moves toward the central part of the shock, VR increases indicating a higher velocity jump across this part of the shock front. As the shock moves away from the Sun it weakens.

In Lario et al. (1998) we have proceeded to simulate the proton flux and anisotropy profiles observed by ISEE-3 for this event at different energies. We have considered Q as a free parameter of the simulation. After the simulation, we have compared the evolution of Q to the evolution of VR at the cobpoint. Figure 2 displays log$Q$ versus VR at different energies. Each dot gives a value of VR and Q used for the simulation at each temporal step. Dashed lines are the result of linear regressions to each set of points. We have found, as a good approximation, a linear dependence log$Q \propto$VR. This dependence is different at different energies. That is a reflection of the multitude of factors that may influence the values of Q at different energies: the presence of a seed particle population to be accelerated, the presence of a turbulent foreshock region which may act as a reservoir of particles, the dependence of the mechanism of acceleration on the angle θ_{Bn} (which at the present state of the model is difficult to compute without large error bars), etc. All these factors may have a significant effect on the result shown in Figure 2. In spite of these uncertainties the dependence log$Q \propto$VR provides us a way to relate the MHD properties of the shock to the injection rate of shock-accelerated particles, and to infer (once the shock is known) the flux profiles at different heliospheric positions. Lario et al. (1998) apply this idea to predict the proton flux observed by Helios-2 after the simulation performed for ISEE-3 observations. Figure 3 shows the observed and simulated flux profiles at low energy in two similar energetic channels of Helios-2 and ISEE-3 for this SEP event. As can be seen, the observed and synthesized profiles for Helios-2 fit closely well.

[1] also 100 MeV and 70 MeV for two particular events

In Lario et al. (1995) we have proceeded in the same way to produce "typical" synthetic flux and anisotropy profiles characteristic of different SEP events. After the analysis of the most intense SEP events associated with interplanetary shocks observed by ISEE-3 between August 1978 and April 1980 (Sanahuja & Domingo, 1987) we have considered an averaged shock whose propagation from the Sun to 1 AU lasts between 45 and 50 hours. The MHD simulation of such shock (see Lario et al. (1995) for details) allows us to know VR along its front and throughout its journey and to deduce the injection rate Q of shock-accelerated particles through a dependence $\log Q \propto$VR. Assuming average properties for particle transport (see Lario et al., 1995) we have produced different synthetic 1-MeV proton flux and anisotropy profiles at different heliospheric positions. Figure 4 shows those profiles overplotted on observations for three SEP events. The fitting of the profiles are surprisingly good in spite of the simplicity of the assumptions made.

4. CONCLUSIONS

Assuming very simple and average conditions we infer a relation that allows us to determine the injection rate of shock-accelerated particles from the MHD conditions at the front of interplanetary shocks driven by CMEs. The "synthetic" particle flux and anisotropy profiles built up using this simple relation can be used as a tool to describe the fluence of particles and its temporal evolution at a particular heliospheric location before the occurrence of SEP events. A study of a larger number of events is required before drawing definite conclusions.

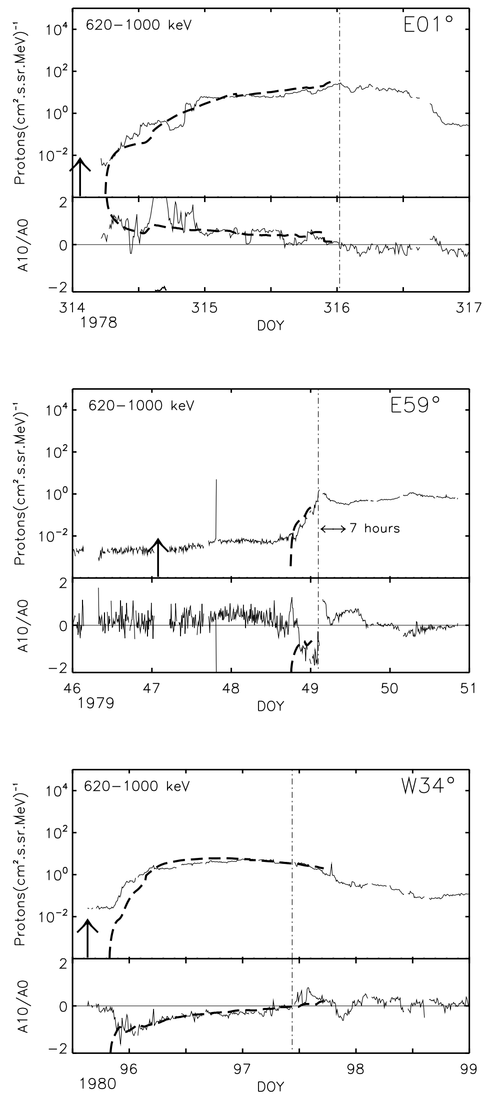

Figure 4. Flux and anisotropy profiles observed by ISEE-3 during three SEP events associated with interplanetary shocks. Dashed lines are the results of the approximation (see text). The vertical arrow indicates the occurrence of the solar event and the dashed vertical line the time of the shock passage. For the E59° event the average shock and the observed shock are displaced 7 hours and the profiles are shifted accordingly (see Lario et al., 1995).

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