# Rigidity Dependence of Characteristic Decay Time in SEP Events

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***Abstract*. The results of a study of the decay rates of SEP events as a function of particle rigidity are presented. Combining data on the decays of different particles (e, p, and alpha) into a common dependence of $\tau$ on particle rigidity R in a wide range of R reveals complicated forms of $\tau(R)$. In many events the variation of $\tau$ with R is not monotonic but displays maxima or minima as well. As in diffusive approximation $\tau$ is inversely proportional to the particle mean free path $\lambda$ , the $\tau(R)$ variation is related to the old problem of the $\lambda(R)$ dependence. The latter, contrary to the standard quasi-linear theory predicting an increase of $\lambda$ with R (and in turn, a decrease of $\tau$ with R) has a broad minimum in some selected events. Possible forms of the dependence $\tau(R)$ according to different spacecraft data are considered.**

***Keywords*: SEP events, decay time, rigidity**

## I. INTRODUCTION

It was shown in our previous studies that at least 90 percents decays of MeV-proton fluxes have an exponential shape [1]. On the one hand it was obtained that the characteristic decay time, $\tau$, qualitatively displays the dependence on the parameters predicted by the formula [2]:

$$\tau = 3r/2V(2 + \alpha\gamma) \quad (1)$$

Here, V is the solar wind velocity, $\gamma$ - the power index of the energy spectrum of particles, r is the distance of an observational point from the Sun, $\alpha = 2$ for particles of non-relativistic energies. This dependence testifies to processes of convective transport and adiabatic deceleration during particle propagation in the interplanetary medium. Qualitatively such a dependence on r, V and $\gamma$ was confirmed by us [1,3]. Note, that this formula is independent of the particle energy. On the other hand a survey of the solar events using data of the CPME instrument aboard IMP-8 satellite for the period of almost three solar activity cycles allowed studying the dependence of the characteristic decay time on particle energy which showed that such a dependence does exist and has a character varying from event to event. On the basis of 147 decays of 2 - 48 MeV protons the distribution of the power-law index n in the $\tau = CE^{-n}$ dependence in all solar events in energetic particles was split into three groups [4]: a) $\tau$ is independent of proton energy $(0.1 < n < 0.1)$; b) decreases $(n > 0.1)$; and ) increases with proton energy $(n < 0.1)$). These dependences were obtained in the narrow interval of energies (or rigidities) however they demonstrate the variety of their functional forms. In the majority of events $\tau$ decreases with energy which may be considered as evidence of the presence of diffusive processes in particle propagation (scattering cannot be completely absent, even when convective and adiabatic processes are dominant [4]). Such dependence for the exponential decay with $\tau$ depending on energy results from a pure diffusion model with an absorbing boundary located at a distance $R_0$ or with a free escape of particles into the interplanetary space [5, 6]. In that case after propagation of the diffusion wave crest to the distance $R_0$ (it is taken usually that $R_0 \sim 2.5$ AU) the solution becomes exponential with

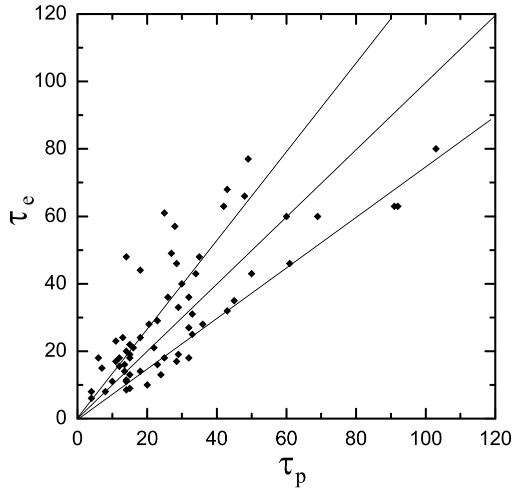


Fig. 1: Scatter plot $\tau_e - \tau_p$ (hours) for 0.5-0.8 MeV electrons and 4.6-15 MeV protons according to the IMP 8 data from 1974 to 2001. The lines are $\tau_e = \tau_p$ and $\tau_e = (1 \pm 0.25)\tau_p$

$$\tau = R_0^2/\pi^2 D \quad (2)$$

decreasing with energy as diffusion coefficient, D, increases.

