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Rate of proton intensity decay in solar cosmic ray events as a generalized characteristic of the interplanetary space

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[1] The transport of solar energetic particles in interplanetary space is determined by the structure and dynamics of the solar wind between the source and the observer. The intensity time profile, in particular the decay phase, is determined by the transport processes. In this paper we discuss the decay phases of solar energetic proton events in the energy range 1–48 MeV for the period 1974–2001. For events with exponential shape of decay, the dependence of the characteristic time τ on the exponent of the energetic spectrum γ, the solar wind velocity V, and the proton energy E assumed in a form $\tau(E) = CE^{-n}$ is given. Such presentation allows us to consider the action of three main mechanisms of propagation (diffusion, convection, and adiabatic cooling) that determine the τ value. It is shown that approximately half of decays with the constant value of V is described quite satisfactorily within the frame of the model with predominant convection and adiabatic deceleration in comparison with particle diffusion. The dependence of n on heliolongitude of the parent flare (the source of particles) is investigated. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2114 Interplanetary Physics: Energetic particles; 2194 Interplanetary Physics: Instruments and techniques; *KEYWORDS:* solar cosmic ray; proton intensity decline; interplanetary space.

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1. Introduction

[2] The time profile of particle fluxes in the solar events has a typical shape with the more or less quick rise, the maximum, and much slower decay towards the level before the flare. The phase of decay contains important information on the physical processes to which particles are subjected in the interplanetary space. Different mechanisms of particle propagation lead to different laws describing the decrease of fluxes at the late stage of the event. Sometimes this picture can be presented in the diffusion approximation. Then, within the elementary diffusion model under the assumption of a pulsed source of particles and the boundary condition $J(r) = 0$ at $r = \infty$ (J is the flux of particles and r is the distance from the source), the time profile of fluxes at the decay phase of the event has a power law shape and it is proportional to $t^{-3/2}$, where t is the time from the moment of the injection of particles. In diffusion models with the absorbing boundary situated at a finite distance from the source, the decline of the intensity can be described by the exponential function with the standard value of the characteristic decay time which does not depend on the parameters of the surrounding plasma and the spectrum of particles.

[3] However, in the interplanetary space, the solar wind providing the convective transport of particles and their adiabatic cooling is usually present. If such processes prevail in comparison with the diffusion, the fluxes decrease exponentially. Power law intensity decrease can frequently be observed for high energies (> 50 MeV), while for smaller energies $\sim$ 10 MeV, convective transport and adiabatic cooling begin to play substantially greater role and the decline of particle fluxes becomes exponential [*Lee*, 2000]. Thus, the very shape of the decay contains certain information about the processes of particle propagation in the interplanetary space. Moreover, the dependence of the decay rate on different parameters clarifies the role of three main mechanisms (diffusion, convection, and adiabatic cooling) during the propagation from the source to the point of observation. We discuss interrelation of the above mechanisms in section 4. Our task is not the description of particular solar energetic particle (SEP) events but the elucidation of statistical regularities that characterize this phase of the event.

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[4] It was shown in our previous papers that in about 90% of events the fluxes of protons with low energies (< 10 MeV) have an exponential decay while for particles with high energies ($> 30 - 60$ MeV) exponential decay is detected much more seldom. We discussed in detail the mean values of τ, as well as the peculiarities of the characteristic decay time as a function of the size of the event (distributions of τ for protons with energies $E > 4$ MeV are practically the same for events with $J_{\max} > 100$ (cm^2 s sr)$^{-1}$ and with $J_{\max} > 2 - 3$ (cm^2 s sr)$^{-1}$ [*Daibog et al.*, 2003a]), parameters of the surrounding plasma (the solar wind velocity and the magnetic field intensity [*Daibog et al.*, 2005a, 2005b]), the angular distance between the source and the point of observations, etc., and also variations of τ during the solar activity cycle [*Daibog et al.*, 2003b; *Kecskeméty et al.*, 2003].

