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Effect of adiabatic cooling on the fitted parallel mean free path of solar energetic particles

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[1] The focused transport equation without adiabatic energy loss is widely used to model solar energetic particles' (SEP) interplanetary propagation by fitting spacecraft data. We incorporate the adiabatic energy loss effect, provided by the divergence of the solar wind flows, into the focused transport equation. The equation is then solved numerically using a time-backward stochastic integration method. We show the comparison between solutions of focused transport equations with and without energy loss. We found the effect of adiabatic cooling is significant on the time profile of the intensity of SEPs. It is also shown that without energy loss, for gradual events, we can only fit the initial phase of SEP events. However, with energy loss, we can fit the entire (initial and decaying) phases. In addition, the values of the mean free path obtained by fitting the SEP events with energy loss is always smaller than that without. The results suggest that including adiabatic cooling effect is another way to partially fix the solar energetic particle mean free paths' "too small" problem discussed by Bieber et al. (1994), i.e., the mean free paths obtained by fitting transport equation to observation data are much larger than the quasi-linear theory results.

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1. Introduction

[2] *Parker* [1965] first provided a diffusion equation with an isotropic distribution to study the transport of cosmic rays in heliosphere. However, because of the magnetic focusing effect by the heliospheric magnetic field, transport of solar energetic particles (SEPs) has to be described by a focused transport equation if significant pitch angle anisotropies exist (for instance, if scattering mean free path becomes a significant fraction of the focusing length or early anisotropic phases are considered) [*Parker*, 1963; *Roelof*, 1969; *Earl*, 1976; *Ng and Reames*, 1994]. On the other hand, since SEPs also experience adiabatic cooling effect, due to divergent solar wind convection, adiabatic cooling should also be included in the SEP's transport equation. Normally, the formula for adiabatic cooling of particles with isotropic distributions is also used [e.g., *Parker*, 1965; *Dorman*, 1965]. *Skilling* [1971] described adiabatic cooling and focusing effects in a general form with the wave-frame approach. *Ruffolo* [1995], *Isenberg* [1997], and *Qin et al.* [2004] studied the anisotropic adiabatic cooling effects for SEPs in the heliosphere. *Qin et al.* [2004] also calculated, using numerical simulations, charged particles trajectories in a Parker field with turbulence and found that the simulation results agree with the anisotropic adiabatic cooling theory. The simulations also show that the adiabatic cooling effect is significant for SEPs traveling from the Sun to 1 AU.

[3] To solve the transport equation, in general, numerical calculations are used, since it is very difficult to do it analytically [e.g., *Ng and Wong*, 1979; *Schlüter*, 1985; *Ruffolo*, 1991; *Kocharov et al.*, 1998]. Although *Kocharov et al.* [1998] found different intensity profiles for SEP transport with and without adiabatic energy loss, in many transport models which numerically fit SEPs' flux-time profiles, adiabatic cooling effects are ignored and the good fits to data are only shown for short time intervals (<1 day) [e.g., *Bieber et al.*, 1994, and references therein]. In fact, it is frequently observed that in large SEP events, intensities decline nearly in a power-law for several days [e.g., *McKibben*, 1972; *Reames*, 1999].

[4] In order to solve the mean free paths' "too small" problem characterized by *Palmer* [1982], i.e., the mean free paths obtained by fitting transport equation to observation data are much larger than the quasi-linear theory results with slab geometry [*Jokipii*, 1966], *Bieber et al.* [1994] suggested using a composite geometry [*Matthaeus et al.*, 1990] composed of 20% slab component and 80% two-dimensional component. With the assumption that two-dimensional component does not contribute to particle's parallel diffusion, reducing the slab component of turbulence can increase the

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predicted mean free path to make the fitting results agree with quasi-linear theory. However, recent simulation results [*Qin et al.*, 2002; *Shalchi et al.*, 2004; *Qin et al.*, 2006] show that two-dimensional turbulence makes a finite contribution to parallel scattering at finite or large amplitude. On the other hand, the adiabatic cooling effects were totally ignored in getting the fitted mean free paths by varies authors compiled by *Bieber et al.* [1994].

