MODELING THE INTERPLANETARY PROPAGATION OF 0.1-20 MEV SHOCK-ACCELERATED PROTONS. II: ENERGY SPECTRUM AND EVOLUTION OF THE INJECTION RATE

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ABSTRACT

Long lasting (i.e., > 2 days) transient proton fluxes associated with interplanetary shocks are generated by particle acceleration at the shock front while it is moving outwards from the Sun and expanding. Therefore, the physical conditions under which the particle acceleration takes place, "the efficiency of the process", change as the shock does. We have evaluated the evolution of this injection rate on different Energetic Storm Particle events, for protons with energies from 91 keV to 20 MeV, by fitting the fluxes and anisotropies observed in their upstream region. The results are discussed in terms of the large-scale structure of the shock and its MHD strength at the point of the front magnetically connected with the observer.

INTRODUCTION

The study of Energetic Storm Particle (ESP) events is affected by an incomplete understanding of the influence of interplanetary shocks on the formation and evolution of the associated particle event. Many ESP events show large anisotropies, not only at their onset but also in the phase of rising flux (upstream region). These persistent anisotropies imply that particles are injected continuously from the shock (Heras et al., 1994), and that their propagation along the interplanetary magnetic field (IMF) must be described by the focused transport equation (Roelof, 1969). In this context, flux and first-order anisotropy profiles are adjusted with the help of two basic parameters: the mean free path of the particles, \( \lambda_f \), and the injection rate of shock-accelerated particles, \( Q \) [cm\(^{-6}\) s\(^{-3}\)/s]. For the first time, Heras et al. (1992 and 1995; hereafter He95) modeled the flux and anisotropy profiles of three intense and long lasting ESP events.

Shocks are more efficient particle accelerators as lower energies are considered. It is rather usual to see a small peak (if any) on the 1 MeV particle flux at the shock passage, together with a jump of two (or more) orders of magnitude at 50 keV. A limitation of Roelof's equation is that, below \(~500\) keV, the effects of the solar wind convection and adiabatic deceleration are important.

The efficiency of shocks as accelerators of particles at energies higher than \(~10\) MeV is under discussion, in other words, it is not clear yet up to which energies interplanetary shocks are able to accelerate particles. The efficiency of particle-acceleration depends on the MHD strength of the shock and/or the angle between the upstream magnetic field and the normal to the front of the shock, \( \theta_{BR} \). These values change as the shock progresses and expands, either because its MHD strength decreases (the shock weakens) or because the region of the shock magnetically connected to the observer slides along the shock front from the nose of the shock to the right wing (for West events). As a consequence, it
would be possible, for example, that a region of the front could efficiently accelerate 20 MeV particles at 0.1 AU, but not when the shock is arriving at 1 AU.

EXTENDING THE ENERGY RANGE OF THE MODEL

Following the aforementioned ideas, we have developed a code for modeling ESP events which allows us to extend the energy range from 50 keV to 10 MeV. Its ingredients are:

(a) a MHD time-dependent code (Smith and Dryer, 1990) which simulates the propagation of the shock from 18 Rs to 1.1 AU, in accordance with interplanetary observations of plasma and IMF, when available;

(b) the COBpoint concept (Connecting -with -OBserver point); this is the point of the shock surface connected with the observer through the IMF, it moves clockwise as the shock expands (see He95);

(c) a first-order transport equation which describes the propagation of particles along a magnetic flux tube including a source term of particles;

(d) an energy dependence for the mean free path of the particles.

Lario et al. (1996) give more details of this code. The main differences with respect to the model used in He95 are:

(i) the transport equation, which now includes adiabatic deceleration and solar wind convection effects (based on Ruffolo, 1995);

(ii) the assumption that the mean free path of the particles depends on the energy, according to the quasi linear theory (QLT, Hasselmann and Wibberenz, 1970);

(iii) and the methodology used to fit the flux and anisotropy profiles.

For a given energy, the transport equation is solved by using the radial coordinate. The fitting of particle flux and anisotropy profiles yields the mean free path of the particles at this energy and the injection rate of shock-accelerated particles per unit of flux tube cross sectional area \( G \). \( G \) is related to the injection rate of shock accelerated particles in the phase space, \( Q \), by \( Q = G / A \) (where \( A \) is the area of the magnetized flux tube). The model assumes an energy spectrum for the injection of particles given by \( G \propto E^{-\gamma} \), and a dependence for the mean free path given by \( \lambda_{\parallel} \propto R^{(2-\vartheta)} \) (Hasselmann and Wibberenz, 1970), where \( R \) is the rigidity of the particles (\( \vartheta \) is fixed from magnetic field observations). Under these assumptions, we significantly reduce the number of parameters needed to fit separately the fluxes and anisotropies for each energy range. In fact, with only three parameters \( \lambda_{\parallel} \), \( G \) at a given energy, and the spectral index \( \gamma \), we can model the flux and anisotropy profiles of several energy channels (usually, between six and ten) at once. For the first fit we usually take the 1 MeV channel.

The main constraints of the model are the assumption of a QLT dependence for \( \lambda_{\parallel} \), the fixed slope for the energy dependence of \( G \), and, in some cases, the existence of a solar-accelerated population of particles when the observer is not magnetically connected with the shock front. To compare with former results we have modeled the same three events studied in He95 (East, Central Meridian and West event, respectively). As we have used the same conditions to describe the evolution of the shock, we refer to He95 for the description of the evolution of the strength of the shock at the COBpoint. This strength is characterized by the normalized velocity jump at the shock, \( VR = (V_s(d) - V_s(u))/V_s(u) \), and the magnetic jump, \( BR = |B(d)|/|B(u)| \) (\( u \) and \( d \) stand for values upstream and downstream of the shock, respectively). The inclusion of solar wind convection and adiabatic deceleration effects on the propagation of particles may be important, even with a continuous injection of particles at the shock front (Lario et al., 1996). When the shock is a weak accelerator of particles (as in the late phases
of West events) the influence of both effects is important, and they can lead to significant changes on $\lambda_p$ (Ruffolo, 1995) and on $G$ to fit the observations.