[5] One can assume that if the decay of particle fluxes in the solar event does not change its character for a long time (of the order of a day or more), then the nearest interplanetary space (IS) is homogeneous and quasi-stationary. This guarantees the constancy of τ in the case of the exponential decline. The statement that the IS is quasi-stationary assumes the invariance of the whole complex of its properties. They are the following: (1) gradient of the particle density in the vicinity of the observation point and the velocity (determined by the diffusion coefficient of particles and their convective outflow) with which particles leave the given region of space, (2) adiabatic cooling of particles in the process of propagation, and (3) possible acceleration of particles in the vicinity of the point of observation. The relative contribution of each of these processes into the formation of a time profile varies in different events. That is why we have to discuss the whole complex of processes what results in the exponential decrease of particle fluxes during an extended period (sometimes up to several days). One can describe this decrease rather strictly by the exponential law with a constant characteristic time τ. The numerical value of τ is the generalized characteristic of the action of space on the time profile of particle fluxes. The investigation of the role of each component of such action is one of the tasks of the interplanetary space exploration. In this paper we investigate the dependences of the characteristic time of proton fluxes decay τ in the events with the exponential decrease as functions of the solar wind velocity, the index of the energetic spectrum, and also the energy of particles. These dependences make it possible to observe the action of the main mechanisms that determine to a considerable extent the value of τ.

[6] It follows from the most general considerations that if the convective transport of particles by the solar wind takes place, τ should decrease with a growth of the solar wind speed V. If the adiabatic cooling of particles takes place, the rate of decline should increase due to the falling particle spectrum $J(E) \sim E^{-\gamma}$ and τ diminishes with a growth of the spectral index γ. With the increase of the distance r from the source, τ grows because it requires more time for particles localized in a larger volume to outflow from this volume.

[7] *Forman* [1970] and *Jokipii* [1972] showed that if the convective transport and adiabatic cooling dominate over the diffusion during the decay stage, the temporal profile of particle fluxes is described by the dependence $J(t) \sim \exp(-t/\tau)$. They obtained analytically an expression for the characteristic decay time τ taking into account the dependences on all three parameters r, V, and γ:

$$\tau = \frac{3r}{2V(2 + \alpha\gamma)} \qquad (1)$$

where $\alpha \approx 2$ for nonrelativistic particles. As far as we consider in this paper measurements conducted on IMP 8, we shall not touch the τ dependence on the distance from the source, assuming the Sun to be always such a source. It should be mentioned that *Kecskeméty et al.* [2005] showed that on the basis of the currently existing simultaneous measurements in high energy channels on board Ulysses (3–5 AU) and IMP 8 (in these measurements 49 events of the solar cosmic rays (SCR) on Ulysses were identified reliably with the events at 1 AU) the rate of proton fluxes decline both at low (4–5 MeV) and high (> 30 MeV) energies at 1 AU is always higher than at 3–5 AU. However, for several events the time profiles for protons with energies > 30 MeV on IMP 8 and on Ulysses coincided [*McKibben et al.*, 2001, 2003]. For the explanation of this phenomenon, these authors used the proposed earlier model of "the homogeneous reservoir of particles" [*McKibben*, 1972; *Roelof et al.*, 1992]. This, however, does not change the general picture.

2. Experimental Data

[8] The characteristic time of proton fluxes decay τ in the events with the exponential decreases was analyzed on the basis of the measurements by the instrument Charged Particle Measurement Experiment (CPME) on the IMP 8 spacecraft during the period from 1974 to 2001. We have used the data for the whole period despite the fact that part of time IMP 8 was within the magnetosphere of the Earth. It looks quite permissible because protons with the energies > 1 MeV within the magnetosphere on magnetic shells with $L > 10$ repeat exactly the fluxes of the similar protons outside of the Earth's magnetosphere, and the orbit of the IMP 8 spacecraft never approached the Earth closer than 20 Earth's radii [*Paularena and King*, 1999]. At such distances the Earth's magnetosphere is not an obstacle even for particles with lower energies.

