STATISTICAL PROPERTIES OF SEP EVENT FLUX DECLINES

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ABSTRACT

The interplanetary space is not a passive medium, which merely constitutes a scene for the propagation of previously accelerated energetic particles, but influences the distribution of particles by changing their energies as well due to interactions with magnetic field inhomogeneities. Such processes manifest themselves in the energy spectra of solar energetic particle (SEP) events. In this paper the fluxes of protons with energies of 4-60 MeV are investigated on the basis of two data sets. Both sets are homogeneous, obtained by the CPME instrument aboard the IMP 8 satellite between 1974 and 2001. The first includes all SEP events where the integral fluxes of >4 MeV protons exceeded 2 particle/cm^2 s sr. The other set consists of fluxes recorded in differential energy windows between 0.5 and 48 MeV. Important characteristics of SEP events include the rates of decrease of particle flux, which, as well as peak flux time, is an integral feature of the interplanetary medium within a considerable region, surrounding the observation point. The time intervals selected cover the decay phases of SEP events following flares, CMEs and interplanetary shocks of different origin. Only those parts of declines were selected, that could reasonably be described by exponential dependence, irrespective of the gradual/impulsive character of the events. It is shown that the average values of characteristic decay time, τ, and energy spectral index, γ, are all changing with the solar activity phase. Distributions of τ and γ values are obtained in SEPs with and without shocks and during different phases of events: just after peak flux and late after maximum.

INTRODUCTION

Many papers have been devoted to the propagation of particles accelerated in solar flares as well as at flare and coronal mass ejection (CME) associated shocks in the interplanetary medium (IM). By considering different propagation modes, particle composition, and energy spectra, different propagation models were constructed. Many works have been concerned with the rising parts of events and especially with the peak fluxes. As a rule, less attention was paid to the declining phase of SEP events, although they also carry very important information about the global character of the magnetic field during that time. Different propagation models predict different time dependencies of flux declines during the late phase of solar energetic particle (SEP) events. A simple diffusion model yields a power law for the differential flux: $J(t) \propto t^{-3/2}$ (Chandrasekhar, 1943), whereas taking convection by the solar wind and particle deceleration into account results in exponential function: $J(t) \propto e^{-t/\tau}$ (Owens, 1979). Starting from the full transport equation and neglecting terms other than adiabatic deceleration Lee (2000) obtained that if $J(t=0) \propto p^{-\Gamma}$ (p is the particle momentum)

$$J(t) \propto p^{-\Gamma} \exp(-2V\Gamma t/3r), \qquad (1)$$

where V is the solar wind speed, r is helioscentric distance. This is valid for the late part of gradual events where anisotropy is small. Earlier, Forman (1970) and Jokipii (1972) gave a similar expression with $\Gamma = 2 + \alpha\,\gamma$ ($\alpha \approx 2$ at nonrelativistic energies), where γ is the differential exponent of the energy spectrum. This result is in accordance with many experimental findings (see e.g. Forman, 1971; Murray et al., 1971, McCracken et al. 1971). A model including focused transport and adiabatic deceleration yields a similar time profile (Ruffolo, 1995).

Power-law temporal variation is usually observed at high energies (>100 MeV), whereas for low energy (<10 MeV) particles convection is of greater importance and the decline becomes exponential. However, rather often, particle propagation is accompanied by different processes of additional acceleration, which inevitably results in the distortion of smooth time profiles impeding its description by definite simple function. A major disturbing factor, and sometimes the only accelerating agent, is the interplanetary shock wave accompanying CMEs (Kahler, 1986), which can result in the quasi-trapping of particles. Such regions of quasi-trapping can be connected to the shock front and also exist between the shock front and strong magnetic fields near the Sun. A recent paper by Dalla et al. (2002), analyzing gradual events at 1 and 5 AU, discussed four models for the decay phase, i.e. continuous shock acceleration, magnetic reservoir, interplanetary diffusion, and extended leakage at the Sun, but found problems with each interpretation.