Figure 1 shows an example of one of these fits for the ESP event associated with an interplanetary shock, observed on the 8th of December 1981 by the ISEE-3 spacecraft. The low-energy spectrometer on board detected proton fluxes in 8 different energy channels between 35 and 1600 keV. This instrument has a 3-dimensional capability, so it is possible to derive the first and second order anisotropies in the solar wind frame (see for details, Sanderson et al., 1985). All the observational data used in this work come from this detector or from the ISEE-3 data pool. The characteristics of the solar activity which triggers this West event and of the shock itself can be found in He95. It is worth noting that this is a slow shock (it takes near 3 days to reach 1 AU), which is continuously injecting particles into the interplanetary medium. This is the only way to explain that the anisotropy evolves so slowly, from $\sim 2$ at the onset of the event to 0 at the passage of the shock.

**EVOLUTION OF THE INJECTION SPECTRUM AND INJECTION RATE**

The fitting of particle flux and anisotropy profiles is performed at 1 MeV while for other energies we assume that $G$ is proportional to $E^{-7}$. The values of the injection rate of particles at the COBpoint, $Q$, are calculated through the dependence on $A$ and the change to physical units at each energy channel. Figure 2 displays the values of $Q$ as a function of the energy for different periods of time. The three panels display, from top to bottom, the $Q$ values for the three events (8 December 1981, 24 April 1979, and 18 February 1979). Each point gives an average of $Q$ over the period of time considered. Two straight lines have been fitted to the set of values of the second period for energies below and above 1 MeV respectively. The values shown in each panel are the slope of the two straight lines, they represent an averaged and smoothed spectral index over the periods indicated.

We will not discuss here the reason of the evolution of the injection rate with respect to the COBpoint (see He95), but note that below 1 MeV $Q$ shows a clear power law dependence. The errors bars at high energy reflects the variation of $Q$ during the period considered and the fact that these energy

![Fig. 1. Observed (thin lines) and fitted (thick-dashed lines) flux and anisotropy profiles for the ESP event detected by ISEE-3 spacecraft on the 8th December, 1981. The thick arrow indicates the time of the solar activity, the dotted-dashed line the passage of the shock, and the vertical line the starting time of the magnetic connection between the shock and the observer (initial COBpoint).](image-url)
channels are too wide (i.e., from 5 to 20 MeV) for a unique fit. We have subdivided the $Q$ values for different energies inside these energy channels, therefore the values represented in Fig. 2 are an average over the whole energy window. Note that at high energy (above ~1 MeV) the efficiency of the shock as a particle accelerator reduces considerably. In fact, if we use at high energy the same slope derived at low-energy (through the corresponding $G$ values), the observed flux and the predicted flux differ in more than two orders of magnitude at the passage of the shock.

![Graph](image-url)

**Fig. 2.** Spectrum of the injection rate of shock-accelerated particles for the three ESP events modeled (see text). The dashed line plotted corresponds to the spectrum for the second period; below ~1 MeV, the differences are very small in all cases. The origin of time is the maximum of the solar activity which triggers the shock, the highest value in each insert corresponds to the passage of the shock at ISEE-3.
The value of $Q$ can now be evaluated all along the evolution of the events (making allowances for the boundary conditions of the model and the size of the grid). Figure 3 shows an example: the evolution of $Q$ with respect to the velocity jump at the COBpoint for the West event (8 December 1981), for four energy channels. Each point represents a time step of the numerical integration, and the slope of the regression line gives the constant of proportionality of $\log Q \propto VR$. The points with higher $VR$ correspond to the first 22.5 hours (after the filament disappearance which triggers the shock), the values below $VR=1.2$ correspond to later stages in the evolution of the event. The decrease of $Q$ with $VR$ is nearly monotonic. A similar relation and behavior is found in the other two events (not shown here). For the Central Meridian and the East events, in contrast to the West event, $VR$ is increasing along the event, and the same trend is followed by $Q$, according to a $\log Q \propto VR$ law.

Finally, it is interesting to note that Lario et al., (1995), assuming such a dependence between $\log Q$ and $VR$, have been able to model the evolution of several ESP events at 1 MeV. The main constraint of those simulations is the adoption of a very simple model for the large-scale structure of the shock and its evolution; it is assumed to be a segment of a circumference propagating at a constant average transit velocity from the Sun to the Earth.

![Fig. 3. Dependence of the injection rate of shock-accelerated particles with respect to the velocity jump. Straight lines follow a $\log Q \propto VR$ dependence. The points to the right correspond to MHD conditions of the shock when it is still close to the Sun. The points to the left, when the shock is close to 1 AU.](image)

CONCLUSIONS

We present the evolution of the injection rate of shock-accelerated particles as a function of the energy and the velocity jump at the COBpoint, for three ESP events. We confirm that there is a clear dependence of the injection rate on the velocity jump; $\log Q \propto VR$. The constant of proportionality changes from one event to another and also depends on the energy considered. The spectral index of $Q$ is constant up to $\sim 1$ MeV but decreases at higher energies. This holds during all the injection process in the upstream region for the three events modeled, in spite of the shocks being very different (slow/fast propagation, well/not-well connected). The conclusion is that the efficiency of the shock, as a particle accelerator, decreases as higher energies (up to 20 MeV) are considered, at least for the three events studied here.
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