Energy Spectrum of Shock-Accelerated Particles

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We have quantified the injection rate of low-energy particles (90–1000 keV) at the front of three interplanetary shocks detected by ISEE-3 spacecraft. We have used a MHD code to simulate the shock propagation and the focused-diffusion equation for particle propagation. This allows us to quantify the injection rate of particles, Q , at the shock by fitting the observed flux and anisotropy at different energies. We relate the variations of the efficiency of the particle acceleration with the interplanetary magnetic field and plasma conditions in the shock front region magnetically connected with the observer. Particularly, with the MHD strength of the shock, the interplanetary magnetic field-shock normal angle, the extent of the shock, and the heliolongitude of the parent solar activity that generates the shock.

1. Introduction

Low-energy (<2 MeV) particle flux enhancements are often observed in association with interplanetary shocks propagating from the Sun to 1 AU. A particle flux enhancement associated with solar activity may be seen at Earth as a prompt or delayed event depending on the location of the parent solar activity on the Sun, but its flux maximum always occurs a few hours after the onset of the solar event. Low-energy particle events associated with interplanetary shocks (ESP events), usually show a flux peak at the shock passage or a few hours later. An important fraction of these events are long-lasting events because the flux upstream of the shock is above the background for more than one day. van Nes *et al.* (1984) made a survey of 75 low-energy ESP events restricted to an 1 hour interval centered at the shock. Nevertheless, at least 40% of these events can be considered as long-lasting ESP events, and many of them show large anisotropies ($\xi > 0.5$; ξ defined as in Sanderson *et al.*, 1985) that cannot be attributed to prolonged injections of particles at the Sun (Heras *et al.*, 1994). It is generally accepted that this type of events shows two components: particle accelerated at the solar corona and particles accelerated at the shock. Furthermore, there is strong evidence that the shock plays the major role during the development of the event, depending on the large-scale structure of the shock and the interplanetary magnetic field (IMF) with respect to the observer (i.e., Evenson *et al.*, 1982; Sanahuja and Domingo, 1987; Cane *et al.*, 1990). Particularly, Heras *et al.* (1994) have demonstrated that the duration of the large anisotropies in the upstream region depends on the heliolongitude of the solar source. We have been modeling the evolution of particle fluxes and anisotropies at low-energies, taking into consideration the large-scale topology of the shock. Our numerical code (Heras *et al.*, 1992) allows to estimate the rate of particle injection at the interplanetary shock many hours before the shock passage, and, therefore, provides some clues on the evolution of the particle acceleration at the shock.

2. The Model: Application to Three ESP Events

The model, described in detail by Heras *et al.* (1992), includes particle injection at the solar corona, a 21/2 MHD simulation for the propagation of the shock between 18 and 237 $R_{\odot}$ (Dryer, 1994), particle injection at the front of the shock, and modeling of the particle propagation along the interplanetary magnetic field lines. The propagation of the particles is modeled by means of the focused-diffusion equation (Roelof, 1969):

$$\frac{\partial f}{\partial t} + v\mu \frac{\partial f}{\partial z} + \frac{v}{2L}(1-\mu^2) \frac{\partial f}{\partial \mu} = \frac{\partial}{\partial \mu} \left[D \frac{\partial f}{\partial \mu} \right] + Q(z, \mu, t).$$

It describes the evolution of the particle distribution function, $f(z, \mu, t)$, at a distance z along the magnetic field line, at a time t , and for a pitch angle cosine μ , when the anisotropy is high and persistent, as is the case; being v the velocity of the particles, D the pitch diffusion coefficient, L the focusing length ($1/L = -1/B \partial B / \partial z$), and Q representing a local source of particles. The basic parameters required to fit the flux and anisotropy profiles, at a given energy, are the mean free path of the particles ($\lambda_{\parallel}$) parallel to the IMF, and the injection rate of particles at the shock front, Q . Here we will focus our attention on Q , a discussion about the role of $\lambda_{\parallel}$ can be found in Heras *et al.* (1995).

Three proton events observed by ISEE-3 (35–1600 keV) have been modeled. For all of them the solar wind is reasonably steady upstream of the shock, and there are other spacecraft (Helios-1 and -2) operating simultaneously in the inner interplanetary medium (Heras *et al.*, 1992, 1994, give more details about their selection). These events can be taken as representative of West (8 December 1981), Central Meridian (24 April 1979) and East (18 February 1979) events. Table 1 gives the time of the passage of the shock, as well as the origin and location of the solar parent activity for the E-, CM- and W-events.

Figure 1 shows two snapshots of the evolution of the fast forward shock for the W-event. Plasma and magnetic field parameters have been used to identify the front of the shock. Several computed magnetic field lines are also represented, and the black dots mark the position of Helios-1 and ISEE-3 spacecraft. The CM event is described in detail in Heras *et al.*, 1992. Our main concern in Fig. 1 is the point of the front which connects with the observer via the upstream IMF line, we call this point the “cobpoint”. Table 1 also gives the time for the first connection between the front and the observer, t_c . For the W-event, ISEE-3 connects with the shock very soon (probably even earlier than 9 h, but the inner boundary for the shock simulation does not allow a more accurate value). For the E-event, however, the connection occurs very late, just a few hours before the shock arrival. The CM-event represents an intermediate case.

