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Dependence of decay rates of SEP events on characteristics of interplanetary medium and on radial distance

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The shape of the particle flux decline in solar energetic particle (SEP) events is of particular importance in understanding the propagation of energetic particles in the interplanetary medium. The majority of few-MeV particle events exhibit exponential declines indicating the importance of adiabatic deceleration and convection transport. Then value of the decay time τ depends on the differential spectral index γ, solar wind speed, and on the distance from the Sun. By analyzing the dependence of τ on environmental plasma parameters we showed earlier that τ tends to decrease with the increase of both solar wind speed and magnetic field strength. Comparing simultaneous observations at various radial distances (at IMP, ACE, Helios, and Ulysses) we find that whereas high-energy (tens of MeVs) proton profiles sometimes are surprisingly identical at different radii, MeV protons in the same events have significantly longer decays at farther locations than near 1 AU. This is incompatible both with pure diffusive particle propagation and with trapping between converging magnetic field lines near the Sun and at the front of traveling shock, but qualitatively supports convection transport and adiabatic deceleration. Using a simple numerical model including diffusion and adiabatic cooling the time profiles are calculated and compared with observations.

1. Introduction

We consider the decay phase of SEP event time profiles and their dependence on different parameters of particles and environmental plasma. Under the most general conditions, from the convective motion of accelerated particles it follows that decay should be faster with increasing solar wind speed, V, and on the other hand, adiabatic deceleration should cause the decay be faster due to energy spectra falling with energy and the characteristic time of the decay, τ, should also decrease with the increase of spectral index γ. If particles fill some volume extending from the Sun, then after the maximum of an event the decaying part of the time profile at larger distance is longer because more time is needed for particles contained in radially more extended volume to pass by an observer.

If the decay profile of the flux is exponential: $J \propto \exp(-t/\tau)$, that is, $\tau = \text{const}$, one expects that an invariant combination of the parameters related to particles and interplanetary medium exists. Lee (2000) obtained a solution of the propagation equation neglecting diffusion, gradients, and drift, but retaining adiabatic cooling which yields

$$\tau = 3r / 2V\,(2 + \alpha\,\gamma),$$

where r is the radial distance, V is the solar wind plasma speed, and $\alpha = (T+2mc^2)/(T+mc^2)$. This formula returns all the three requirements mentioned above. It would be desirable to build a "time profile" of current value of this combination of r, V and γ, having in mind heliolongitudinal spacing through the event as well, but this seems hard to realize. We analyzed separately pair correlations between τ and the values of parameters V, γ and r [4].

2. Dependence on the distance from the Sun

We have used data on simultaneous observations of proton fluxes in SEP events as measured at various radial distances by Helios 1-2 (Kiel experiment, PI: H. Kunow, energies 4-27 MeV), IMP-8 spacecraft (CPME, PI: S.M. Krimigis, 1-25 MeV), as well as at Ulysses (COSPIN, PI: B. McKibben, 1-19 MeV). As compared to our earlier single spacecraft studies [2-4] at two points, contamination from different disturbances, additional and merging events, and the necessity to compare the same events make the situations complicated and drastically limits the statistics available.

2.1 Observations inside 1 AU

In addition to the difficulties mentioned, simultaneous observations of SEP events at Helios1-2 and IMP-8 in the inner heliosphere are very sensitive to the relative longitudinal locations of flares and s/c. Furthermore, the time profiles at <1 AU are contaminated by non-flare particles to a higher extent than at 1 AU and beyond. Earlier we analyzed events observed on Helios 1 and 2 at distances 0.3-0.6 AU near the Sun-Earth line [2] and found that Helios intensities became nearly equal to those observed at IMP-8 after the shock crossed the respective s/c. Here we consider all events observed simultaneously at IMP-8 and at Helios 1, 2 at R<0.7 AU. From this a subset of 16 was selected which have smooth time profiles and regular behavior without data gaps. In 7 events, τ at IMP-8 exceeded that at Helios s/c, in 5 events the values were nearly equal and in 3 events τ at Helios s/c was larger. It is worth noting that Helios 1-2 heliolongitudes closer to the Sun changed more rapidly than near 1 AU hence the angular spacing of Helios and the flare site varied quickly affecting the decay profile significantly. This way the longitude effect [5] sometimes exceeded the difference due to radial separation.

