THREE LOW-ENERGY PARTICLE EVENTS: MODELING THE INFLUENCE OF THE PARENT INTERPLANETARY SHOCK

A. M. HERAS
Space Science Department of ESA, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands

B. SANAHUJA AND D. LARIO
Department d’Astronomia i Meteorologia, Universitat de Barcelona, Avenida Diagonal 647, 08028 Barcelona, Spain

AND

Z. K. SMITH, T. DETMAN, AND M. DRYER
NOAA Space Environment Laboratory, 325 Broadway, Boulder, CO 80303

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ABSTRACT

We have reproduced the 35–1600 keV fluxes and anisotropies of two large particle events associated with interplanetary shocks triggered by solar activity (a flare or a filament disappearance). These events, 1979 February 18 (E59°) and 1981 December 8 (W45°), together with the 1979 April 24 event (E10°) already modeled by Heras et al. (1992), constitute a set that allows a comparative study of the influence, upstream of the shock, of the large-scale shock structure on the associated low-energy particle event. Using a compound model for shock and particle propagation in the interplanetary medium (up to 1 AU), we have derived the injection rate of shock-accelerated particles released into the interplanetary medium as a function of time, and the mean free path for their propagation along the interplanetary magnetic field. We stress the relevance of the initial time of connection between the shock and the spacecraft, which is associated with the heliolatitude of the solar source, to explain the observed flux and anisotropy profiles. We have quantified the variations of the efficiency of shock particle acceleration as the shock approaches the spacecraft, relating them to the magnetic field and plasma conditions at the shock region magnetically connected to the observer. We find that for the east and central meridian events this efficiency increases as the shock approaches the observer’s position, while it decreases for the west event, trends which are also followed by the representative velocity and magnetic field jumps across the shocks. The absence of solar particles and the existence of a wide turbulent foreshock region also appear to be relevant factors to explain the derived values of the injection rates.

Subject headings: acceleration of particles — interplanetary medium — MHD — shock waves — Sun: particle emission

1. INTRODUCTION

Particle flux and anisotropy profiles observed in solar energetic particle (SEP) events result from particle acceleration in relation to solar activity phenomena and modulation during particle propagation along the interplanetary magnetic field (IMF). If an interplanetary shock develops as a consequence of the same solar activity (for a thorough discussion about the sources, see Kahler 1992), it can also accelerate particles as it propagates outward in the interplanetary medium. The corresponding large enhancement in the particle flux at the passage of the shock by the observer’s position is usually referred to as an energetic storm particle (ESP) event. Many analyses have been devoted to “pure” SEP or ESP events, but it is also possible to distinguish the presence of both components in many low-energy proton events (e.g., Domingo, Hynds, & Stevens 1979; Wenzel, Reinhard, & Sanderson 1981; Sanahuja & Heras 1992). The analysis of SEP and ESP events can provide information about how protons are accelerated and propagate into the interplanetary medium and about this medium itself. To unravel this information, however, it is necessary to consider the effects of the scattering processes while particles propagate and to make some assumptions on the contribution of the solar- and shock-accelerated protons to the flux profiles. At low energies (E \leq 10 \text{ MeV for protons}) this problem becomes particularly hard to handle since protons can be accelerated at the Sun (flare site or coronal shock) or by an interplanetary shock, with a similar efficiency during the event.

The study of particle flux and anisotropies has led to an increasing appreciation of the fundamental role of the spatial and temporal evolution of a shock in the development of the associated particle event (e.g., Sanahuja & Domingo 1987; Cane, von Rosenvinge, & McGuire 1990; Kahler, Reames, & Sheeley 1990; Kallenrode 1993; Heras et al. 1994), even at energies higher than 50 MeV (e.g., Evenson, Meyer, & Yanagit 1982; Kahler et al. 1986; Kallenrode et al. 1993). In addition to the local strength of the shock, the large-scale shock structure and the heliolatitude of the parent solar activity (Cane, Reames, & von Rosenvinge 1988, 1991; Domingo, Sanahuja, & Heras 1989; Cane et al. 1990; Sanahuja & Heras 1992; Marsden et al. 1992; Kallenrode 1993; Kallenrode et al. 1993) have proved to play an important role in the development of particle events. In particular, the phenomenological multispacecraft analysis performed by Kallenrode et al. on 11 events at low and high energies provides further support of the relevance of the shock geometry and the efficiency of the particle acceleration at the shock front. Some shocks do not accelerate particles up to 1 MeV (i.e., van Nes et al. 1984; Bavassano-Cattaneo et al. 1986), and only half of them up to 10 MeV (Reames 1990). Tsurutani & Lin (1985) surveyed the effects of 37 interplanetary shocks on the associated population of electrons (E > 2 \text{ keV}) and ions (E > 47 \text{ keV}) and...
found an ambient population of energetic particles upstream of every interplanetary shock which they regarded as being the seed particles for shock acceleration. The preexistence of this suprathermal population of particles is not a sufficient condition for an efficient acceleration of particles at shocks. Tsurutani & Lin (1985) concluded that the shock must travel at least with a speed of \( \approx 250 \text{ km s}^{-1} \) in the upstream solar wind frame along the IMF to have a significant influence (i.e., to be efficient enough) on the acceleration of particles.