INVESTIGATION METHOD

We performed a statistical analysis of the rates of decrease in SEP events on the basis of two homogeneous data sets obtained by the CPME instrument aboard the IMP 8 satellite between 1974 and 2001. The first includes all SEP events where the integral fluxes of >4 MeV protons exceeded 2 particle/cm^2 s sr. Time intervals were selected during the decay phase of SEP events following flares, CMEs and interplanetary shocks of different origin. Only those parts of declines were selected, which could reasonably be described by exponential dependence. The reason behind this selection is that exponential declines of medium energy protons are observed relatively frequently, and are theoretically explained by convective and adiabatic cooling effects or by acceleration at interplanetary shocks. This choice allows to include smaller, more frequent SEPs observed up to ~50-100 MeV (protons), thus extending the statistics of analyzed events considerably. Out of 528 exponential intervals examined 131 were shock-associated, 259 without shocks and 138 unclear (no plasma and field data). For the second data set of differential energy fluxes the limit was even lower, but we required that the decay profile be reasonably straight on the logarithmic scale of the flux for at least 20 hours in at least 2 energy channels, although some short-time departures were accepted. As we focused on the shape of the intensity profile, no preselection has been made according to the gradual/impulsive scheme; however, the majority of events were impulsive. This way for all exponential declines the spectral index, γ and the e-folding time, τ, was obtained in 2 integral (>4 and >10 MeV) and 6 differential energy intervals (between 0.5 and 48 MeV). The analysis of two different data sets performed nearly independently provided a possibility for crosschecking. A smaller set of smooth decay profiles are better approximated by power-law as predicted by pure diffusion. As expected, these are more frequent at the higher energy channels (>15 MeV), but constitute only about 10% of all smooth profiles in the energy range 1-15 MeV. Expression (1) gives τ values reasonably close to the fitted slopes in nearly half of all cases if one uses the average V values measured later when the relevant plasma in which particles were convected arrives to the observer. This might be a surprisingly high number bearing in mind that in rare cases remains V constant for a sufficiently long time.

Exponential declines of particle intensities are registered during various time intervals from event to event. Sometimes they last from the maximum to the background intensity, other times they are seen during a part of an event only, followed by large fluctuations, and then can become exponential again with the same or different decay time, τ. During time intervals when exponential flux declines are observed, the neighboring interplanetary medium (IM) has to be quasi-stable and homogeneous, otherwise it is difficult to explain constancy of τ.

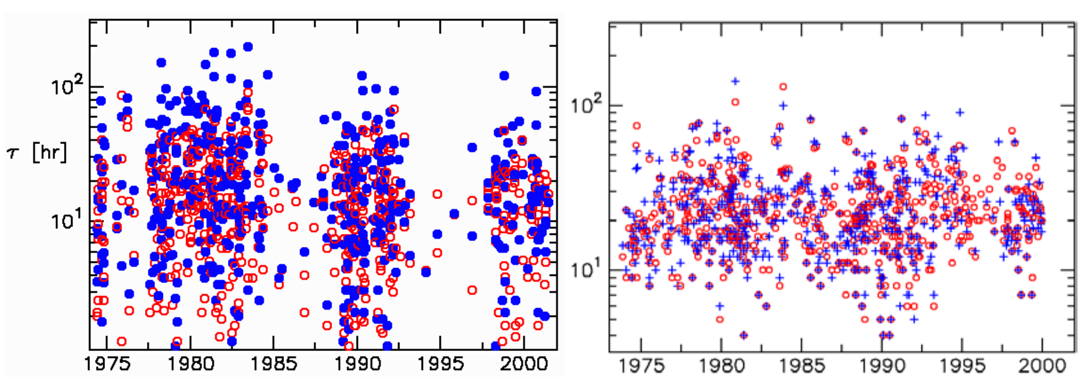

Fig. 1. Temporal variation of τ for integral channels of protons (left panel: open circles: >4 MeV, full circles: >10 MeV) and differential (right panel: circles 1-2 MeV, plusses: 2-4.6 MeV) between 1974 and 2001.

The analysis of temporal characteristics is rendered difficult by spatial variations related to the rotation of the Sun. In effect, a hypothetic observer, located constantly in the same magnetic flux tube, would only detect purely temporal variations. Real measurements, however, take place in magnetic flux tubes changing all the time where magnetic conditions, as a rule, are different. However, relatively frequently, as multispacecraft observations confirm, propagation conditions remain unchanged over wide spatial regions which follows from the coincidence of intensities at far distant points during the most time of event after its maximum (Reames et. al., 1996, Daibog et. al., 2001). The identity of time profiles at far angular distant points means that as particle propagation takes place even in a case of prolonged particle injection from a propagating shock, independently of the propagation model, the conditions in the interplanetary space should be identical in these points as well because it is difficult to think of such a superposition of acceleration and propagation that results in similar intensities in a wide spread region. Sometimes particle events are identified only within a very limited angular range: two s/c only 10° apart can record strongly different intensities, whereas in other cases fluxes are highly stable over very large (>100°) angular distances. This means that in the former case the different s/c were in regions with different magnetic characteristics, and in the latter a wide angular region exhibited homogeneous magnetic field properties.