[9] The channels of registration for protons with the energies 2–4.6, 4.6–15, 15–25, and 25–48 MeV were used. Within the whole period 1974–2001, we detected 642 exponential declines. For each of them the characteristic times of decrease τ for the energies of protons with sufficiently large fluxes were determined. The background is estimated for each channel (this is usually a general instrumental background, determined from the shape at the end of the decay, when observed) and subtracted from the fluxes. The greater part of the decays was related to the events with small particle fluxes. The τ values for them were obtained only for low-energy channels. The amount of events with large particle fluxes that allowed us to investigate high-energy channels (15–48 MeV) comprised 147 events. This gave an opportu-

nity to perform a statistical analysis of different energetic dependences.

3. The τ Dependences on the Solar Wind Velocity and the Spectrum of Particles

[10] An ideal verification of the correctness of formula (1) would be the invariance of the value of the right hand part of (1) with current values of r, V, and γ during the whole decay. But the construction of the "time profile" described by (1) cannot be realized in practice. Thus, to investigate the correspondence of formula (1) to the observed tendencies in the behavior of τ as a function of V and γ, we have chosen from the total amount of decays only those events for which the solar wind speed V was constant (within 5%) and which allowed to determine the index γ of the energy spectrum (the value of γ was determined at the beginning of the exponential decay). We found 52 such decays. The relation between the measured value of τ, $\tau_{\rm exp}$, and the value of $\tau_{\rm theor}$, calculated from formula (1) is presented in Figure 1. Despite the significant scatter of points, one can see that approximately one half of the events is described by this formula quite satisfactorily (26 declines with accuracy $< 25\%$ and 17 declines with accuracy 25–50%). It is worth noting, that the overwhelming majority (9 out of 13) events with $\tau_{\rm exp} > \tau_{\rm theor}$ beyond the limits of the accuracy of 25%, correspond to values of the solar wind velocity > 400 km s^{-1}. On the contrary, the majority (10 out of 13) events with $\tau_{\rm exp} < \tau_{\rm theor}$ correspond to < 400 km s^{-1}. This effect can be partly related to the changes of γ during the decline. According to (1), if the spectrum during the decay becomes harder (γ diminishes) τ should increase and vice versa. However, the periods of decays with $V = \text{const}$ were not sufficiently long (between 12 and 50 hours) that changes in the spectrum exponent could play a significant role in the changes of τ.

[11] On the other hand, it can mean that approximately one half of the solar events does not satisfy simultaneously all the accepted criteria: events have a more complicated character (the outcome of particles is not pulsed, acceleration takes place not on the Sun but at the lower values of r, particle fluxes are not large enough, the background fluxes cannot be estimated accurately, etc.).

4. Dependence of τ on the Energy of Protons

[12] The time of the first arrival of particles after the flare to the point of observation and the time of the flux growth up to its maximal value in the overwhelming majority of events decreases with an increase of the particle energy. The energy dependence of the rate of decays in solar energetic particle (SEP) events is not so definite. Besides the events in which τ decreases with an energy growth, the cases with inverse dependence of τ on the energy, as well as the cases in which there is no dependence of τ on the energy are detected.

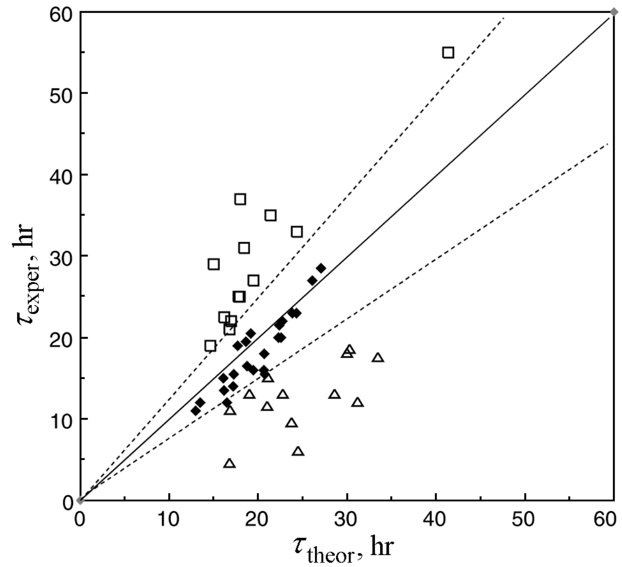

Figure 1. Relation between $\tau_{\rm exp}$ and $\tau_{\rm theor}$, calculated using formula (1). Solid line indicates $\tau_{\rm exp} = \tau_{\rm theor}$, dotted line indicates the $\pm 25\%$ deviation from $\tau_{\rm exp} = \tau_{\rm theor}$. Diamonds, squares, and triangles correspond to declines with the deviation of $\tau_{\rm exp}$ from $\tau_{\rm theor}$ less than 25%, $\tau_{\rm exp} > 1.25\tau_{\rm theor}$, and $\tau_{\rm exp} < 0.75\tau_{\rm theor}$, respectively.