It has been repeatedly pointed out that, in addition to the study of flux profiles at different energies, analysis of the physical processes responsible for the generation of particle events must also rely on knowledge of the flux anisotropies (Beeck et al. 1987; Tan et al. 1992; Heras et al. 1992, 1994, hereafter HE92 and HE94, respectively). In particular, HE94 have demonstrated that the flux profiles and the large (\( \geq 0.5 \)) long-lasting (several hours) anisotropies in the region of low-energy particle events (\( \leq 1 \text{ MeV} \)) cannot be interpreted in terms of solar acceleration alone. Furthermore, they have shown that particle anisotropies show a distribution with respect to the longitude of the solar source that has triggered the event. In this paper we will refer to the solar particle component of an event (population of particles accelerated at the flare site or in the corona by a coronal shock) as the "SEP component," while the population of particles accelerated by the interplanetary shock will be the "SEP component." In recent literature these have been respectively identified as the "solar" and "shock" (or "interplanetary") components, but we prefer to keep the former classification to include pure SEP or ESP events as extreme cases.

Most of the work already done on ESP events is based on statistical analyses of interplanetary data from which phenomenological models are developed. These analyses usually involved short periods of time centered at the shock passage (to test particle acceleration theories). The simulation of long-lasting ESP events showing large anisotropies is a complex task. In addition to a model for particle transport in the interplanetary medium, it is necessary to incorporate another model for the traveling shock that can provide us, at a given moment, with the position of the shock front and with the structure of the shocked IMF. More precisely, the IMF connection between the observer and the front of the approaching shock is explicitly considered. A combined model of this kind must also include injection in the interplanetary medium of both solar- and shock-accelerated particles as a function of the shock evolution. In HE92, we presented the first compound numerical model to study the influence of the large-scale interplanetary shock topology on the associated low-energy particle event upstream of the shock. This model includes particle injection at the solar corona, a magnetohydrodynamic (MHD) simulation of the propagation of the shock, particle injection at the shock front, and modeling of the particle propagation through the interplanetary medium. The model was applied to analyze a particle event that was triggered by a filament disappearance (FD) centered at E10° (thereafter the "central meridian" [CM] event) showing large and persistent anisotropies in its upstream region. Among other conclusions, we proved that most of the particles in this event (for \( E \leq 1.6 \text{ MeV} \)) were shock-accelerated particles.

An issue closely considered since the work of HE92 is the relevance of the "connection time," \( t_c \), when the IMF line connecting the Sun and the observer is intersected by the shock front, where particle shock acceleration is efficient enough to contribute to the total flux of the event. HE94 showed that the values obtained for \( t_c \) show a distribution with respect to the longitude of the solar source that can be reproduced, on average, with a simple model. However, in order to improve our understanding of the processes involved in the generation of SEP-ESP particle events, individual events must be analyzed in detail. The main purpose of this paper is to extend the quantitative study made by HE92 to individual west and east events, in order to estimate the injection rates of particles as the shock propagates and derive their dependence on the large-scale structure of the shock. Preliminary ideas on this project can be found in Sanahuja & Domingo (1984) and Domingo et al. (1989), while some partial results have been already presented in Heras et al. (1991a, b) and Sanahuja & Heras (1992). In § 2 we briefly describe the characteristics of the numerical code that we have developed. In § 3 the main features of the selected particle events are described. The simulations of the shock and of the respective particle events are described in §§ 4 and 5, respectively. Finally, in § 6 we discuss the results and present the conclusions of the paper.

2. THE NUMERICAL MODEL

In order to study the large-scale influence of an interplanetary shock on the associated particle event, we have developed a numerical model that reproduces the observed upstream particle fluxes and anisotropy profiles and, thereby, allows us to derive the conditions for particle propagation in the interplanetary medium and the particle injection rates at the shock. A detailed description of this model is given in HE92. Particles accelerated by a solar flare (or by an FD or a coronal shock) can diffuse through the corona and propagate outward, spiraling along the IMF. These particles will be detected by the observer if they reach the root of the IMF line connecting with him. Meanwhile, if an interplanetary shock develops, it can also accelerate particles if the conditions are appropriate. These shock-accelerated particles start being detected after the shock front intersects the IMF line that connects with the observer (at \( t = t_c \)). We will call this point of intersection the "cobpoint" (connecting-with-observer point at the shock front). As the shock expands and propagates through the interplanetary medium, the cobpoint slides clockwise along the surface of the discontinuity. That means that the conditions for particle acceleration, as well as the parameters for interplanetary particle propagation close to the shock, change as a function of time. In order to simulate these processes, the model consists of three parts: particle injection at the solar corona (e.g., Beeck et al. 1987), simulation of the propagation of the shock and of the particles through the interplanetary medium, and particle injection at the shock front.

The shock modeling is carried out by means of an MHD time-dependent code which simulates disturbances that propagate in the interplanetary medium, within the ecliptic plane. This model was designed by Wu, Dryer, & Han (1983) to model the \( 2 \frac{1}{2} \)-dimensional propagation of solar-generated disturbances, including shocks. The \( " \frac{1}{2} " \) refers to consideration of the out-of-ecliptic components of the solar wind velocity and IMF vectors, thereby allowing consideration of rotating non-linear Alfvén and MHD waves. Only the two-dimensional feature (i.e., without this and with components is considered in the present work. The complete code has been used in a number of applications, and it has been recently extended to a fully three-dimensional MHD time-dependent model (see the reviews by Dryer 1982, 1994). The simulation of the shock
propagation in each event is based on the observations of \textit{ISEE 3}, and \textit{Helios 1} and 2 when available; the model provides, as a function of time, the location of the point of the shock surface which is magnetically connected with the observer (copolant) as well as the shock characteristics there.