2.2 Observations beyond 1 AU

The comparison of simultaneous observations at 1 AU (at IMP and ACE) and at 2-3 AU (at Ulysses) indicated that whereas high-energy (tens of MeVs) proton profiles sometimes are surprisingly identical at different radii [6], <10 MeV protons in the same events have considerably longer decays at farther locations. Dalla [7] compared the decay phases of SEP events at 1 and 5 AU found no satisfactory explanation of time profiles in terms of four different models.

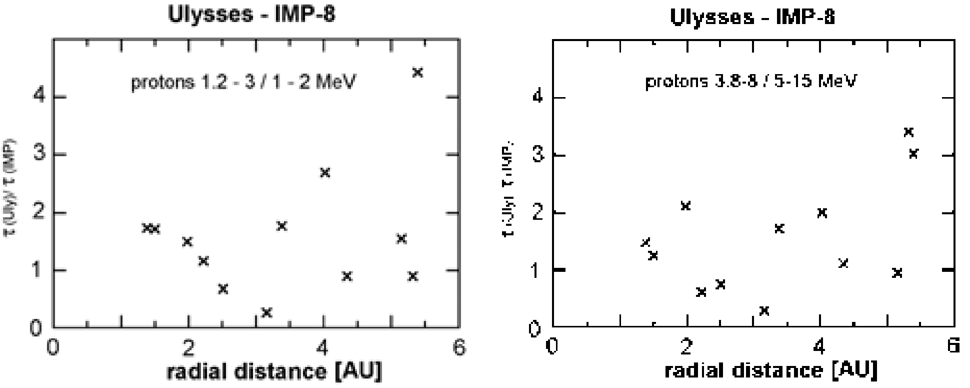

Figure 1. Variation of τ values with radial distance as compared to 1 AU values at two proton energies in 12 SEP events.

To analyze the dependence of τ on r farther away from the Sun we used data from the LET (COSPIN) telescope aboard Ulysses. 49 SEP events were selected at distances more than 1.3 AU according to Ulysses data between 1990 to 2002 that can be reliably correlated with 1 AU SEP observations. We have not yet carefully connected all particle events to parent flares, however, from the simultaneous observations at and beyond 1AU the qualitatively impression is that the longitudinal effect at Ulysses is much smaller than at 1 AU (see also [6]). At energies >30 MeV none of these decays was steeper at Ulysses than at IMP-8; 4 had similar τ, and 34 decays were faster at 1 AU. At lower energies (~4 MeV), the situation was similar: for 3 events τ at Ulysses was smaller, for 3 nearly equal and in 26 events longer. In order to suppress latitude effects, then we have excluded all events where Ulysses was outside of the [-10, +10 deg] latitude interval. For the remaining 12 events the radial variation of the ratio τ (r)/τ (1 AU) was obtained as shown in Figure 1. Although the sample is small, the majority of τ values at >1 AU are larger and a slight increasing tendency outwards can be observed. It is necessary to note that merging of events following one by one often observed at large r, clearly distinguished at 1 AU, is due to increase of τ with increasing r.

Analytical time-dependence at late phase of decay in commonly used models has a form: (1) Diffusion: $f(r,t) = f_0\ (4\kappa pt)^{-3/2}$, κ is diffusion coefficient. If, however, $\kappa = \kappa(r)$ then, depending on the functional form, the profile can be exponential as well, for instance if particles leak out freely at a certain distance R. (2) Trapping: $\tau = t/(2+2\alpha\gamma)$. (3) Convection and adiabatic deceleration leads to radially dependent $\tau = 3r/2V(2+\alpha\gamma)$. If combined with diffusion, exponential is retained if becomes small at r > R. The observed radial dependence of τ for MeV energy protons is incompatible both with pure diffusive particle propagation and with trapping between converging magnetic field lines near the Sun and at the front of traveling shock, but qualitatively supports convection transport and adiabatic deceleration. Based on the actual values of V for a large sample of events at 1 AU a similar conclusion was achieved [4]. The observed identity of radially distant high energy fluxes was interpreted by means of the idea of "uniform particle reservoir" [8], which produces a uniform flux within the inner heliosphere independent of longitude, latitude, or radius (up to several AU). After formation, the reservoir dissipates as a result of diffusion, convection and adiabatic cooling. Particles with E > 30 MeV are involved in these processes to a lesser extent and radial dependence at higher energies is less pronounced.