Figure 2 shows the examples of different behavior of decays as a function of energy: the decay rate does not depend on energy (Figure 2a), it decreases with energy (Figure 2b), and the decay rate increases with energy (Figure 2c).

[13] For the investigation of this dependence, from the total amount of events with the exponential decay available to the authors (obtained by the instrument CPME on board IMP 8 for the period from 1974 to 2001), those events were selected for which it was possible to determine the characteristic decay time τ for protons with energies at least 15–25 MeV. In the channels < 2 MeV, as a rule, particles accelerated near the observation point are present. In our analysis, these channels were excluded from the consideration. As it has been mentioned above, the total amount of 147 events was selected, where τ could be determined at least in 4 energy intervals. The value of n was determined for them from the functional form $\tau(E) = CE^{-n}$, where E is the kinetic energy of protons and the values of exponent n were obtained from least squares fits. The usual statistical error of n was about 0.05. Figure 3 shows the distribution of values of n for all 147 events. One can consider this distribution as consisting of three different groups: (1) no τ dependence on proton energy ($-0.1 < n < 0.1$; 54 events), (2) a decrease of τ with energy ($n > 0.1$; 72 events), and (3) an increase of τ with energy ($n < -0.1$; 21 events). In the first case, the proton spectrum does not change with time during decay; in the second case the spectrum becomes softer; and in the third case it becomes harder. Thus, one can see that in the prevailing number of cases, τ either does not depend on the particle energy or decreases with an energy growth.