A full description of the method of computation, input pulse models and steady state used in the ecliptic plane, is given in the parametric study of Smith & Dryer (1990). Interplanetary shocks were initialized at the inner boundary (18R$_\odot$ $\approx$ 0.08 AU), a representative position immersed in the supersonic and super-Alfvénic region. Variable initialized widths and piston-driving times were used with various initial shock velocities at that position. Motivation for these particular parameters was provided by the proxy observations, respectively, of coronal mass ejection (CME) widths in the meridional plane (assuming similar widths in the ecliptic), soft X-ray durations (assuming, in the absence of any other proxy predictor, that the shock moves with constant velocity for that duration), and type II radio bursts that, with a reasonable coronal density model, provide the shock velocity in the inner corona. This procedure has several limitations, namely: the shock width could be wider than the CME associated with the flare, if the latter exists; the X-ray duration is the lone obvious diagnostic that characterizes the piston-driving time; and there is no complete assurance that the type II velocity in the inner corona will remain constant up to the inner boundary of the two-dimensional model's computational domain. The detailed numerical procedure for solving the finite-differenced equations of mass, momentum, and energy conservation for a single-fluid, dissipationless (except at the shock) plasma, together with Maxwell's equation, is given by Han (1977).

For the injection of particles accelerated at the solar activity site we have used the biparametric expression of Reid (1964; see HE92) to quantify the solar diffusion of particles through the corona. The existence of such a mechanism for coronal transport has been accepted for a long time (Reid 1964; Jokipii & Parker 1968; Lin 1970). Nevertheless, recent studies (Cane et al. 1988; Reames 1990; Kallenrode 1993) indicate that coronal shocks could be a key process for particle propagation in the corona (in fact, for particle acceleration at different points of the corona). Kahler (1992) gives broad evidence that supports the main role of CMEs in the production of SEP events, and the presence of a coronal shock could be an important factor in the association of CMEs with SEPs. On the other hand, there are no quantitative models for coronal shock propagation and how they evolve into interplanetary shocks. As Kahler (1992) said, the roles of flare-driven blast-wave shocks and CME-driven shocks have not yet been defined. The simulation of these processes is beyond the scope of our model, and moreover, the initial inner boundary is located at 0.05 AU. Therefore, the use of Reid's equation can be considered as an appropriate parameterization of what actually happens before 0.05 AU. If the observer is already connected to the solar source at the onset of the event, a constant injection of particles is assumed instead of coronal diffusion. When there are no signatures of solar particles in an event, solar particle injection is not considered in the simulation.

The calculation for the propagation of the particles is based on the focused-diffusion model that describes the evolution of the particle distribution function (Roelof 1969):

$$\frac{Df}{Dt} + \nu \frac{df}{d\mu} + \frac{v}{2L} \left(1 - \mu^2\right) \frac{df}{d\mu} = \frac{\partial}{\partial \mu} \left[D \frac{df}{d\mu}\right] + Q(\zeta, \mu, t),$$  (1)

where $v$ is the velocity of the particles, $D$ is the pitch diffusion coefficient, $L$ is the focusing length $\left[1/L = \frac{-1}{B_\parallel B_\perp \varepsilon_\parallel}\right]$, and $Q$ is the parameter which represents the particle injection rate at the shock. The expression for $L$ has been derived assuming an Archimedean topology for the IMF. The inner and outer boundaries are defined as absorbing boundaries, and the initial distribution of particles in the interplanetary medium is assumed to decrease exponentially with radial distance from the Sun. The expression for the pitch diffusion coefficient is derived from the "standard model" for the IMF fluctuations, $D(\mu) = A(\mu)^{-1} \left(1 - \mu^2\right)^{-1}$, where $A = 3\pi/2L_{\|}(4 - \eta)(2 - \eta)$ (Hasselmann & Wibberenz 1968). In order to minimize the number of free parameters, we have derived $\eta$ from the power density spectra of the observed IMF fluctuations (e.g., Tranquille et al. 1987). Summarizing, the free parameters of the model that are required to fit the particle flux and anisotropy profiles are $\lambda$, $\eta$, and two that describe the injection at the solar corona, if applicable. The application and validity of equation (1) for our purposes have already been discussed in HE92. Note that we do not intend to simulate the physical processes that lead to particle acceleration at the shock. Instead, we obtain a measure of the particle acceleration shock rates, $Q$, by iteratively fitting the output of this equation to particle observations.