## II. RIGIDITY DEPENDENCE OF $\tau$

The comparison of the decays of particles of different kinds is of particular interest. Here we study characteristic decay times, $\tau$, of electrons and protons according to the IMP 8 (CPME) data. Fig. 1 is a scatter plot of

$\tau_p - \tau_e$ for 64 exponential decays (sufficient for statistical consideration) of 4.6 - 15 MeV protons and 0.5 - 0.8 MeV electrons. It follows from Fig. 1 that points are grouped along the line $\tau_e = \tau_p$. In approximately a half of cases, $\tau_e$ deviates from $\tau_p$ by no more than 25 percents; this fact indicates that the propagation of electrons in the interplanetary space in at least a half of cases is related to the same processes as the propagation of protons. It is noteworthy that most decays outside of this interval are related to cases with $\tau_p < \tau_e$, including some decays where $\tau_e$ exceeded $\tau_p$ by a factor of more than 2.

To expand the rigidity range for further study we used the data on different particles of the same event from different s/c. Those were electrons of 0.038 -0.315 MeV (ACE EPAM DE) and 0.25 -10.4 MeV (SOHO EPHIN), protons of 0.04 -6 MeV (SOHO LION), protons and alpha-particles 4.3 -53 MeV/n. (SOHO EPHIN), which correspond to the rigidity interval 0.2 -450 MV. In spite of inevitable discrepancies between values of fluxes at different s/c, we rely upon identity of their decay rates. However to avoid difficulties with instrumental and physical backgrounds we considered only decays during which fluxes exceeded background by at least one order of magnitude. We selected 22 events with full data sets. Fig. 2 demonstrates the patterns of $\tau(R)$ dependences during 10 decays. One can see that this dependence is differently shaped from event to event. In this rigidity range there were those independent of the value of rigidity in the whole R range (1999 (DOY 126), 2005 (DOY 135)) and $\tau = const$ slightly differed for electrons and protons (2005 (DOY 199)); regularly decreasing (2001 (DOY 223), 2005 (DOY 238)); having a broad minimum (2001 (DOY 269), 2006 (DOY 342)) or maximum (2001 (DOY 106), 2005 (DOY 262) 2005 (DOY 158)). Here DOY is the date of the beginning of the decay. Only those longer than 24 hrs (and up to 4-5 days) were considered. Some of the decays had irregular form. It should be noted the decrease of $\tau$ for the highest values of rigidity (corresponding to alpha-particles) independent of the previous behaviour of $\tau(R)$.