[5] In this article we model a gradual SEP event observed by Ulysses/COSPIN instruments [*Simpson et al.*, 1992] with a focused transport equation including adiabatic cooling effects, which is solved by a method of time-backward Markov stochastic process simulation [*Zhang*, 1999]. We consider anisotropic adiabatic cooling effects theory in SEP transport equation. We compare simulation results with and without adiabatic cooling effects to show that the effect of adiabatic cooling is significant on the transport of SEPs. It is also shown that without energy loss, for gradual events, we can only fit the initial phase of SEP events. However, with energy loss, we can fit the entire (initial and decaying) phases, and the derived mean free paths are always smaller than that without energy loss. Therefore including adiabatic cooling effects is another way to address the SEP mean free paths' "too small" problem discussed by *Bieber et al.* [1994].

2. Transport Equation

[6] In our model the focused transport equation with adiabatic cooling effect in a mixed frame system (**x**, **p**), where **x** is particle's position in solar frame, and **p** is particle's momentum in solar wind frame, can be written as [e.g., *Skilling*, 1971; *Schlickeiser*, 2002; *Qin et al.*, 2004; *Zhang*, 2006],

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \mathbf{V}^{sw} \cdot \nabla f + \frac{dp}{dt}\frac{\partial f}{\partial p} + \frac{d\mu}{dt}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = Q(\mathbf{x}, \mathbf{p}, t), \tag{1}$$

here μ is the pitch angle cosine, v is the particle speed, $\mathbf{V}^{sw}$ is the solar wind velocity, Q is the source term, and z is the coordinate along the magnetic field spiral. The SEP's adiabatic cooling effect term, dp/dt, may be written as [*Skilling*, 1971; *Qin et al.*, 2004]

$$\frac{dp}{dt} = -p\left[\frac{1-\mu^2}{2}\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y}\right) + \mu^2 \frac{\partial V_z^{sw}}{\partial z}\right]. \tag{2}$$

If we assume $dp/dt = 0$, the equation (1) is reduced to the focused transport equation without adiabatic cooling [*Roelof*, 1969]. The time evolution of μ including magnetic focusing effect and the divergence of the solar wind flows effect could be written as [e.g., *Roelof*, 1969; *Isenberg*, 1997; *Kóta and Jokipii*, 1997]

$$\begin{aligned}\frac{d\mu}{dt} &= \frac{1-\mu^2}{2}\left[-\frac{v}{B}\frac{\partial B}{\partial z} + \mu\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right] \\ &= \frac{1-\mu^2}{2}\left[\frac{v}{L} + \mu\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right],\end{aligned} \tag{3}$$

where **B** is the background interplanetary magnetic field with direction **z**, magnetic focusing length L is defined by

$$\frac{1}{L} = -\frac{1}{B}\frac{\partial B}{\partial z}. \tag{4}$$

Note that for energetic particles $v \gg V^{sw}$ the focusing effect is more important than the divergence of the solar wind effect, for the numerical calculations reported in next section we find we can get the same results if we drop the divergence of the solar wind effect (not shown). In this work we ignore the particle's perpendicular diffusion to assume SEP do not transport across the magnetic field.

[7] If particles have an isotropic pitch angle distribution, the parallel mean free path $\lambda_\parallel$ can be written as [*Jokipii*, 1966; *Hasselmann and Wibberenz*, 1968, 1970; *Earl*, 1974]

$$\lambda_\parallel = \frac{3v}{8}\int_{-1}^{+1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}}, \tag{5}$$

and the radial mean free path can be defined as

$$\lambda_r \equiv \lambda_\parallel \cos^2 \psi, \tag{6}$$

where ψ is the angle between the magnetic field, **B**, and $\hat{r}$, the unit normal in the radial direction [e.g., *Bieber et al.*, 1994].