3. SELECTION OF THE EVENTS

We have used low-energy proton data (35–1600 keV), solar wind plasma data, and IMF data obtained by the experiments on board the \textit{ISEE 3} spacecraft. From 1978 August until 1982 September, \textit{ISEE 3} was located in a halo orbit around the inner Lagrangian point of the Sun-Earth system. For a description of the low-energy proton instrument (DFH) see Sanderson et al. (1985), and see Bame et al. (1978) for the solar wind instrument. The flux anisotropy considered in the model is parallel to the IMF in the solar wind frame, and it has been calculated from the observational data following Sanderson et al. (1985). As a first application of our model, we simulated the particle event—the CM event—associated with an interplanetary disturbance observed on 1979 April 24, which was triggered by an FD located at E10° (HE92). To complete the picture derived from the simulation of this CM event, we looked for two intense particle events that originated on the west and east hemispheres. The selection of the events was made according to the following criteria: (1) the solar wind velocity and the IMF direction were steady during the development of the event (therefore, the actual conditions were as similar as possible to those assumed in the model); and (2) other spacecraft were operating simultaneously in the interplanetary medium so that their data could be used to obtain a more accurate simulation of the propagation of the shock. As a result, the events on 1979 February 18 and 1981 December 8 were selected as representatives of east and west events, respectively (the dates indicate the time of the shock passage at \textit{ISEE 3}). It should be kept in mind, however, that the conditions for the propagation of the particles, as well as the absolute efficiency of shock acceleration, may vary significantly between individual events and cannot be generalized. Figure 1 displays the time and solar longitude of the source that originated each event and the time of the shock passage at \textit{ISEE 3}. For comparison, Figure 1 shows the particle flux (top panel) and anisotropy (middle panel) in the energy range 620–1000 keV for these events (east, E; central meridian, CM; and west, W). The thin lines represent the observations, and the thick lines the results.
of the simulation in the upstream region of the shock. The vertical lines in each flux panel indicate the time when the magnetic connection with the shock is established (\(t_\text{s}\), solid line) and the time of the passage of the shock (dashed line). The 1979 April 24 low-energy particle event, and details of its observational features, has already been described in Sanahuja et al. (1983) and in HE92. The anisotropy sign is defined with respect to the IMF direction; therefore, the negative values for the 1979 February 18 and 1981 December 8 events simply indicate that the particles were propagating antisunward when the IMF direction was sunward. In order to study in more detail the characteristics of the local IMF during the development of each event, we have calculated the power density spectra, one-hour averaged, of the IMF fluctuations \(Ck^{-4}\). The bottom panel of Figure 1 shows the evolution of the magnetic field spectral density at 1 Hz, \(C\). As can be seen, the turbulence is lower on average during the east and west events than during the CM event. Another important difference in this event is the high turbulence observed just before the arrival of the shock, which is not detected for the other two events in this timescale.

This characteristic was taken into account by HE92 in the simulation of the event by assuming a narrow region upstream of the shock in which the mean free path was smaller than farther in the interplanetary medium.

3.1. 1979 February 18 East Event

An interplanetary shock was observed by ISEE 3 on 1979 February 18 at 0219 UT, associated with an increase in the particle flux in the energy range 35–1600 keV. The solar origin of this event has been identified as a 3B flare located at N16\(^\circ\), E59\(^\circ\) (Cane 1985), that reached the maximum in H\(_x\) at 0512 UT on the February 16. A second flare was observed at E01\(^\circ\) on 1979 February 17 peaking in H\(_x\) at 1439 UT. Although particles triggered by this flare could also have been observed during the event, there are no clear signatures of their influence on the flux and anisotropy profiles. Therefore, we have not considered their possible contribution, on the assumption that it does not affect our conclusions. No particle enhancement is observed just after the occurrence of the flare; nevertheless, only 6 hr before the passage of the shock by ISEE 3, an important increase in the flux is already observed between 35 keV and 20 MeV (Sanahuja & Domingo 1987). Since no solar particles were detected, it is a pure ESP event. The observed shock was classified as a class B shock by van Nes et al. (1984), namely, a quasi-perpendicular shock where presumably shock drift acceleration took place. Helios 2 (located at E30\(^\circ\), heliocentric distance 0.97 AU) observed a shock around 1979 February 17 at \(\approx\)1900 UT. This time and the derived transit shock

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**TABLE 1**

**OBSERVATIONAL CHARACTERISTICS OF THE SELECTED EVENTS**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>1979 Feb 18 (E)</th>
<th>1981 Dec 8 (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar origin</td>
<td>3B flare 16/0152 UT</td>
<td>FD S/ (\approx) 1215 UT</td>
</tr>
<tr>
<td>Heliolongitude</td>
<td>E59(^\circ)</td>
<td>W35(^\circ)-45(^\circ)</td>
</tr>
<tr>
<td>Shock at ISEE 3</td>
<td>18/0219 UT</td>
<td>8/1358 UT</td>
</tr>
</tbody>
</table>

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**Fig. 1.—** Upper and middle panels: Flux and anisotropy observations at 620–1000 keV (thin lines) and the corresponding fits obtained with the model (thick lines) for the three selected events. The solid vertical lines indicate the initial time of the connection between the shock and the observer, and the dashed vertical lines the passage of the respective shocks at ISEE 3. The arrows in the upper panel show the times corresponding to the snapshots represented in Fig. 1. Lower panel: Magnetic field spectral density at 1 Hz. The origin of time is set at the occurrence of the solar parent activity.
velocities at Helios 2 and ISEE 3 support the fact that both shocks were the same. At Helios 1 (E60°, at ≈0.98 AU), in the time interval during which the shock would have been expected, a substantial velocity jump was observed. This jump was not a well-identified shock because it was preceded by an unusual "void," or "hole," in the solar wind plasma. That is, the density decreased abruptly by about an order of magnitude, while the velocity and the temperature increased slightly and became unsettled for the duration of the density dropout. This signature could perhaps be explained as a result of the interaction of the shock with a rarefaction region in the solar wind. We used this feature to establish the approximate timing of the shock passage.