[14] It is worth noting that to our knowledge the energy de-

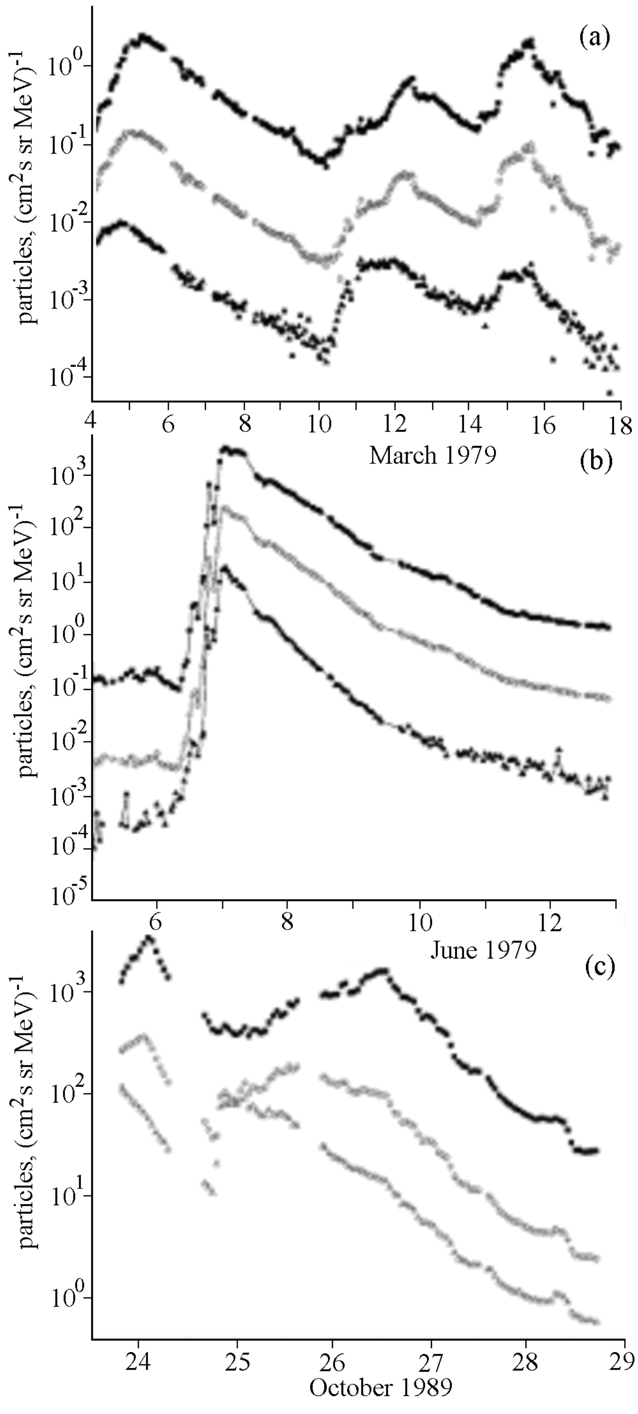

Figure 2. Examples of different behavior of declines as a function of particle energy according to the data obtained by IMP 8. Top, middle, and bottom curves correspond to protons with the energy 4.6–15 MeV, 15–25 MeV, and 25–48 MeV, respectively: (a) τ does not depend on energy (March 1979), (b) τ decreases with energy (6 June 1979), and (c) τ increases with energy (25 October 1989).

pendence of the characteristic decay time τ has not been analyzed quantitatively before. Actually, the existence of decays with τ independent of particle energy was mentioned before [*Daibog et al.*, 2000; *Reames et al.*, 1997] in the so-called invariant events when in connection with the passage of the shock wave initiated by the coronal mass ejection (CME), the state of the interplanetary space provided equal rates of proton flux declines with different energies in different points of space situated far from each other. Unfortunately, this analysis was performed only for several selected events most of which, probably, were related to the trapping of accelerated particles between the front of a shock wave (associated with CME) and strong magnetic fields on the Sun. Strictly speaking, in this case the decay phase probably should be described (as it is the case in the diffusion model) by a power law but not by the exponential dependence [*Reames et al.*, 1996].

[15] For the diffusion events, the rate of flux declines depends significantly on the energy: the higher the particle energy, the faster is the flux decline. It is quite natural because the density of particles after the maximum in the elementary diffusion approximation is proportional to $(Dt)^{-3/2}$, and the diffusion coefficient $D = \lambda v/3$ grows with energy (here λ is the mean free path related to the scattering at irregularities of the magnetic field, which is assumed to increase with energy, and v is the velocity of particles). Formally, the exponential decay with τ depending on the energy can be obtained in the diffusion models with absorbing boundary located at a finite distance R_{abs} [*Forman*, 1971, and references therein]. In this case, after the propagation of the crest of the diffusion wave up to the distance R_{abs}, the solu-

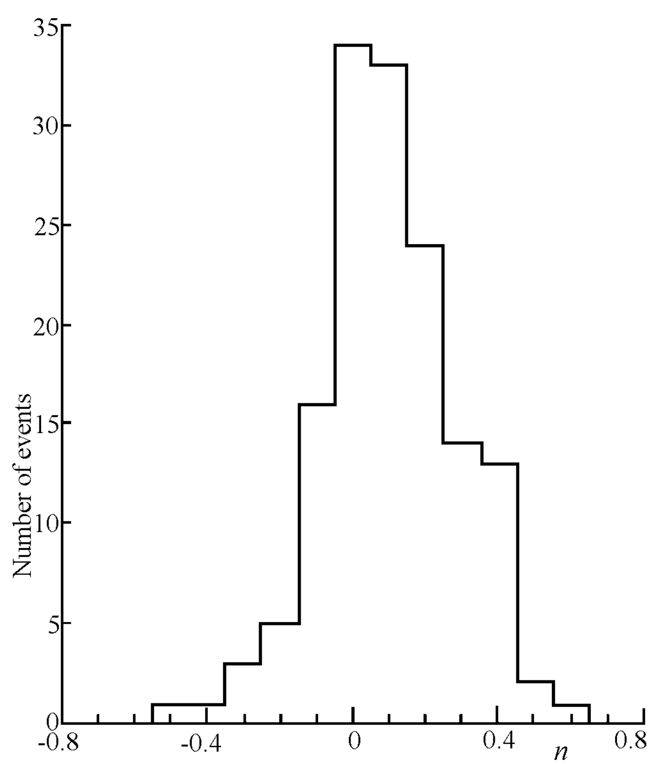

Figure 3. Distribution of values of n for 147 discussed events in the presentation $\tau = CE^{-n}$, where E is the kinetic energy of protons.

