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Generalized parameters characterizing the state of the interplanetary medium (IM) include the functional form and the rate of decline of charged particle flux in solar energetic particle (SEP) events. The shape of the particle flux decline is of particular importance: power-law time dependence indicates the dominance of diffusive propagation, whereas exponential-law decline emphasizes adiabatic deceleration and convection. A statistical investigation extended for a long period suggests that about 90% of SEP decays are characterized by exponential declines. Variation of the decay time with energy and angular distance of the observer from the flare are considered as well.

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Some Statistical Properties of the Decay Phase of SEP-events

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Abstract

Generalized parameters characterizing the state of the interplanetary medium (IM) include the functional form and the rate of decline of charged particle flux in solar energetic particle (SEP) events. The shape of the particle flux decline is of particular importance: power-law time dependence indicates the dominance of diffusive propagation, whereas exponential-law decline emphasizes adiabatic deceleration and convection. A statistical investigation extended for a long period suggests that about 90% of SEP decays are characterized by exponential declines. Variation of the decay time with energy and angular distance of the observer from the flare are considered as well.

1. Introduction

This paper considers SEP events after their maxima having exponential decay phases between 1973 and 2001 as a continuation of a systematic statistical study of decay phases of SEP events [1,2]. Here we analyze the dependence of τ on the flare site and on proton energy for all events satisfying our selection criteria. Distributions of durations of shock-associated and non-associated events are also considered.

2. Distributions of total durations of decays and their functional form

Time intervals were selected on the basis of a homogeneous data set obtained by the CPME instrument aboard IMP 8 between 1974 and 2001 [1,2] during the decay phase of SEP events following flares, CMEs and interplanetary shocks of different origin. Only those parts of declines were examined, which could reasonably be described by exponential dependence. Fig. 1 displays the distributions of the total durations, ΔT, of shock-associated exponential declines and those without shocks. The distributions differ insignificantly for $\Delta T > 10$ hrs, whereas for shorter events the relative number of shock associated events is 30-40% higher than without shocks. This can be due to the fact that at our selection criteria

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short duration events often represent regions of shock-trapped particles, which rapidly pass by the observer. In most cases, when the time profile following the maximum is smooth and free of disturbances, the exponential function gives the best approximation in nearly 90% of the cases for proton energies above 1 MeV.

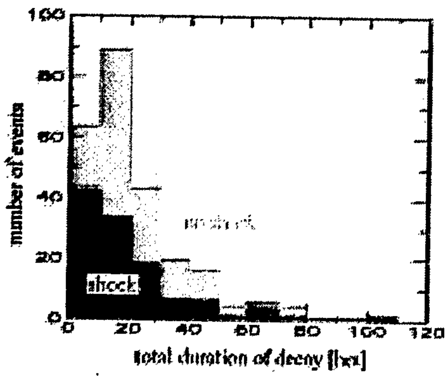

Fig. 1. The distribution of decay times.

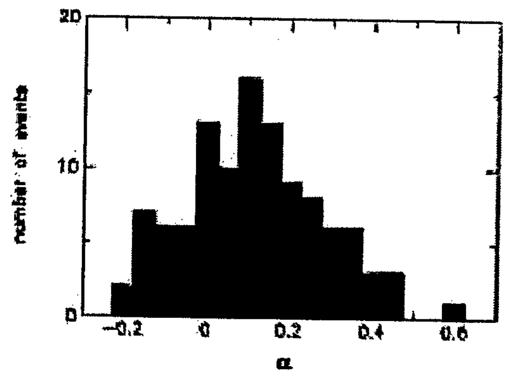

Fig. 2. The distribution of α values.

The comparison of experimental values of characteristic decay times, τ, with those obtained previously in different theoretical models [4,6] shows that theoretical τ values are reasonably close to the fitted slopes in nearly 50% of all cases if one uses the average V solar wind speed values measured later when the corresponding plasma in which particles were convected arrives to the observer. This might be a surprisingly high number bearing in mind that in rare case remains V constant for a sufficiently long time.