3.2. 1981 December 8 West Event

An intense particle event was observed at ISEE 3 associated with a shock detected on 1981 December 8 at 1358 UT. The disappearance of a long filament, located at W35°–45°, N15°–30°, that began to erupt at ≈1215 UT, has been identified by Kahler et al. (1986) as the origin of the event. The FD was followed by Hz brightenings at 1315 UT and has been associated with a CME observed by the white-light coronograph (Solwind) on the P78-1 satellite (Michels et al. 1982). High-energy particles (18–70 MeV) were detected shortly after at ISEE 3. Kahler et al. (1986) suggested that the most likely source for particle acceleration at this stage was a high-altitude coronal shock. The onset of the event at lower energies shows velocity dispersion (as in the CM event, Sananujia et al. 1983). By comparing the flux profile at 1 MeV (Fig. 1) and at higher energies (Kahler et al. 1986; Lario 1993), it is clear that this event shows a typical SEP profile between 6.5 and 45 MeV; while for E < 1 MeV, the profile shows a large SEP component associated with the shock. Helios 1 (located at W103°, 0.42 AU) observed a shock around December 6 at ≈1400 UT. At this time Helios 2 was too misplaced to supply relevant information on this event.

4. SIMULATION OF THE PROPAGATION OF THE SHOCK

As commented in § 2, the MHD model can produce an accurate simulation of the two-dimensional shock’s propagation in the ecliptic plane. The shocks were detected and measured by plasma analyzers and magnetometers in various operating spacecraft. Then the evolution of the simulated shock could be fitted with the multispacecraft shock detections; only a few iterations of the initialization parameters used by Smith & Dryer (1990) were necessary, together with the appropriate time delay between the solar parent occurrence (Table 1) and the shock detection time at these spacecraft. The initialization parameters for the model are the initial shock velocity, V₀; its longitudinal angular width, ω, where the largest strengths is at the center (i.e., at the central meridian of the solar activity and decaying to zero strength at both extents of this angle); and the temporal duration of the piston’s driving time, t. Table 2 shows the values for these three parameters adopted for the 1979 February 18 east and 1981 December 8 west events. Shocks generally decelerate at all longitudinal positions after t ≥ tₑ, and the anisotropic nature of the MHD wave propagation (including the shock) makes them expand longitudinally, beyond the original width, ω. The shock strength will decay longitudinally along the flanks until it eventually becomes a simple MHD wave, no longer capable of particle acceleration.

Table 3 shows the good agreement between observational values at Helios 1, Helios 2, and ISEE 3, and the corresponding ones obtained from the simulation of each event: local shock velocity, V, and transit time, TT, from the Sun to these spacecraft.

The four panels in Figure 2 show two snapshots, for each event, of the propagation of the shock detected by ISEE 3 (left, 1981 December 8; right, 1979 February 18). The origin of the time is set at the time of the solar activity which originates the event (Table 1), and the front of the shock is explicitly located within the steep density gradient of the isocurves [log₁₀ (density of particles) in cm⁻³]. The space locations of Helios 1 and Helios 2 are also indicated. As can be seen for the west event, ISEE 3 is already magnetically connected to the shock front before tₑ = 9 hr (but this is not the case for Helios 1). We cannot give a more accurate value of tₑ for the west event because the inner boundary for the shock simulation is set at 0.08 AU, though ISEE 3 was probably connected with the shock front from the very beginning of the event. It is worthwhile to note that at t = 34 hr the compton for this event has slipped from its position at t = 12 hr, W45°, to approximately W20°, which implies that shock-accelerated particles detected by ISEE 3 come from different points of the front. Thus, while the compton is sweeping the front (starting at tₑ and up to the shock passage by ISEE 3), the efficiency of the acceleration varies because of changes in the MHD strength and in the angle between the normal to the shock and the upstream IMF, θₑ. The value of this angle at the compton at tₑ is 87°, and at the shock arrival at ISEE 3, it is 15° (see Table 4; the values have been calculated following the method of Chao & Hsieh 1984). In other words, the shock at the compton evolves from quasi-perpendicular to quasi-parallel conditions.

For the east event the situation is rather different; the spacecraft connects with the shock front 37 hr after the onset of the

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1979 Feb 18 (E)</th>
<th>1981 Dec 8 (W)</th>
</tr>
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<tbody>
<tr>
<td>V₀ (km s⁻¹)</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>ω</td>
<td>90°</td>
<td>54°</td>
</tr>
<tr>
<td>t (hr)</td>
<td>1.5</td>
<td>24</td>
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### Table 3

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<th>Parameter</th>
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<th>1981 Dec 8</th>
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<tbody>
<tr>
<td>Vₑ (km s⁻¹)</td>
<td>900</td>
<td>830</td>
</tr>
<tr>
<td>Vₑ2 (km s⁻¹)</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>Vₑ3 (km s⁻¹)</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>T Tₑ (hr)</td>
<td>29</td>
<td>32</td>
</tr>
<tr>
<td>T Tₑ2 (hr)</td>
<td>38.5</td>
<td>37</td>
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<tr>
<td>T Tₑ3 (hr)</td>
<td>48.5</td>
<td>49</td>
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### Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1979 Feb 18 (E)</th>
<th>1979 Apr 24 (CM)</th>
<th>1981 Dec 8 (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tₑ (hr)</td>
<td>37 ± 1</td>
<td>18 ± 0.5</td>
<td>&lt;9</td>
</tr>
<tr>
<td>θₑ at tₑ</td>
<td>76°</td>
<td>89°</td>
<td>87°</td>
</tr>
<tr>
<td>θₑ at tₑ slick</td>
<td>88°</td>
<td>45°</td>
<td>15°</td>
</tr>
</tbody>
</table>
Fig. 2a