Here only those intervals of decay phase not shorter than 12 hrs were considered (integral channels), i. e. the angular size of magnetic flux tube was at least 6-7 degs. Even shorter periods were included when the intensity decreased by a factor more than 3. In these cases the s/c located in a region with rapidly changing characteristics, which is also of great interest.

RESULTS AND DISCUSSION

Figures 1 and 2 display all values of τ and γ obtained for exponential declines that match the selection criteria between 1974 and 2001**.** Here τ is characteristic decay time of proton flux at energies 4-60 MeV (integral channels) and 0.5-48 MeV (differential channels) during the time of exponential decline; the value of γ is taken at the initial moment of the exponential decline period.

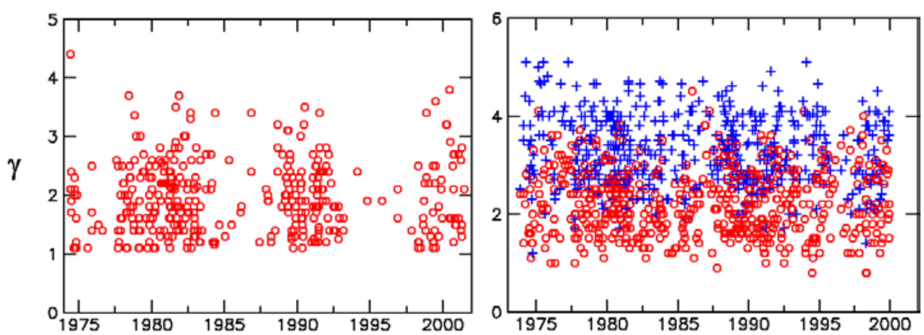

Fig. 2. Temporal variation of γ for integral (left) and differential (right, circles: 1-4.6 MeV, crosses: 4.6-25 MeV) channels.

The variation of τ and γ over three solar cycles indicates little variation with energy, although in individual cases they can differ considerably which means that γ can change during the time of the decay phase. We did not discriminate according to the character of event, whether it was diffusive, associated with shock

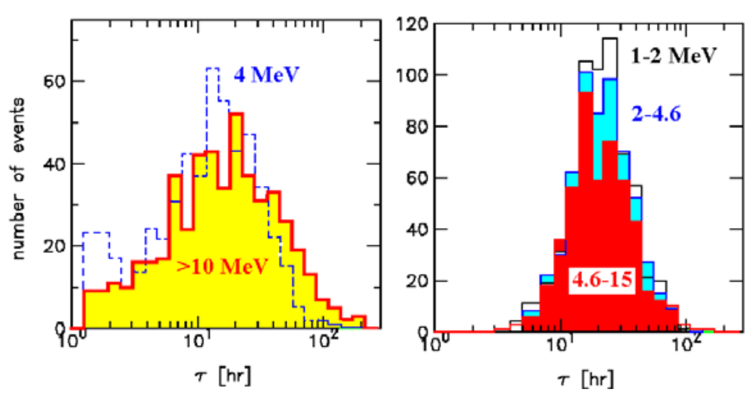

Fig. 3. Distributions of τ values of the integral (left, two energies) and differential fluxes (right, 3 energies).

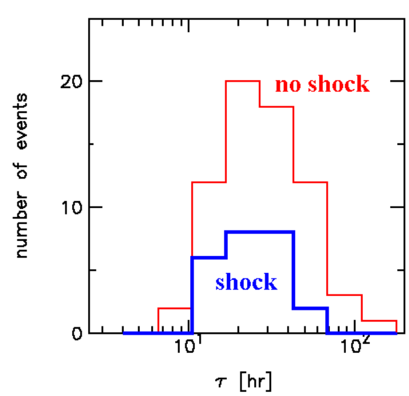

Fig. 4. Distributions of τ for intervals including and without shock.

waves or other phenomena. In Figures 1 and 2 all possible kinds of particle enhancements are represented independently of their nature, and thus, the observed spread of values of τ and γ apparently reflects the totality of phenomena in the IM. Apart from the minima, neither τ nor γ does experience obvious variation with the level of solar activity. Near the minima the width of the distributions seems to drop, presumably reflecting the stationary character of the interplanetary medium, to which it returns after various disturbances. In solar activity minimum there are less many disturbances and the IM can return to its undisturbed state. Near maximum, however, the medium is disturbed practically all the time. The number of declines observed is changing from cycle to cycle; it was by about 20% higher during the 21st cycle than in the 22nd.