tion becomes exponential with $\tau = R_{\rm abs}^2/\pi^2 D$ [*Dorman and Miroshnichenko*, 1968]. The solution decreases with energy growth, but for $D(r) = \text{const}$ it is independent of the parameters entering (1). However, τ depends statistically on all three parameters. So, the exponential form of the decay probably testifies that the main role belongs not to the diffusion but to the convective transport of particles and their adiabatic cooling, and in the case of exponential decays we could always expect τ to be independent of the particle energy. Therefore, the obtained result shows that probably in the case of exponential decays, in many events the influence of the diffusion becomes apparent only at the early stage of the propagation near the Sun.

[16] It is worth noting that generally speaking, the problem of the relation between the diffusion, convective, and adiabatic terms in the equation of particle transport is marked by some paradox. The exponential solution of the equation of particles transport was obtained by *Forman* [1970] and *Jokipii* [1972] assuming that one may neglect the diffusion of particles. However, it should be mentioned that convective transport and adiabatic cooling, in principle, are impossible without diffusion. Indeed, in the absence of scattering, particles cannot be captured by the solar wind. What does it mean that one may neglect the diffusion in comparison with other processes? Diffusion propagation is completely absent in two cases: (1) the diffusion coefficient $D \to \infty$ (this is a free expansion, but if there is no scattering, neither convection nor adiabatic cooling can exist) and (2) the diffusion coefficient $D \to 0$. This means that in the absence of the solar wind, particles will remain in the place of their injection and their propagation in IS would not occur. The radial expansion of the solar wind provides in this case the convection and adiabatic cooling. *Lee* [2000] discussed the case of adiabatic cooling without convection and obtained a solution partly different from (1):

$$\tau = \frac{3r}{2V\Gamma} \quad (2)$$

where Γ is the differential momentum spectral index. In principle, such a suggestion is non-contradictory if particles are contained in some expanding volume under absence of solar wind. In the presence of the solar wind, adiabatic cooling cannot exist without convection. Indeed, both these phenomena are consequences of the same process: the capture of particles by expanding solar wind (however, if the solar wind was present in the tube with a constant cross section, one-dimensional case, contrary to *Lee* [2000], the convection would exist without adiabatic cooling). Therefore, even with the dominating convection and adiabatic cooling, the diffusion always plays a certain role in particle propagation through the interplanetary space.

[17] Especially unexpected is the presence of the group of events with negative n, what cannot be explained by any of the three considered mechanisms of propagation. In this group, the growth of τ with the particle energy is observed almost for all values of τ: $5 < \tau < 30$ h. This means that the negative values of n are not a consequence of uncertainties related to the measurements (e.g., enhanced values of the background fluxes). We tried to find an explanation for these unusual decays as the influence of some additional particle source analyzing what effects shocks and shock particles might have on values of n. From 21 decays of this group, 10 were shock associated. Only 4 definitely looks as shock-influenced, 3 are doubtful. For 11 decays without shocks $\langle n \rangle = -0.17$, for 10 shock related decays $\langle n \rangle = -0.20$. If extreme $n = -0.48$ is excluded, for other 9 decays $\langle n \rangle = -0.17$. Thus, both subgroups have nearly the same values of n and shocks could not be an explanation of existence of negative values of n and in spite of our earlier result that the presence of a shock statistically makes τ smaller [*Daibog et al.* 2003b], this small group of decays (21) does not demonstrate this feature. This result shows that there exist events with exponential declines, in which either additional mechanisms act that have not been taken into account by formula (1) or that such decays are formed by the joint action of parameters of IS with the corresponding dependence on the energy.