Fig. 2b

Fig. 2.—Snapshots of the simulation of the propagation of the shock for (a) the 1981 December 8 west event and (b) the 1979 February 18 east event. The density contours (log_{10} cm^{-3}) and some IMF lines are represented at two different times for each event. The shocks are explicitly located within the steep density gradients. The outer shock is a MHD fast forward shock, and the inner one is a fast reverse shock. Both the plasma and the field parameters are used in making these identifications. The locations of Helios 1 and Helios 2 are also shown when applicable. The arrows indicate the position of the solar source.
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Fig. 3.—Bottom two panels: Temporal evolution of the coordinates of the copoint (radial distance from the center of the Sun and angle with respect to the CM) for the selected west, CM, and east events as the shock approaches the spacecraft. Second panel: Evolution of VR (see text) at the copoint. Top panel: Magnetic field downstream-to-upstream ratio at the copoint. The origin of time is set at the occurrence of the solar parent activity.

event, only 12 hr before the shock arrival at ISEE 3 (Tables 2 and 3). It is interesting to note that, as seen from the Helios 1 position, this is a CM event. When the magnetic connection is finally established, the copoint lies on the west wing of the shock, approximately 85° away from its central part. As can be seen in Table 4, from then up to the shock passage by ISEE 3 the shock is quasi-perpendicular. At this time, both Helios spacecraft are well inside the downstream region of the perturbation.

The efficiency of the particle-acceleration mechanisms at the shock also depends on its MHD strength. We have discussed this point for the CM event in HE92; now we extend the discussion to include the east and west events. The two bottom panels of Figure 3 show the evolution of the copoint position as given by the MHD simulation of the shock: in the lowest panel its radial distance from the Sun is represented, while the other panel shows the angle between the vector Sun-copoint and the Sun-Earth line. The distance of the copoint from the Sun increases (as a consequence of the shock expansion) almost linearly, while the angle decreases from 45° (west event) or 25° (east event) to 0°, as expected. For each event, the characteristics of the copoint are represented since the magnetic connection between the front and the spacecraft is established \( t = t_1 \) until the shock arrival at ISEE 3. Consequently, the evolution for the east event is much shorter than for the CM and west event.

The two top panels of Figure 3 show the evolution of the downstream-to-upstream magnetic field ratio, \( |B|_u/|B|_w \), and of the normalized plasma velocity ratio, \( VR = (V_*(d) - V_*(u))/V_*(u) \) at the copoint, as derived by the MHD simulation (subscripts \( u \) and \( d \) stand for upstream and downstream of the shock, respectively). These parameters give, respectively, a local measure of the magnetic and hydrodynamic strength of the shock at this point. The velocity jump across the front increases for the CM event as the shock approaches ISEE 3, but it decreases for the west event. The hydrodynamic strength of the shock at the copoint increases in the case of the CM event because this point moves toward the central part of the shock. For the west event, however, the copoint is slipping clockwise toward the east flank of the disturbance, where the velocity jump weakens. VR also increases for the east event since the copoint moves farther from the flank as the shock propagates, although the velocity jump is weaker than for the CM event. The value of \( |B|_u/|B|_w \) decreases for the west event because the copoint moves from the central part of the shock to regions close to the flanks (\( \approx 60° \) away from the nose), where the IMF gradient across the shock is much smaller. The evolution of \( |B|_u/|B|_w \) provides a better visual guide of the shock evolution than the VR evolution. For the CM event, initially increases and then keeps approximately constant until the shock arrival. In this case, the fact that the copoint moves to stronger regions of the shock is compensated by the weakening of the shock as it propagates outward in the interplanetary medium. On the other hand, one should also take into account that the values of these parameters depend not only on the heliolongitude of the source, but also on the initial conditions of the MHD perturbation at the Sun.