Figure 2 shows, for the W- and E-events, the particle flux and anisotropy observed by ISEE-3 and the result from the modeling for three of the five energy channels computed. The solid and dashed vertical lines mark, respectively, t_c and the passage of the shock by ISEE-3. In both cases, the IMF was pointing towards the Sun, thus negative anisotropy values mean that particles are mostly flowing outwards from the Sun. From these fittings for each event we can derive $\lambda_{\parallel}$ and Q values.

Table 1. Observational characteristics of the selected events.

Characteristics	18 Feb. 1979 (E)	24 Apr. 1979 (CM)	8 Dec. 1981 (W)
Solar origin	3B flare 16/0152 UT	FD 22/2326 UT	FD 5/~1215 UT
Heliolongitude	E59°	E10°	W35–45°
Shock at ISEE-3	18/0219 UT	24/2328 UT	8/1358 UT
t_c (h)	37 ± 1	18 ± 0.5	<9
θ_{Bn} at t_{shock}	88°	45°	15°

Fig. 1. Simulation of the shock observed at ISEE-3 on 8 December 1981. The density contours ($\log_{10} \text{ cm}^{-3}$) are represented at 12 and 34 hours. The arrow indicates the heliolongitude of the parent solar activity. The positions of ISEE-3 and Helios-1 spacecraft are also shown.

Fig. 2. Particle flux and anisotropy profiles detected by ISEE-3 at three energy channels (thin lines). The fit obtained from the model is represented by the thick curves. (a) Event on 8 December 1981; and (b) event on 18 February 1979.

3. Evolution of Injection Rate and Energy Spectrum

Lower panel of Fig. 3 displays the values of the injection rate of particles at the front of the shock needed to fit the observations at 620–1000 keV, as a function of time, for the three modeled events. Each line extends from t_c up to time of the passage of the shock. It is interesting to note that Q increases when the shock approaches ISEE-3 for the East and Central Meridian events. For the West event, however, this rate decreases. For the East and CM events, this behavior can be explained by noting that the cobpoint moves clockwise along the front, from the left wing, as seen from the Sun, to the central part while the shock expands and propagates. Therefore, the cobpoint successively scans regions of the shock front whose MHD strength increases (gauged by the velocity and the magnetic field jump across the shock, as can be seen in upper and middle panels of Fig. 3). Since the efficiency is related to the MHD strength (van Nes *et al.*, 1984), Q increases when the cobpoint moves towards the nose of the shock. There are many observations of interplanetary shocks generated by solar activity at very different heliolongitude that

Fig. 3. Upper and middle panels: Evolution of the downstream to upstream magnetic field ratio, $[B(d)]/[B(u)]$, and of the plasma velocity ratio, $VR = [V_r(d) - V_r(u)]/V_r(u)$ (u and d stand for upstream and downstream of the shock at the cobpoint, respectively). Lower panel: Temporal evolution of the particle injection rate at the shock, Q , for each event in the energy range 620–1000 keV. The origin of times is set at the occurrence of the solar source.

Fig. 4. Spectrum of the injection rate at the shock for the three events. A power law has been fitted for two of the spectra in each panel.

yields to an interpretation in such a way (i.e., Kallenrode, 1993). For the W-event the cobpoint slides towards the right flank scanning regions of the front of decreasing MHD strength. The consequence is that the efficiency of the particle accelerating mechanism decreases, thus it does the injection rate as shown in Fig. 3.

Taking into account different energetic ranges, the evolution of the injection rate of particles at the

front of the shock is similar, but Q decreases with energy since the shock becomes a less efficient accelerator as higher energies are considered.

The E-event shock injection rates are lower than for the W and CM event ones, which agrees with the velocity jump ratio at its cobpoint being lower. However, since the difference is more important for higher energies, the lack of solar particles that could act as seed particles may have also contributed to the lower Q values for the E-event. The values of Q for the W and E events becomes closer as time passes, a trend that is also followed by the velocity jump values across these shocks. The evolution of this parameter also seems to be related to the higher Q values for the CM event with respect to the other two events.

Figure 4 shows the spectrum of the injection rate of particles at the shock front for the three events, for different times in each case. The slope of the power-law, fitted for the three events, for different times in each case. The slope of the power-law, fitted for two cases in each panel, shows the the Q spectrum of the E-event is getting harder as the shock approaches. This may be related to the rapid increase of the magnetic field jump across the shock at the cobpoint for this event, together with the fact that the shock is quasi-perpendicular (Table 1, last row). For the CM and W events, however, this slope stays almost constant and the shocks evolve to oblique and quasi-parallel conditions, respectively. Finally, we would like to point out that the variation of Q at high energies is much larger than at low energies. That is, our model is less sensitive to the influence of the changing conditions at the shock at lower energies.

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