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Comparison of theoretical and experimental values of the decay rate of SEP events

K. KECSKEMÉTY[1], E.I. DAIBOG[2], YU.I. LOGACHEV, AND J. KÓTA[3]
[1]*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[2] *Nuclear Physics Institute, Moscow State University, Russia*
[3]*Lunar and Planetary Laboratory, University of Arizona, Tucson, USA*
kecske@rmki.kfki.hu

Abstract: The profiles of MeV protons and electrons are compared in the decay phase of SEP events. The decay time τ of exponential profiles are interpreted in terms of a simple analytic model assuming convection and adiabatic cooling only. The energy dependence of τ is also compared with the predictions of a numerical model.

Introduction

The time profiles of particle fluxes during SEP events usually exhibit a fast rise, followed by a long decay, which in many cases are of exponential or power-law shape. For few-MeV protons nearly all decays are exponential, while the profiles of mid-relativistic electrons are predominantly of power-law shape. The few clear power-law proton decays appear usually before the arrival of the shock for CME-initiated SEP events, whereas behind the shock the profiles almost exclusively become exponential.

The comparison of experimental values of decay times τ_{obs} in exponential profiles, with those obtained in theoretical models [1] considering convection transport and adiabatic deceleration shows that the expected values $\tau_{theor} = 3r/4V(1+ \gamma)$ (V the solar speed, γ spectral exponent, r radial distance), are within about 25 % to fitted slopes in about half of all cases where the solar wind speed stays approximately constant [2]. The events where τ_{obs} is significantly different from theoretical values might be explained by the variation of magnetic connection between the observer and the source through the decay due to the solar rotation the flare site approaches to (Eastern flares) or diverges from (Western flares) the observer's footpoint and consequently τ_{obs} increases or decreases as compared to τ_{theor}.

Data analysis

Based on IMP-8 CPME flux data of 1-25 MeV protons between 1974 and 2001, from a statistics of 528 events 49 were selected where the variation of the solar wind speed V did not exceed

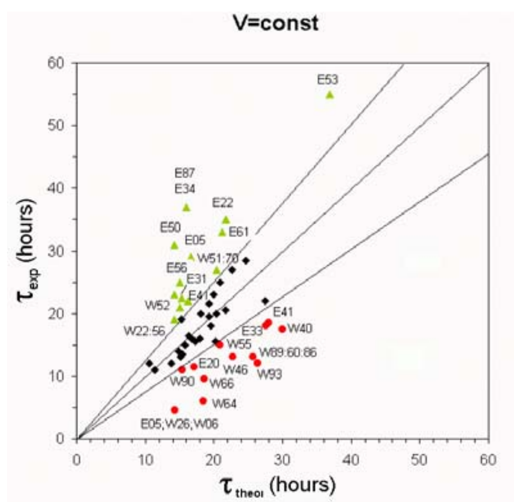

Figure 1: Scatter plot of τ_{exp} vs. τ_{theor} for protons with V=const. Black diamonds: events within ±20%, green triangles $\tau_{exp} > \tau_{theor}$, red dots: $\tau_{exp} > \tau_{theor}$. The longitudes of the parent flares are indicated next to the symbols.

10% throughout the decay phase. Fig. 1 displays this longitude effect by comparing τ_{obs} and τ_{theor} at various longitudes for constant solar wind speed events. Whereas about half of all events (24 out of 49) fell between the ±25% lines, those where τ is underestimated by the theoretical formula are due mostly to eastern events (upper part in Fig. 1) and the overestimated ones to western events. The latter cases, where the correlation between τ_{theor} and τ_{obs} fails, can be due to that the flare site and the place of particle escape from the Sun do not coincide, but might also indicate incorrect association between particle event and parent flare.

About half of all SEP event profiles are distorted by the "heliolongitudinal profile" of particle injection. However, if during some time V decreases in a way that the observer is connected to the same point on the Sun rotating with it, the event profile is not distorted by the above heliolongitudinal effect. This idea can be traced back to solar wind "dwells" [3], when the intensity history at the s/c should be similar to injection history at the corona. Such a decrease of V (with definite rate) is rare, but among exponential decays > 24 hrs, a few satisfied this condition. No considerable change of τ outside the periods with decreasing V was observed.

Proton and electron decay times

In order to compare the propagation parameters of protons and electrons we used simultaneously measured proton (4.3-7.8, 7.8-25 MeV) and electron (0.25-0.7 MeV) flux data from SOHO COSTEP in the period of 1998-2005. Out of 88 clear-shaped decays of 7.8-25 MeV protons and 0.25-0.7 MeV electrons of nearly equal velocities in most cases the shapes of electron and proton decays are similar (exponential or power-law). The decay parameters of protons and electrons were compared in 15 major flare associated events. The rate of electron decay turned usually equal or slower than that of protons (see Fig. 2), suggesting that electrons can be subject to the same processes (convection and adiabatic deceleration) as protons.