Figure 3a (left panel) depicts distributions of τ values for protons >4 and >10 MeV for the whole observation period. These distributions include 476 intervals with exponential flux declines for which both τ and γ could be obtained. This means a lower number of SEP events actually; parts with different decay times were included as separate entries (about 40% percent of the events was described two or more τ values). The average τ is about 15 hours. As was mentioned above, there is no significant variation with energy, the maximum being shifted from 15 to about 22 hours at >10 MeV, but for >10 MeV protons many more cases with τ >100 hr are observed. This can be due to that at higher energies the background is higher (it is difficult to determine accurately as it depends on the ambient particle population, preceding events, etc.) and can imitate somewhat longer τ values. Generally, the evaluation of t is stopped when the profile begins considerably deviating from the overall fitting (straight line). The number of such events, however, does not exceed 20% and not influence the picture significantly. The distributions of τ for 3 differential channels obtained from 642 time intervals (some are parts of the same event) are presented in Figure 3b (right panel). They are also nearly symmetric and peaked around 20 hrs, which give some confidence that the selection criteria did not influence the results artificially. Nevertheless, the profiles are narrower, Gaussian-like, in contrast to the rather "triangular" ones of the integral channels with apparently little contribution below 10 hr and above 80 hr (72 and 71% of all values fall within 11 and 35 hr for the 1-2 and 2-4.6 MeV energy intervals, respectively). The deficiency below 10 hr as compared with the integral distribution is at least partly due to selection criterion as intervals shorter than about 15 hrs were omitted there.

Figure 4 shows the distributions of τ for time intervals accompanied and non-accompanied by shocks. They suggest that the presence of a shock makes the decay faster: the average values of τ are 10.9 vs 16.5 hours. The distributions of γ (not shown) for the whole period are far more compact than distribution of τ. There are no large deviations from the average value of $<\gamma> \approx 1.85$. Shock-accompanied declines exhibit somewhat softer energy spectra as compared to periods without shocks ($<\gamma> \approx 2.0$ vs. 1.8). This suggests that acceleration mechanisms and possible proton trapping connected with the shocks are more effective for low energy particles.

The distributions of τ and γ for the first decay after maximum of SEP-event (for events with J_{peak} (>10 MeV) > 10 p/cm^2 s sr and with J_{peak} < 10 p/cm^2 s sr) when the main decrease of intensity takes place are similar (not presented). This result is not unexpected, because in both cases the density of magnetic field energy ($B^2/8\pi$) is sufficiently higher than the proton energy density, which cannot influence IMF parameters. This means that solar particles can be used as a probe of IMF diagnostics practically for all peak fluxes of non shock-associated SEPs. The distributions of τ and γ for the first 5 years of the rising phase of 21st, 22nd, and 23rd solar activity cycles vary considerably from cycle to cycle; this is in agreement with observations of other solar activity parameters (number of sunspots, radio emission data, etc.).

CORRELATIONS

We obtained correlations of the decay time of particle intensity with the speed of the shock, U, observed at a given SEP-event. The characteristic decay time, τ, as a function of the shock speeds is plotted for two criteria of event selection: 1) first exponential part of declines after the maximum (as a matter of fact, this includes the shock peaks in many cases), 2) parts of declines after the shock peaks, if any. The first criterion concerns with the time just after that the shock passed the observation point; the second one could be attributed to particle trapping, described above. Figures 5a and 5b display the resulting correlations between τ, γ, and U, including shock peaks (circles) and without shock peaks (crosses). No obvious functional dependence between τ and U (Figure 5a) can be seen, however, in spite of the large scatter of points, some limiting dependence apparently exists. This means that very large τ takes place only for small values of U and that high shock speed is associated with small τ. This qualitatively agrees with the dependence obtained by Jokipii (1972) assuming that diffusion is negligible for low energy particles at the decay phase, whereas convection and adiabatic deceleration are of major importance: $\tau = 3r/2V(2+\alpha\gamma)$.