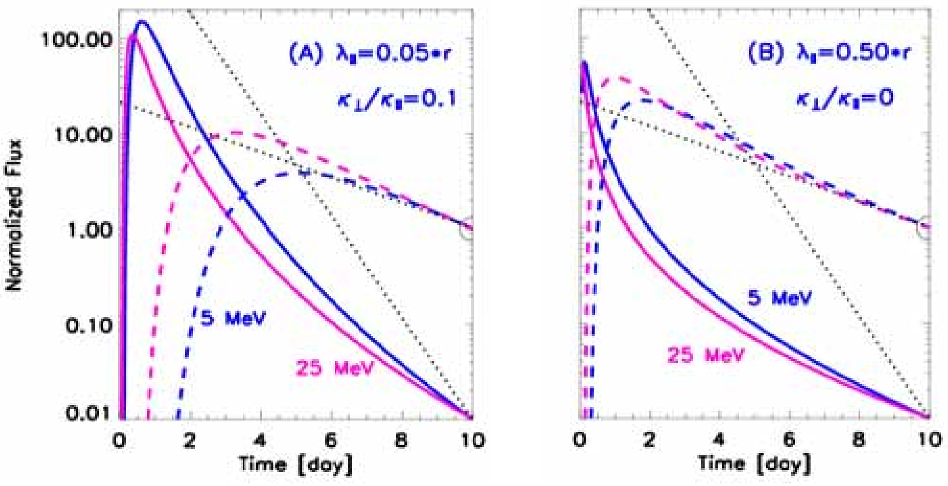

Figure 2. Comparison of simulated time profiles at 1 and at 4 AU normalized at 10 days for small (left panel) and large $\lambda_{\|}$ (right panel) at two energies. Solid lines refer to 1 AU, dashed ones to 4 AU, dotted lines: theoretical prediction [1].

3. Numerical results

The flux variation was simulated in the frame of a simple particle model involving scattering and adiabatic cooling, assuming propagation in a Parker magnetic field with an impulsive power-law source spectrum of $f = p^{-\gamma^*}$ (p denotes momentum). Here the exponent is $\gamma^* = 8$, which corresponds to $\gamma = 3$. The calculations are restricted to low latitudes. The radial diffusion coefficient, $\kappa_{rr} = \kappa_{\parallel}\cos^2\psi + \kappa_{\perp}\sin^2\psi$, includes the radial dependence of diffusion mean free path, $\lambda_{\parallel}$ ($\propto$ r and independent of p) and the effect of the spiral angle, ψ, reducing κ_{rr} as the spiral is more tightly wound at larger radii. The ratio $\kappa_{\perp}/\kappa_{\parallel}$ was taken constant. Figure 2 displays the temporal variation of fluxes normalized at t = 10 days for two different values of the interplanetary mean free path $\lambda_{\parallel}$. We find that a smaller diffusion coefficient tends to give decays closer to the theoretical prediction [1] (inferred from the assumption of fast diffusion).

4. Discussion

We analyzed data on simultaneous observations of protons in SEP events measured at various radial distances. The comparison of Helios and IMP profiles indicates that the decay time is longer at 1 AU in the majority of events. The decay profiles of events seen by Ulysses at 1.4 to 5.4 AU (at latitudes within 20° from the ecliptic) suggest that, in agreement with [2], the decays at 2-5 AU are even longer. Although the points in Figure 1 are scattered, they indicate that τ rises by a factor about 2 from 2 to 5 AU at energies 1-10 MeV. Assuming power-law increase with r as $\tau \propto r^{-\beta}$ this would correspond to an exponent of $\beta \sim 0.5$ as compared to 1 from the theoretical formula, but it is in a better agreement with low κ numerical results which correspond to a value of ~0.4.

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