



ENERGY SPECTRUM OF LOW-ENERGY FLUXES OF PARTICLES ACCELERATED BY INTERPLANETARY SHOCKS

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ABSTRACT

The injection rate of particles at the front of interplanetary shocks has usually been studied locally, around the shock passage by the observer's position, but little is known of how the efficiency of the particle-acceleration process evolves as the shock propagates from the Sun to the Earth. In many events accelerated particles are observed long in advance of the arrival of the shock (from 5 hours to 2 days), and they show large anisotropies. We have used a compound shock-particle model to derive the injection rate of particles at the shock front and their energy spectrum, as a function of time, by fitting the observed particle fluxes and anisotropies between 100 and 1000 keV. We have studied three individual low-energy particle events taken as representatives of West, Central Meridian and East events.

INTRODUCTION

An important fraction of the low-energy (<2 MeV) particle events associated with interplanetary shocks observed at 1 AU are long-lasting ESP events: their flux profile upstream of the shock is significantly above the background for more than 5 hours, in some cases up to 48. Van Nes et al. /1/ showed that 40% of 75 low-energy ESP events can be considered as long-lasting ESP events; many of them also show large anisotropies that cannot be attributed to prolonged injections of particles at the Sun. Heras et al. /2/ interpreted these large and long-lasting anisotropies, for a set of 18 events, assuming continuous particle acceleration at the front of the propagating interplanetary shock. To fit the evolution of these fluxes and anisotropies for individual events, Heras et al. /3/ built a numerical code which estimates the rate of particle injection in the interplanetary medium long in advance of the arrival of the shock at the observer's position.

THE MODEL. APPLICATION TO THREE EVENTS

We have used the 2 1/2 MHD code of Dryer /4/ to simulate the shock propagation, and the diffusion-convection equation for particle propagation along the IMF /3,5/, to model the low-energy (147–1600 keV) particle flux and anisotropy profiles of such events. The parameters required to fit the flux and anisotropy profiles at a given energy are the parallel mean free path of the particles, $\lambda_{//}$, and the injection rate of particles at the shock front, Q . This allows us to derive the spectrum of the injected particles at the

shock front. The variations in the efficiency of the particle acceleration can be related to the plasma conditions at the region of the shock front magnetically connected with the observer, which changes as the shock progresses and expands.

We have modeled three proton events (35–1600 keV) observed by ISEE-3 (/3/ and /6/ give all the details on their characteristics) which can be taken as representative of West (8 December 1981), Central Meridian (CM, 24 April 1979) and East (18 February 1979) events. Figure 1 shows two snapshots of the evolution of the shock associated with the West event. Several computed magnetic field lines are also represented, and the black dots mark the position of Helios-1 and ISEE-3 spacecraft. Our main concern in this figure is the point of the front which connects with the observer via the upstream IMF line, we call this point the “cobpoint” (Connecting-with-OBServer POINT). For this event, ISEE-3 connects with the shock very soon (9 hours after the solar activity). For the East event, however, the connection of the cobpoint occurs very late, 37 hours after the flare which triggers the whole event. The CM event represents an intermediate case, the connection takes place 20 h. after the parent solar activity.

Figure 2 shows the evolution of the downstream to upstream magnetic field ratio, $BR = |B(d)|/|B(u)|$, 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, respectively). BR and VR are a local measure of the magnetic and hydrodynamic strength of the shock at the cobpoint. As can be seen, VR increases for the CM event as the shock approaches ISEE-3, but it decreases for the West event. VR increases because the cobpoint moves clockwise towards the central part of the shock. For the West event, however, this point is slipping towards the right flank of the disturbance where the velocity jump weakens. VR also increases for the East event since the cobpoint displaces from the flank to the central part of the shock as it propagates, although VR is smaller than for the CM event. Fittings of particle flux and anisotropy profiles for these events can be seen in Fig. 7 of /3/ and Fig. 4 of /6/.

EVOLUTION OF THE INJECTION RATE OF ACCELERATED PARTICLES AND THEIR ENERGY SPECTRUM

Figure 3 displays the values of the injection rate of particles at the front of the shock needed to fit the observations, as a function of time, for three of the five energy channels modeled. The values of the injection rates can be correlated with some characteristics of the shock at the cobpoint. Q decreases with energy since the shock becomes a less efficient accelerator as higher energies are considered. On the other hand, Q will increase when the cobpoint moves towards the nose of the shock, since the efficiency of the acceleration processes is related to the MHD strength of the shock there (gauged by VR and BR ; /1/). Q increases with time for the CM and East events and decreases for the West event, a trend that is also followed by the VR and BR at the cobpoint (see Fig. 2.). For the East and CM events the cobpoint moves along the front clockwise, towards the central part of the shock, while for the West event it moves to the flank of the shock. Likewise the variation of Q during the West event is as gradual as the variation of the shock parameters at the cobpoint. All this indicates a good correlation between Q , and VR and BR .