[8] We follow *Beeck and Wibberenz* [1986] [see also *Qin et al.* 2005] to use a model of pitch angle diffusion coefficient

$$D^r_{\mu\mu} \equiv D_{\mu\mu}/\cos^2\psi = D_0 v R^{-1/3}\left\{|\mu|^{q-1} + h\right\}(1-\mu^2), \tag{7}$$

where D_0 is a constant indicating the magnetic field fluctuations level and R is particle's rigidity. The constant h is introduced to simulate the particles' ability to scatter through $\mu = 0$. In this work we choose $h = 0.2$. $q = 5/3$ is related to the power spectrum of magnetic field turbulence $P_{xx}(k_z) \sim k_z^q$ in inertial range. If $h = 0$ the choice of the pitch-angle dependence of $D_{\mu\mu}$ is reduced to the QLT limit [*Jokipii*, 1966]. If $q = 1$ it is reduced to the isotropic scattering model. For gradual SEP events with small anisotrpy as we study in this work, the pitch-angle dependence of $D_{\mu\mu}$ does not contribute to the fitted mean free paths [*Qin et al.*, 2005]. In the numerical calculations reported in the next section we also change $D_{\mu\mu}$ model by varying variables q and h to get the same results (not shown). This form of pitch angle diffusion coefficient assumes particles' radial mean free path is independent of radial distance but has rigidity dependance $\lambda_r \sim R^{1/3}$ [*Bieber et al.*, 1994].

3. Numerical Methods and Results

[9] In order to solve the focused transport equation (1), we use the Markov stochastic process theory [*Zhang*, 1999]. In order to deal with expanded source energy spectrum easily, we use the time-backward Markov stochastic process method. Using this process, we have to trace SEPs back to the initial time and, at that initial time, only those particles

in the source region then contribute to the statistics. However, in simulations most particles are not in the source region when traced back to the initial time and there is a lot of waste in computation power. To overcome this difficulty, we modify the equation as follows.

[10] We define a new function g as

$$g = f/(M + \mu) \tag{8}$$

with constant $M > 1$ to keep g positive. Inserting equation (8) into the focused transport equation with adiabatic energy loss effects equation (1), we have

$$\begin{aligned}\frac{\partial g}{\partial t} = & -\mu v \frac{\partial g}{\partial z} - \mathbf{V}^{sw} \cdot \nabla g - \frac{dp}{dt}\frac{\partial g}{\partial p} + \left(\frac{\partial D_{\mu\mu}}{\partial \mu} + \frac{2D_{\mu\mu}}{M+\mu} - \frac{d\mu}{dt}\right)\frac{\partial g}{\partial \mu} \\ & + D_{\mu\mu}\frac{\partial^2 g}{\partial \mu^2} + \left(\frac{\partial D_{\mu\mu}}{\partial \mu} - \frac{d\mu}{dt}\right)\frac{g}{M+\mu} + \frac{Q}{M+\mu},\end{aligned} \tag{9}$$

where $d\mu/dt$ is described by equation (3), and dp/dt is described by equation (2) with adiabatic cooling effects or $dp/dt = 0$ without adiabatic cooling effects. The solution to equation (9) in terms of time-backward Ito stochastic differential equation may be written as [see *Gardiner*, 1983; *Freidlin*, 1985; *Zhang*, 1999]

$$\begin{aligned}g(x,y,z,p,\mu,t) = \Bigg\langle \int_0^t & \frac{Q(X(s),Y(s),Z(s),P(s),\Phi(s),s)}{M+\Phi(s)} \\ & \times \exp\left[\int_0^s \left(\frac{\partial D_{\mu\mu}(P(\tau),\Phi(\tau))}{\partial \Phi} - \frac{1-\Phi^2(\tau)}{2}\right.\right. \\ & \left.\cdot\left(\frac{V}{L} + \Phi(\tau)\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right)\right) \\ & \left.\cdot \frac{d\tau}{M+\Phi(\tau)}\right] ds \Bigg\rangle,\end{aligned} \tag{10}$$

where $\langle\rangle$ indicates average over all the particles traced, with zero contribution for those hitting the outer boundary. The exponential term is the result of creation, arising from the introduction of g defined by equation (8), during the processes. $X(s)$, $Y(s)$, $Z(s)$, $P(s)$, $\Phi(s)$ are time-backward stochastic processes described by