The ratio of the decay times were computed using Forman's formula is $\tau_e/\tau_p = (1+\gamma_p)/(1+\gamma_e)$, where γ_e and γ_p are the exponents of the differential energy spectrum of electrons and protons, respectively.

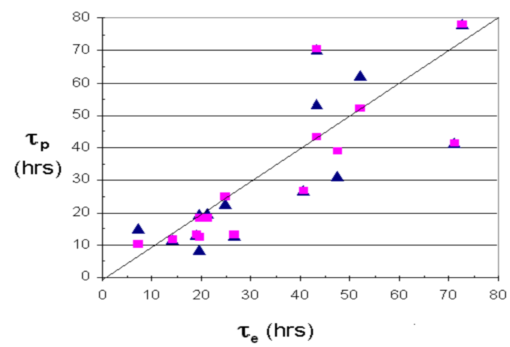

Figure 2: Proton (triangles – p1: 4.3-7.8, squares, p2: 7.8-25 MeV) vs electron (e1: 0.25-0.7 MeV) decay times from 15 major SOHO SEP events. Velocities of p2 protons and e2 electrons are nearly equal.

Fig. 3 indicates that in contrast to the linear increase with $(1+\gamma_p)/(1+\gamma_e)$ expected from the model, τ_e/τ_p is rather independent or even negatively correlated with that quantity.

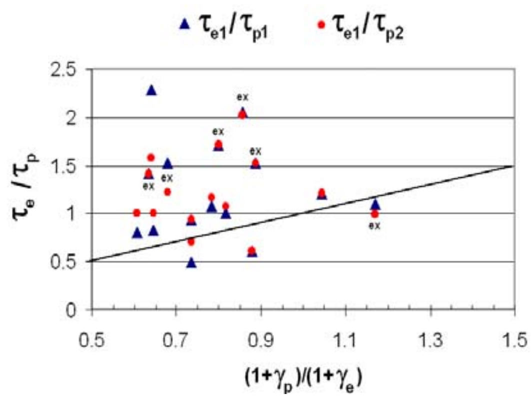

Figure 3: The τ_e/τ_p ratios as a function of the ratio $(1+\gamma_p)/(1+\gamma_e)$ for 4.3-7.8 MeV (triangles) and 7.8-25 MeV (full circles) protons (ex refer to "extreme events").

Another survey using 0.3-0.8 MeV electrons and 13-27 MeV protons measured aboard Helios 1 and 2 between 1974 and 1979 yielded that in most cases the shapes of proton and electron decays are similar. Out of 31 decays for 16 τ_e and τ_p were nearly equal, whereas for 15 events τ_e was larger than τ_p.

Numerical simulation

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 scattering mean free path is $\lambda_{rr} = \lambda_{\|}\cos^2\psi + \lambda_{\perp}\sin^2\psi$, where $\lambda_{\|} \propto r$ and $\lambda_{\perp} / \lambda_{\|}$ = const. The model also includes a shock propagating outward as well as a free escape boundary, assumed to take place at 20 AU. Calculations were made with various dependences of λ on rigidity P (either independent of $\propto P^{1/3}$). Fig. 4 suggests that on one hand the profiles are closest to exponential at lowest energies, and on the other hand the running τ values fitted to the profiles are nearly constant ahead of the shock. The increase of τ with energy behind the shock, however, is in contrast to the decrease usually observed (see [4]).

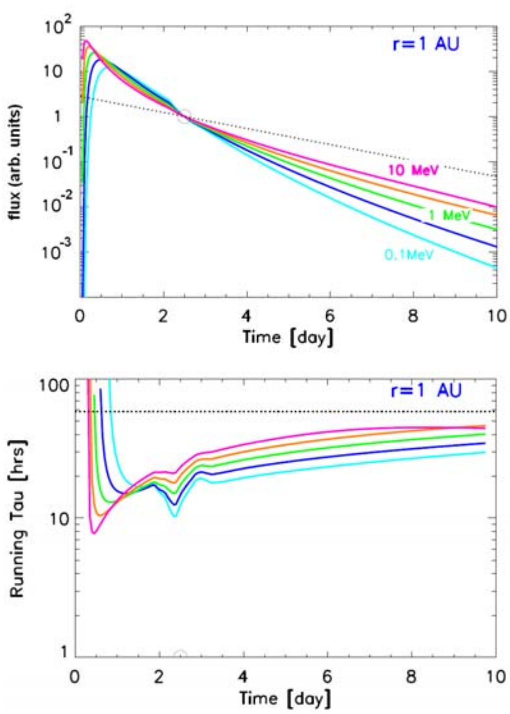

Figure 4: Upper panel: time profiles of 0.1, 0.3, 1, 3 and 10 MeV protons at 1 AU from a numerical model with $\lambda_{\|} \propto r = 0.3$ AU at 1 AU, independent of P, $\lambda_{\perp} / \lambda_{\|} = 0.01$. Lower panel: running τ values calculated from the profiles.

Acknowledgment

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