5. SIMULATION OF THE PARTICLE EVENTS

5.1. Simulation of the 1979 February 18 East Event

Figure 4 shows the observed particle flux and anisotropy in five energy channels (thin lines) and the fit obtained with the model (thick lines). In column (2) of Table 5, some characteristics of the particle simulation are summarized. Solar particle injection is not needed to fit the observed flux profiles, only particle injection at the shock front which is assumed to start 37 hr after the occurrence of the flare, when the connection between the shock and the observer is established according to the shock simulation. It has not been necessary to assume a foreshock region of enhanced scattering to fit the profiles, which is in agreement with the observations of IMF turbulence shown in Figure 1, and with the fact that the shock is quasi-perpendicular (Tsurutani, Smith, & Jones 1983). A drawback for the simulation is the fact that there is no velocity dispersion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1979 Feb 18 (E)</th>
<th>1979 Apr 24 (CM)</th>
<th>1981 Dec 8 (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal injection</td>
<td>No</td>
<td>( \beta = 3 ) hr, ( \tau = 1.5 ) hr</td>
<td>Constant</td>
</tr>
<tr>
<td>Beginning of particle injection at the Sun (hr)</td>
<td>...</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Beginning of particle injection at the shock (hr)</td>
<td>37</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Upstream shock region with lower ( \lambda )</td>
<td>No</td>
<td>Yes (0.15 AU wide)</td>
<td>No</td>
</tr>
<tr>
<td>( q )</td>
<td>1.8</td>
<td>1.3</td>
<td>1.6</td>
</tr>
</tbody>
</table>
at the onset of the event; that is, a tube of flux already populated with shock-accelerated particles is suddenly detected, probably after the passage of an IMF discontinuity. In spite of the uncertainty about the onset of the event, there is a good agreement between the results of the model and the observations. The anisotropy for the high-energy channels can be properly reproduced. For the low-energy channels there is an initial increase of the anisotropy that does not appear at higher energies and that cannot be fit by our model. This increase may be due to a local feature in the IMF that is not associated with the acceleration at the shock. Column (2) of Table 6 displays the values of the mean free path adopted for the simulation. In Figure 5, the spectra of the particle injection at the shock as derived from the model for each interval of time is shown: $Q$ increases for all energies, and the spectrum hardens as the shock approaches the spacecraft, an expected result taking into account that the observer connects closer to the nose of the shock as time passes.

### 5.2. Simulation of the 1981 December 8 West Event

The observed flux and anisotropy and the results of the simulation are represented in Figure 6 (thin and thick lines, respectively) and the characteristics of the simulation are displayed in column (4) of Table 5. During this event, the observer is magnetically connected to the particle source from the time of occurrence of the solar activity. Therefore, we have initially assumed a constant injection of particles at the root of the IMF line, until the moment when the shock reaches the inner boundary in the MHD model (0.08 AU), $t_i = 9$ hr. In order to fit the onset of the event at the considered energies, the initial injection of particles has been assumed to start 5 hr after the FD that triggered the event. At this time, a prominence-associated CME was observed (Kahler et al. 1986). The adopted values for the mean free path, which have been defined for three intervals of time (Table 6), decrease as a function of time. This implies an increase of turbulence, which is also suggested by the 1 hr averages of the IMF power spectral density, $C$, represented in Figure 1. No foreshock region of enhanced scattering has to be considered in the simulation of this event. However, the flux jump at the arrival of the shock suggests the existence of a narrow turbulent foreshock region, which is not reflected in the 1 hr average values of $C$ at the shock arrival. Therefore, if this turbulent region is present, it is probably too
narrow to be included in our simulation due to the grid size in our numerical model. This also justifies the impossibility of simulating the sudden flux increase observed at the shock passage. The derived injection rates at the shock decrease for all energies as the shock propagates (Fig. 7). This result is consistent with a scenario in which the cusp point moves away from the central shock region as the shock approaches the spacecraft, where it is weaker and less likely to be efficient in particle acceleration.

6. DISCUSSION

Although the IMF, shock parameters, and efficiency in particle acceleration fluctuate with time, the study of their average evolution can provide a global view of the processes involved in the development of the observed particle events. The modeling performed on the low-energy particle events of 1979 February 18 and 1981 December 8 provides further quantitative information for understanding the large-scale influence of interplanetary shocks on the associated particle events. We will not comment here on the model reliability and limitations for the simulation of particle injection and propagation through the interplanetary medium. For a thorough discussion of these points, see § 4 in HE92. We will focus on the results for these two events in comparison with the 1979 April 24 event.

We have reproduced the observed flux and anisotropy profiles assuming that the shock-accelerated particles contribute to the observed flux from the time when the magnetic connection between the shock and the observer is established. By using an MHD model to perform a simulation of the propagation of the shock that reproduces the observations, we have been able to calculate accurately $t$, for three events representa-
ative of west, CM, and east events. The magnetic connection with the shock is established for the west event around the time of occurrence of the solar activity, for the CM shock at $t_s = 18$ hr (when the shock cusp point is at 0.3 AU), and for the east event at $t_e = 37$ hr (when the shock cusp point is already at 0.5 AU). This is consistent with the general scenario proposed in HE94, in which $t_s$ increases as shocks originating more to the east are considered and which obviously implies that the time during which shock-accelerated particles are observed is longer for west than for east events. For these three events, the assumption of particle acceleration taking place at the cusp point is supported by the fact that the shock velocity along the upstream magnetic field, from $t_e$ up to the arrival of the shock, is greater than 250 km s$^{-1}$, the minimum value for a shock to be efficient in particle acceleration (Tsurutani & Lin 1985). Only during the last 10 hr of the west event, when the injection rate reaches its minimum value, is this condition not satisfied.

An interesting result of the particle simulations is the large mean free paths obtained for the 1979 February 18 east and for the 1981 December 8 west events, in many cases greater than 1 AU. During the 1979 April event, on the other hand, the mean free path is never greater than 0.5 AU. This result is in agreement with the level of turbulence being higher during this event than during the east and west events, as shown by the values of C represented in Figure 1. According to Tan & Mason (1993), scatter-free transport for $\approx$1 MeV particles can occur at $q < 2$ when the power level of the IMF turbulence is a factor of 10 lower than the average turbulence power levels, as is the case for both events. Moreover, the unusually large values of the anisotropy observed during these events can only result from the combined effect of a large mean free path and a continuous injection of particles into the interplanetary medium (HE94). It is also worth pointing out the decrease with time of the derived mean free path during the 1981 December 8 event, which indicates a gradual increase of the turbulence as the shock approaches the spacecraft and which is also partially suggested by the values of C represented in Figure 1.