The highest injection rate of accelerated particles correspond to the CM event and the lowest to the East event, the difference being greater for the high energy channels. This trend is also followed by VR across the shock at the cobpoint, which is lower for the East event but not by BR ; it is higher for the East than for the West event. This suggests that

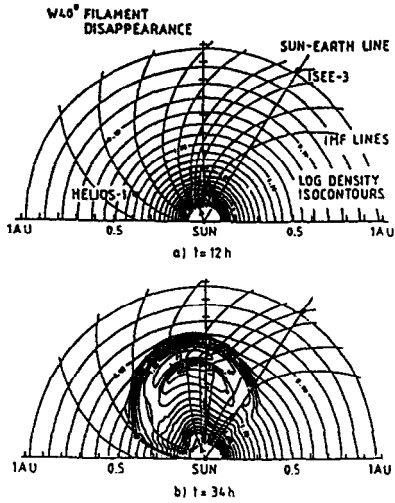


Fig. 1. Simulation of the shock observed at ISEE-3 on 8 December 1981. The density contours ($\log_{10}\text{cm}^{-3}$) are represented at 12 and 34 hours. The arrow indicates the heliolongitude of the parent solar activity. The positions of ISEE-3 and Helios-1 spacecraft are also shown.

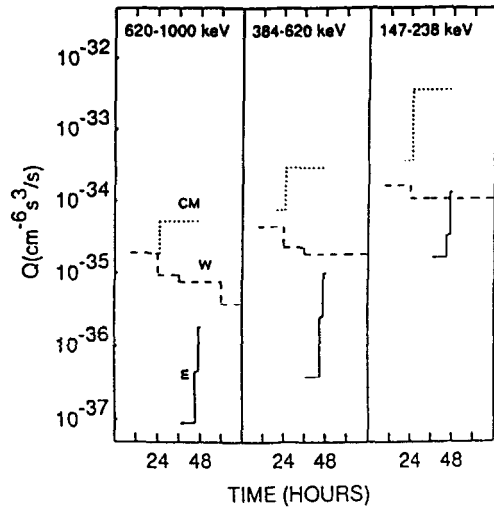


Fig. 3. Injection rate at the shock for the East, Central Meridian and West events, in the energy range 147-1000 keV

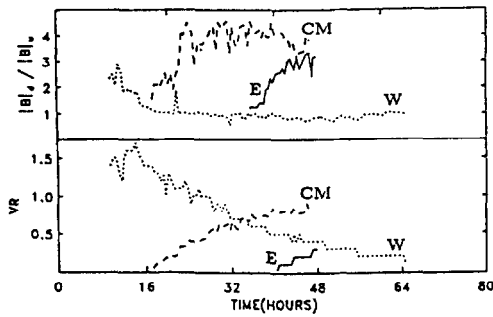


Fig. 2. Evolution of the downstream to upstream magnetic field ratio, BR (upper panel), and of the velocity ratio, VR at the cobpoint (see text).

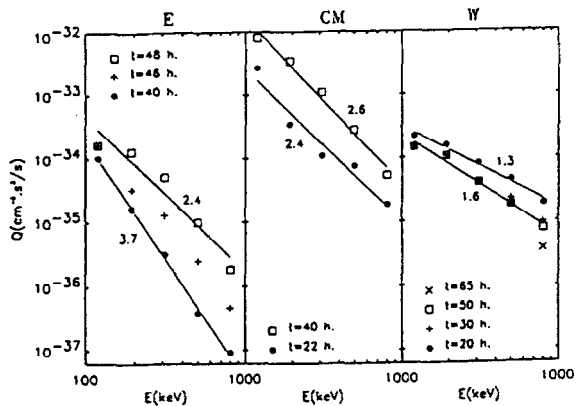


Fig. 4. Spectrum of the injection rate at the shock for the three events. A power-law has been fitted for two of the spectra in each panel.

VR is more determinant for the particle injection rate than BR. Moreover, the values of Q for the West and East events become closer as time passes, in the same way as VR does. These results agree with the conclusions of Bavassano-Cattaneo *et al.* /7/, who found that the value of the peak flux at the shock passage was better correlated to the magnetosonic Mach number than to the magnetic field ratio. The East event shows the lowest values of Q , most probably because this shock has a low VR, but also due to the absence of solar seed particles (in contrast to the CM and West 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 two cases in each panel, shows that the Q spectrum for the East event hardens as the shock approaches. This may be related to the rapid increase of BR and VR at the cobpoint, together with the fact that the shock is quasi-perpendicular. For the CM and West events the slope of the spectra does not change substantially, BR remains almost constant as the shock evolves to quasi-parallel conditions.

CONCLUSIONS

Using a compound shock-particle model we have studied the injection rate of particles at the shock front of interplanetary shocks and its temporal evolution. The correlation between Q and the characteristics of the shock at the cobpoint indicates that VR, BR and Q evolve similarly for a particular event. When comparing different events, however, the seed particle flux and other characteristics of the shock should be taken into account to justify the derived Q values.

Acknowledgments. This research was supported by the Spanish DGYCIT, Ministerio de Educaci n y Ciencia, under projects PB90-0448 and PB92-0794, D. Lario acknowledges the CIRIT from Catalunya for partial financial support, and the Centre de Supercomputaci de Catalunya for the computational support provided.

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