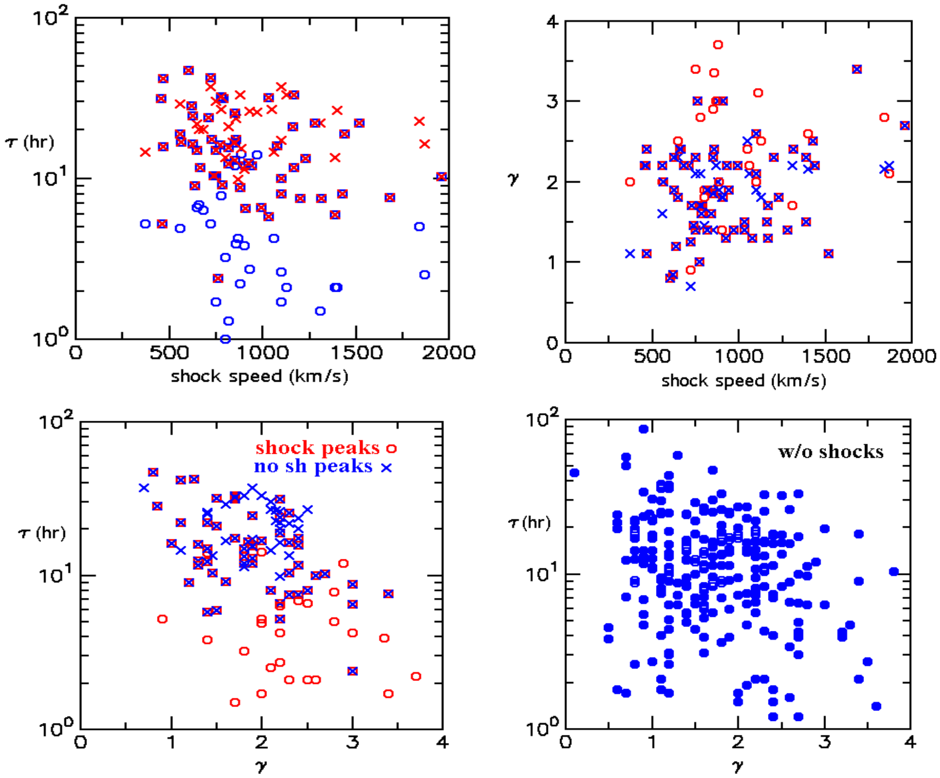

Fig. 5. Correlation of τ and γ with shock speed (upper panels, a, b including – circles and omitting shock peaks – crosses); mutual correlation of τ and γ for integral channels (lower panels, c, d).

The decay times were analysed as a function of spectral indices. They were considered using the same two criteria of event selection. The parts of time profiles with and without shocks were considered separately (Figure 5c – including and without peaks, 5d – no shocks). The tendency of decreasing τ with increasing γ can clearly be observed in shock-associated events. Nevertheless, like in previous plots, a limiting dependence for parts of time profiles without shocks should be noted as well. Qualitatively, Figures 5c and 5d differ at small values of γ and τ.

Recently, the widely accepted point of view is that energetic particles in gradual SEPs are accelerated by CME-driven shocks. In the model developed by Reames et al. (1996) particles are supposed to be quasi-trapped in an expanding flux tube between the strong magnetic field near the Sun and the moving strong magnetic field region downstream of the travelling shock. They suggest that the declines are caused only by the expanding volume and adiabatic deceleration. As mentioned by Ruffolo (1995), deceleration alone leads to a decay time in the expanding wind:

$$\tau = \tau_d / (\gamma - 1),$$

where τ_d can be obtained from $1/\tau_d = 2V/3r$. Thus τ depends on γ and V. Reames et al. (1996) estimated the decay time for assumed power-law radial dependence of the particle distribution. They proceed from the model that describes the evolution of the particle distribution as being governed by transport equation in mixed coordinates (Ruffolo, 1995) taking into account streaming, convection, pitch angle diffusion, adiabatic focusing and adiabatic deceleration.

Successive simplifying suggestions (e.g. ignoring fresh particle injection from the receding shock; scatter-free motion in the whole volume except for the shell mentioned above; negligible cross field diffusion; isotropic particle distribution with negligible gradient along the flux tube; power-law energy spectrum with constant power index) permit to approximate the decay of differential particle intensity as $\tau = t/(2\gamma + 2)$, where t is the time. A similar result may be obtained by formulating the simplest task of particle motion in an expanding one-dimensional volume and assuming that all particles moving parallel and reflecting from the ends go away. Following Reames et al. (1996), we suppose that particles at any moment are uniformly distributed within the volume and their momentum spectrum can be expressed as $p^{-2\gamma}$, p is momentum. Then the continuity equation leads to $\tau = t/(2\gamma - 2)$.