3. Energy dependence of characteristic decay time in exponential decays of proton SEP events

To study the energy dependence we selected events with exponential decays for which τ could be determined within an accuracy of 10% for high-energy differential channels (4.6-48 MeV), i.e. sufficiently powerful events, and where the time profiles following the maxima were smooth and free of considerable disturbances. Here the fluxes of 4.6-15 MeV proton usually reach 1 p/(cm^2 s sr MeV). 109 such events were found during the period 1973-2001, and the exponent assuming power-law energy dependence $\tau = CE^{-\alpha}$ was determined (E is the proton kinetic energy). Due to the wide energy intervals, the errors in determining τ was about 10% due to not strict exponentiality and small flux variations. The accuracy of determination of α is about 30%. Presented in Fig. 2, the distribution of α values can be considered to consist of three separate groups: (1) τ independent of proton energy ($-0.1 < \alpha < 0.1$, 40 events); (2) τ decreasing with energy ($\alpha > 0.1$, 57 events); and (3) a small group with τ increasing with energy ($\alpha < -0.1$, 12 events). Thus predominantly, τ is either independent of or decreases with proton energy. A constant τ results in spatial and temporal invariance in the spectra of energetic particles in gradual solar events discussed in [7] when nearly identical spectra are seen over large heliolongitude region some time before or after shock arrival depending on the relative positions of the flare and observation point. We assume that it is possible to interpret the second group (decreasing τ) as having a "memory" of diffusion propagation at the early stage near the Sun. Indeed, diffusional decay time profile (power-law shaped) is proportional to $D^{-3/2}$, where $D = \lambda v/3$ (λ is scattering mean free path, v is the particle speed) is diffusion coefficient increasing with the particle energy under reasonable assumptions about λ dependence on particle energy. Thus even exponential decays, which are most probably related to convection and adiabatic deceleration rather than to diffusion, are in some cases evidently are influenced by diffusion. The most surprising result is the presence of the group with negative α. This group includes events with practically all possible values of τ from 5 to 30 hours. Since the background was subtracted, this means that a negative (α is not simply an instrumental effect and might indicate that some additional exotic effects of propagation and/or acceleration can play a role.

4. Dependence of characteristic decay time on the flare site

If the parent flare occurred near W60 heliolongitude, then particles accelerated at the flare site would arrive to the observer along the shortest way. If the flare took place at other solar meridian one could expect another rise time and slower decay after peak intensity. The properties of decay phase of a few solar flare events according to Pioneer 6-9 observations was studied in [5]. They obtained that in events registered simaltaneously at different heliolongitudes τ differs by $1/\psi_0\ d\psi/dt$ where $d\psi/dt = 0.54\,\text{deg}\,hr^{-1}$, ψ_0 is about $\pm 30\,\text{deg}$. Indirect indication for such a dependence was also obtained in [3], where ΔT was considered as a function of ψ. We examined if such dependence exists for our whole statistics of events. Based on more than 200 events, the dependence τ on the parent flare heliolongitude during 1974-2001 was analyzed. The result is that τ is statistically independent from the flare heliolongitude (Figure 3), while the particle arrival and peak time in some cases are significantly delayed with the increase of the distance of the flare site from the optimal heliolongitude where magnetic field line is connected to the observation point.

In [5] indications were also obtained for the events considered that at late times (> 2 days) the spectral exponent, γ, near 10 MeV depends on the heliolongitude of the observer relative to the centroid of the particle population injected by the flare. This effect results in a variation in spectral exponent over the range $2.0 < \gamma < 4.5$. Again, our statistical consideration does not confirm this observation. This suggests that after SEP event maximum particle propagation in the interplanetary medium is controlled mainly by IM conditions in the neighborhood of observation point, and the structure of coronal magnetic fields does not

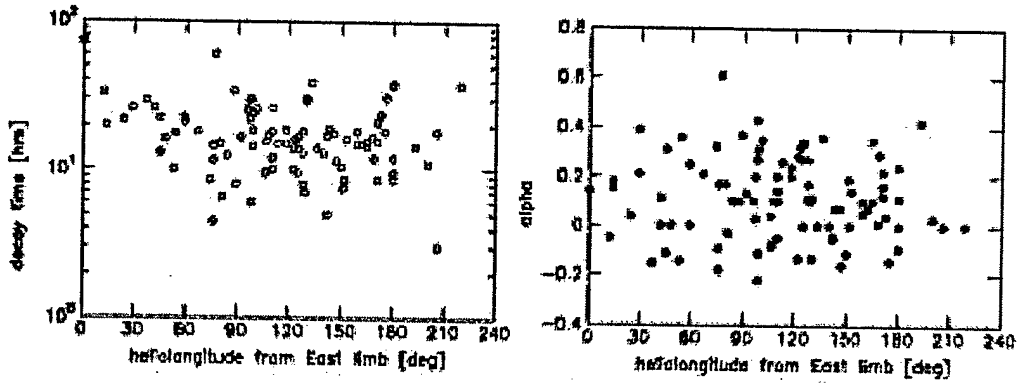

Fig. 3. Dependence of τ and α on heliolongitude for 4.6-15 MeV protons.

influence on the shape of time profile during this phase.

5. Conclusions

1) The distributions of total durations, ΔT, of exponential declines with and without shocks differ insignificantly for $\Delta T > 10$ hrs, while for $\Delta T < 10$ hrs the relative number of shock associated events is 30-40 % higher.
2) The distribution of exponent α from $\tau = CE^{-\alpha}$ representation consists of 3 separate groups: i) τ independent of proton energy ($-0.1 < \alpha < 0.1$, 40 events); ii) τ decreasing with energy ($\alpha > 0.1$, 57 events), and iii) a small group of τ increasing with energy ($\alpha < -0.1$, 12 events).
3) Both the characteristic decay time, τ, and spectral index, γ, are statistically independent of the parent flare heliolongitude.

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