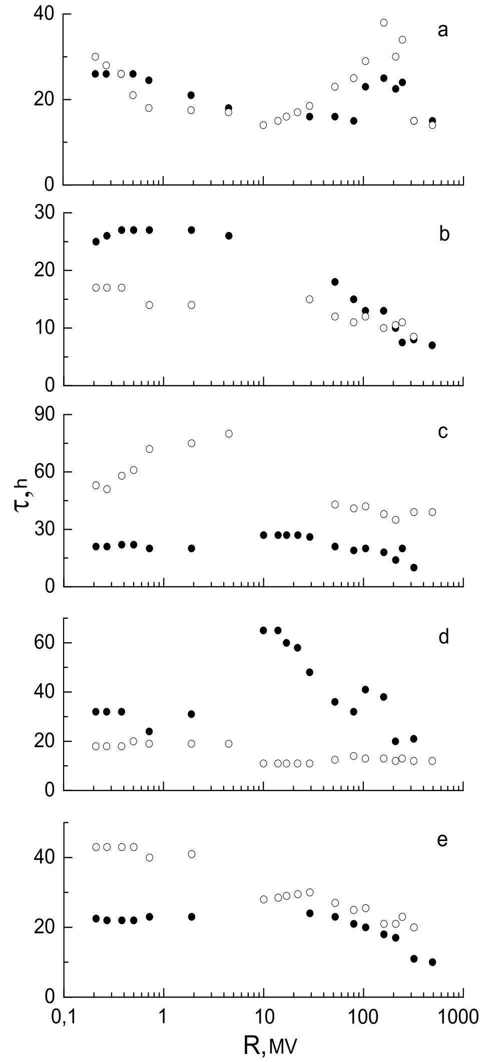


Fig. 2: Patterns of differently shaped $\tau(R)$ dependences during the decays: a) 2001 (DOY 269) open circles, 2006 (DOY 342) filled circles; b) 2001 (DOY 106) open circles, 2001 (DOY 223) filled circles; c) 2005 (DOY 262) open circles, 1999 (DOY 126) filled circles; d) 2005 (DOY 135) open circles, 2005 (DOY 238) filled circles; e) 2005 (DOY 158) open circles, 2005 (DOY 199) filled circles

## III. Discussion and conclusions

Lets discuss first $\tau$ independent of R. Since diffusive propagation of charged particles in the interplanetary space occurs due to scattering on the interplanetary magnetic field inhomogeneities and is determined by their spectrum and particle rigidity, it might turn out that the propagation of electrons and protons with the energies under consideration in the interplanetary space significantly differ (average rigidities in the case of IMP-8 were 1 and 130 MV, respectively). However, similar electron and proton decay phases in a half of events indicate that the spectrum of interplanetary magnetic field inhomogeneities in the range of frequencies responsible for propagation of electrons and protons of energies under study often has the same slope, which, apparently, provides generality of their propagation mechanisms. As in diffusive approximation $\tau$ is inversely proportional to the particle mean free path, $\lambda$ ($D = \lambda v/3$, v is a particle velocity), the $\tau(R)$ variation is related to the old problem of the $\lambda(R)$ dependence. Therefore independence of $\tau$ (and thus,$\lambda$ ) of rigidity suggests the generality of propagation conditions and mechanisms in the whole interval of R. Decreasing $\tau(R)$ qualitatively can be understood in terms of the quasi-linear theory, predicting increase of $\lambda(R)$ (and in turn, a decrease of $\tau$ with R). The events in which $\tau(R)$ have maximum are of particular interest. Under inversion of this dependence into $\lambda(R)$ the latter must have a broad minimum that was discussed in detail in [7]. Similar dependence for the first time was demonstrated in [8] for 1 -1000 eV protons (R 43 -1000 MV) in three events in energetic representation. In [7] it was supposed that contrary to the standard quasi-linear theory predicting an increase of $\tau$ with R, the shape of the rigidity dependence does not vary much between individual events, even if the absolute values of $\lambda$ vary by two orders of magnitude. It is approximately flat between 1 to 10 MV, and increasing moderately toward lower and higher rigidities. It was shown in [9] that dynamical quasi-linear theory together with the specific assumptions on the magnetic field fluctuations gives a good agreement between the predicted and observed absolute values and the rigidity dependence of mean free paths for solar particles from keV electrons to relativistic protons, though understanding this shape is still problematic. The same concerns the events with $\tau(R)$ having minimum ($\lambda(R)$ having maximum). We see however that the variety of the shapes of $\tau(R)$ dependences exists, and as all conclusions about $\lambda$ are based upon approximation of particle time profiles (including the decays phase) this concerns the shapes of $\lambda(R)$ as well. It must be noted that one can speak only about qualitative correspondence of $\tau(R)$ and $\lambda(R)$ because diffusion is not the only mechanism of particle propagation, moreover, as was shown earlier [10,11], often processes of convection and adiabatic deceleration dominate during the decay phase.

Its prematurely to speak about any statistical significance. However we definitely can conclude, that there is no uniform $\tau(R)$ (and thus $\lambda(R)$) dependence either in individual events in the wide range of rigidities 0.2 -450 MV or statistically in the narrower rigidity interval 1 - 130 MV according to $\tau_e - \tau_p$ plot. It can be noted that in the latter case corresponding values of $\tau_e$ and $\tau_p$ in principle could belong to different branches of bended dependence. This could be an explanation of exotic events with $\tau$ increasing with energy obtained in [4]. We consider this study not as the definitive answer but rather as renovation of the interest to the old problems of particle propagation on the new basis of consideration of characteristic decay times.

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