Thus, we see that the assumptions similar to Reames et al. (1996) lead to τ depending on t. About 90% of observed declines, however, are exponential (this concerns both small and major events, of course, impulsive events represent the majority). In the framework of the models discussed above either convection with adiabatic deceleration in the expanding solar wind is more adequate to the physics of processes during the decay phase of the most of SEPs, or the majority of the events selected do not meet the assumptions of Reames et al. and some ignored moments (for example fresh injection) must be taken into consideration.

Although these three formulae on γ-dependence of τ are different in details, the essential fact is that all the three solutions predict τ decreasing with increasing γ as qualitatively confirmed by Figure 5. In this context we must underline that this situation contradicts neither to the pure diffusive model nor to the model of particle trapping between the shock front and the Sun.

CONCLUSIONS

- In most SEP events, where the time profile following the maximum is smooth and free of additional injection and disturbances, the exponential function gives the best approximation in nearly 90% of the cases for protons with energies above about 1 MeV.
- For the major part ($\approx$70%) of all events the τ values are between 9 and 21 hrs (integral channels, weighted by the length of intervals), and 11 and 35 hrs (differential channels, not weighted) that is, in about 70% of the time IMF is in a “basically disturbed” state.
- Near solar activity minima the scatter of both τ and γ values decrease.
- The characteristic decay times of fluxes as well as the energy spectra, where interplanetary shocks are observed significantly differ from those not accompanied by shocks ($\tau \approx 10.9$ vs 16.5 hrs, $\gamma \approx 2.0$ vs 1.8).
- The correlation between the values of τ and γ are in agreement with theoretical models taking into consideration convection and adiabatic deceleration. However, this does not permit to prefer either the pure diffusive model or the model with particle trapping between the shock front and the Sun. Most probably, an adequate model has to take into account continuous particle acceleration by shocks.

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REFERENCES

Chandrasekhar, S., Stochastic problems in physics and astronomy, *Rev. Mod. Phys*., **15**, 1-89, 1943.

Daibog, E.I., V.G. Stolpovskii, G. Erdős et al., Study of decay phases in gradual and impulsive solar energetic particle events, *Proc. Int. Cosmic Ray Conf*., 2001, 3631-3634, 2001.

Dalla, S. J., A. Balogh, B. Heber, et al.: Observation of decay phases of solar energetic particle events at 1 and 5 AU from the Sun, *J. Geophys. Res*. **107**, 1360, DOI 10.1029/2001JA009155, 2002.

Forman, M.A., The equilibrium anisotropy in the flux of 10 MeV solar flare particles and their convection in the solar wind, *J. Geophys. Res*., **75**, 3147, 1970.

Forman, M.A., Convection-Dominated Transport of Solar Cosmic Rays, *J. Geophys. Res*., **76**, 759, 1971.

Jokipii, J.R., Propagation of solar cosmic rays in the solar wind, in: *Solar Activity Observations and Predictions*, Progress in Astronautics and Aeronautics, v.30., eds. P.S. McIntosh and M. Dryer, MIT Press, 1972., p.247

Kahler, S.W., in: *High energy solar physics*, eds. R.Ramaty, Woodbury, New York, p61, 1986.

Lee, M.A., Acceleration of energetic particles on the Sun, in the heliosphere, and in the galaxy, in *Acceleration and Transport of Energetic Particles Observed in the Heliosphere*, AIP Conf. Proc. 528, pp3-18, 2001.

McCracken, K.G., U.R. Rao, et al., The decay phase of solar flare events, *Solar Phys*. **18**, 100-132, 1971.

Murray, S.S., et al., Interplanetary deceleration of solar cosmic rays, *Phys. Rev. Lett.,* **26**, 663-666, 1971.

Owens, A.J., Interplanetary diffusion of solar cosmic rays - A new approximate analytic solution, *J. Geophys. Res*., **84**, 4451-4456, 1979.

Reames, D.V., L.M. Barbier, C.K. Ng, The spatial distribution of particles accelerated by coronal mass ejection-driven shocks, *Astrophys. J*., **466**, 473-486, 1996.

Ruffolo, D., Effect of adiabatic deceleration on the focused transport of solar cosmic rays, *Astrophys. J*., **442**, 861-874, 1995.

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