[18] Out of 147 events for which the value of n was determined, we managed to connect 104 events with flares, i.e. with the sources of particles on the Sun. For the protons with energies > 4 MeV, *Daibog et al.* [2006] considered in detail the dependence of τ on heliolongitude of the flare. They showed that statistically τ does not depend on heliolongitude of the observer for events associated with flares occurring eastward from the optimum heliolongitude. At the same time, in the case of flares occurring westward, there exists a tendency of the decrease of τ with a growth of the angular distance between the flare and the point of observation. This manifests the influence of the solar rotation. The data available allow us to investigate the problem how τ depends on the heliolongitude of a flare for particles with different energies and consequently, the dependence of the exponent n that enters the law $\tau(E) = CE^{-n}$, on the heliolongitude of a flare (a source of the particles). Figure 4 shows such dependence of n based on 104 events. One can see in Figure 4 that statistically there is no dependence of n on the heliolongitude of a flare. Concerning solar event intensities, this result shows that the transverse propagation of particles (coronal or interplanetary) can only slightly influence the energetic characteristics of the decline rate.

5. Conclusion

[19] The decay phase of particle fluxes carries significant information on the interplanetary medium. The total amount of solar events detected by the instrument CPME on board IMP 8 during almost three solar cycles allows us to consider the dependence of the characteristic decay time on different factors. The performed analysis has shown the following:

[20] 1. In a significant amount of cases (up to 50%) when V remains constant during the whole decay, τ is described satisfactorily by the formula obtained under assumption, that convective transport and adiabatic cooling prevail over diffusion.

[21] 2. The distribution of the exponent n in the dependence $\tau(E) = CE^{-n}$ makes it possible to split all solar events in energetic particles into three groups: (1) τ does not depend on the proton energy ($-0.1 < n < 0.1$; 54 events);

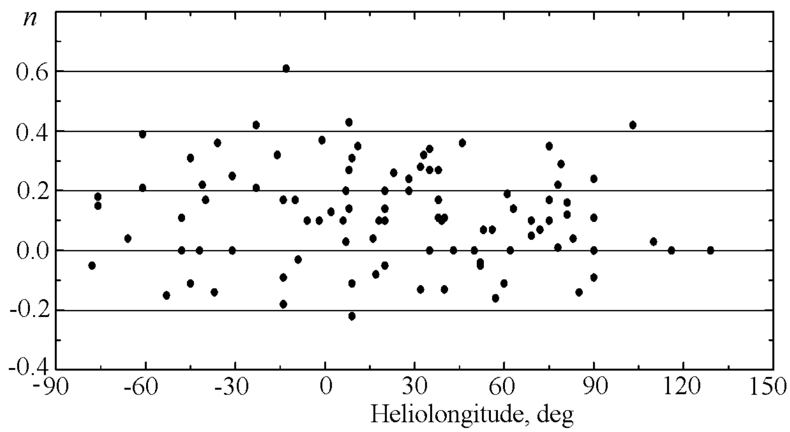

Figure 4. Dependence of n on flare heliolongitude.

(2) τ diminishes with the proton energy ($n > 0.1$; 72 events); and (3) relatively small group of events with τ increasing with the growth of proton energy ($n < -0.1$; 21 events). In the first case the proton spectrum does not change in time during the event, in the second case the spectrum becomes softer, and in the third case it becomes harder. Thus, in the prevailing amount of cases, the decay rate τ either does not depend on particle energy or decreases with an energy growth. This result manifests the action of the diffusion mechanism of propagation along with convection and adiabatic cooling. The existence of events with spectrum becoming harder during the decay phase should become the object of further investigation.

[22] 3. The exponent n in the formula $\tau(E) = CE^{-n}$ statistically does not depend on the heliolongitude of a flare, i.e., the source of particles on the Sun. *Daibog et al.* [2006] have obtained earlier the result confirming that the characteristic time of proton flux decay τ (for events associated with flares occurring eastward with respect to the foot point of the observer's magnetic field line) is statistically independent of the heliolongitude of the parent flare. This testifies that statistically the conditions of particle propagation up to 1 AU do not depend on heliolongitude of a flare with respect to the point of observation. Hence, there exist periods when the total amount of values of IS parameters in the inner heliosphere makes IS homogeneous and quasi-stationary over significant angular intervals.

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