One of the main goals of our study is to correlate the values of the injection rates at the shock with the shock characteristics at the cusp point. In Figure 8, the injection rates are represented as a function of time for the three events in each energy channel considered. As can be seen, $Q$ increases with time for the CM and east events and decreases for the west event, a trend that is also followed by the velocity and magnetic field ratios at the cusp point given by the MHD model, as shown in Figure 3. Moreover, the variation of $Q$ during the east event is the steepest one, just like the variation of the shock parameters at the cusp point, while the evolution of $Q$ during the west event is as gradual as the variation of the shock parameters at the cusp point. For the higher energy channels, the injection rates during the west event are clearly more intense than for the east event. Likewise, the velocity jump across the shock at the cusp point is also larger for the west event, although this is not the case for the magnetic field ratio. The values of $Q$ for the west and east events become closer with time, like the velocity ratio and unlike the magnetic field ratio. Both results suggest that the velocity ratio is more determinant for the particle injection rate, which agrees with the conclusions of Bavassano-Cattaneo et al. (1986), 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.

In order to further analyze the correlation of the injection rate at the shock with the parameters at the cusp point, we have plotted in Figure 9 the values of $Q$ obtained in the energy range 620–1000 keV, against the parameters $VR$, $\theta_{sc}$, and $|B_{\parallel}|/|B_{\perp}|$, averaged over the corresponding time intervals. As mentioned above, the lowest values of $Q$ are derived for the east event, in which the shock is characterized by low values of VR, high values of $|B_{\parallel}|/|B_{\perp}|$, and quasi-perpendicular conditions. But before concluding that this is the reason for the lower particle acceleration efficiency at this shock, it must be taken into account that, in contrast to the CM and west events, no solar particles are observed in association with this event. If, as proposed by Tan et al. (1989), particles gain a factor of 2 in energy due to their encounter with the shock, the small population of SEPs that act as seeds is probably a determinant factor in the shock particle acceleration efficiency. The reduced solar seed particle flux in the east event allows us to explain that (1) for almost the same shock parameter values, the injection rate is much higher for the CM event than for the east event and (2) the spectrum of $Q$ in the east event is harder as the shock approaches the spacecraft while for the west and CM events it becomes softer.

As can be seen in Figure 9, the highest value of $Q$, which corresponds to the CM event, is not associated with the highest value of VR but with the highest value of $|B_{\parallel}|/|B_{\perp}|$. If we assume that the Fermi acceleration mechanism operates in this event, the presence of a wide, high turbulent foreshock region has also probably contributed to the high acceleration efficiency in spite of the moderate VR-values. Summarizing, there is a good correlation between the temporal evolution of $Q$ and VR and $|B_{\parallel}|/|B_{\perp}|$ for each event. When comparing among the
Fig. 8.—Temporal evolution of the particle injection rates at the shock, $Q$, for each event in five energy ranges. The origin of time is set at the occurrence of the solar source.

Fig. 9.—Some shock parameter values at the cusp point, averaged during time periods of constant particle injection rates (as given by our model), against the respective injection rates, for the east event (circles), CM event (squares), and west event (triangles) in the 620–1000 keV energy range.

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three events, the seed particle flux, $\theta_{\text{res}}$, and the degree of turbulence in the foreshock region also appear to be relevant to justify the derived $Q$-values.

HE94 have shown that the connection time, $t_c$, is essential to studying the influence of the heliolongitude of the solar activity on the flux and anisotropy profiles of the associated particle event observed at 1 AU. We consider that $t_c$ is not just an ad hoc parameter of the model but a real variable. The constraints of the MHD simulation, such as the fact that only the ecliptic plane is considered, the inner boundary adopted, and uncertainties in the shock angular extent and in the actual initial conditions for the steady solar wind, may cause the $t_c$-values derived for the events of our study to differ from the actual ones. However, these uncertainties do not affect the validity of our scenario, in which the magnetic connection between the shock and the spacecraft is established at a certain time after the shock is generated at the Sun. For a given shock velocity and angular extent, this time satisfies $0 \leq t_c \text{ (west)} < t_c \text{ (CM)} < t_c \text{ (east)} \leq t_\text{arrival}$ of the shock at 1 AU. It is worthwhile to point out that the angular extent of the shock for a particle observer may not be the same as its physical extent. That is, the observer at 1 AU receives information from the characteristics of the shock at shorter heliodistances through the shock-accelerated particles. The region of the shock flanks, where the acceleration efficiency is low or nonexistent, will not be detected at 1 AU if there are no probe particles that reach the spacecraft. The consequences is that, although the magnetic connection between the shock and the spacecraft is established, it will not have an effect on the observed particle flux until the copoint moves to a region efficient in particle acceleration.

The model presented in HE92 and used here allows us to derive particle injection rates at the shock and the respective spectra far in advance of the shock reaching the spacecraft. The application of the model to a larger number of events is necessary for a more general understanding of the evolution of the injection rates at the shock and their contribution to the observed flux.

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