$$\begin{aligned}dX &= -V_x^{sw} ds \\ dY &= -V_y^{sw} ds \\ dZ &= -\left(\Phi V + V_z^{sw}\right) ds \\ d\Phi(t) &= \sqrt{2D_{\mu\mu}}\, dW_\mu(s) \\ & \quad - \frac{1-\Phi^2}{2}\left[\frac{V}{L} + \Phi\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right] ds \\ & \quad + \left(\frac{\partial D_{\mu\mu}}{\partial \Phi} + \frac{2D_{\mu\mu}}{M+\Phi}\right) ds \\ dP &= P\left[\frac{1-\Phi^2}{2}\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y}\right) + \Phi^2 \frac{\partial V_z^{sw}}{\partial z}\right] ds,\end{aligned} \tag{11}$$

where the pseudo-velocity V corresponds to the pseudo-momentum P, the divergence of solar wind $\partial V_x^{sw}/\partial x$, $\partial V_y^{sw}/\partial y$, and $\partial V_z^{sw}/\partial z$ are functions of pseudo-position (X, Y, Z). the Parker field $\mathbf{B}$ is set so that its magnitude is 5 nT at 1 AU, solar wind is radial flow with V^{sw} = 400 km/s, and $W_\mu(t)$ is a Wiener process. If energy loss is not considered, the last equation of the equation set (11) would be $dP = 0$. The source flux is set in small region (<0.05 *AU*) with a power law spectrum. An outer escape boundary is set at r = 50 AU. The source particles with a power law spectrum γ_0 injected in a small region (<0.05 AU) at the Sun is represented by a Reid-Axford profile [*Reid*, 1964]

$$Q(z < 0.05AU, E_k, t) = \frac{C}{t}\frac{E_k^{-\gamma_0}}{p^2}\exp\left\{-\frac{\tau_c}{t} - \frac{t}{\tau_L}\right\}, \tag{12}$$

where E_k is source particle's kinetic energy, τ_c and τ_L indicate the rise and decay timescales, respectively.

[11] By introducing the new function $g = f/(M + \mu)$, we get a time-backward stochastic processes equation (11) with better chance for virtual particles to have Φ increased when traced backward because of the additional term $2D_{\mu\mu}ds/(M + \mu)$ in the right-hand side of the $d\Phi$ expression, and consequently, to get Z decreased. In this way, we increase the probability that a particle traced backward to the initial time falls into the source region. The ability to force virtual particles to be back to source region can be adjusted by modifying the constant M. The smaller the value of M, the sooner the virtual particles will be forced back to the source. However, if M is too small ($M \rightarrow 1$), we cannot get a profile with long time interval. In simulations we find $M = 3$ is a good choice.

[12] We model a gradual SEP event with different proton channels observed by Ulysses COSPIN instruments LET and HET after day 315 of 1990. In order to avoid the local effects we only choose those channels with energy larger than 10 MeV. Among the channels we consider there is one from instrument HET with pitch angle distributions (eight bins) data, and all others only have the pitch angle averaged flux data. The time resolution of the flux data for all channels is 10 min. During the SEP event Ulysses located at 1.1 AU near the equatorial plane. We assume protons from all the channels have the same source function, i.e., they have the same value of τ_c = 0.05 days and τ_L = 0.35 days in equation (12). We find the above values allow our numerical simulations to fit the spacecraft data for this event well. If we change the two time constants slightly, the results do not change significantly because the two time constants are much shorter than the time of propagation of the particles in all energy bands. Therefore we feel that we can choose the same injection function for all energies. We choose a source spectral index $\gamma_0 = -3$ to get the best fit to the spacecraft data. The simulation results are not very sensitive to γ_0; they do not change much as γ_0 varies in the range of $-2.7\sim-3.5$.

[13] Figure 1 shows fits to the flux and anisotropy profiles of Ulysses HET 34–92 MeV proton data. For all the panels, thin solid lines indicate the spacecraft data and thick solid, dotted, and dashed curves indicate three simulations with different mean free paths and model constraints. The thick solid and dotted curves indicate simulations with adiabatic cooling effects (E loss) and without adiabatic cooling effects (No E Loss), respectively, with radial mean free path, λ_r = 0.3 AU. Dashed curves indicate a simulation without

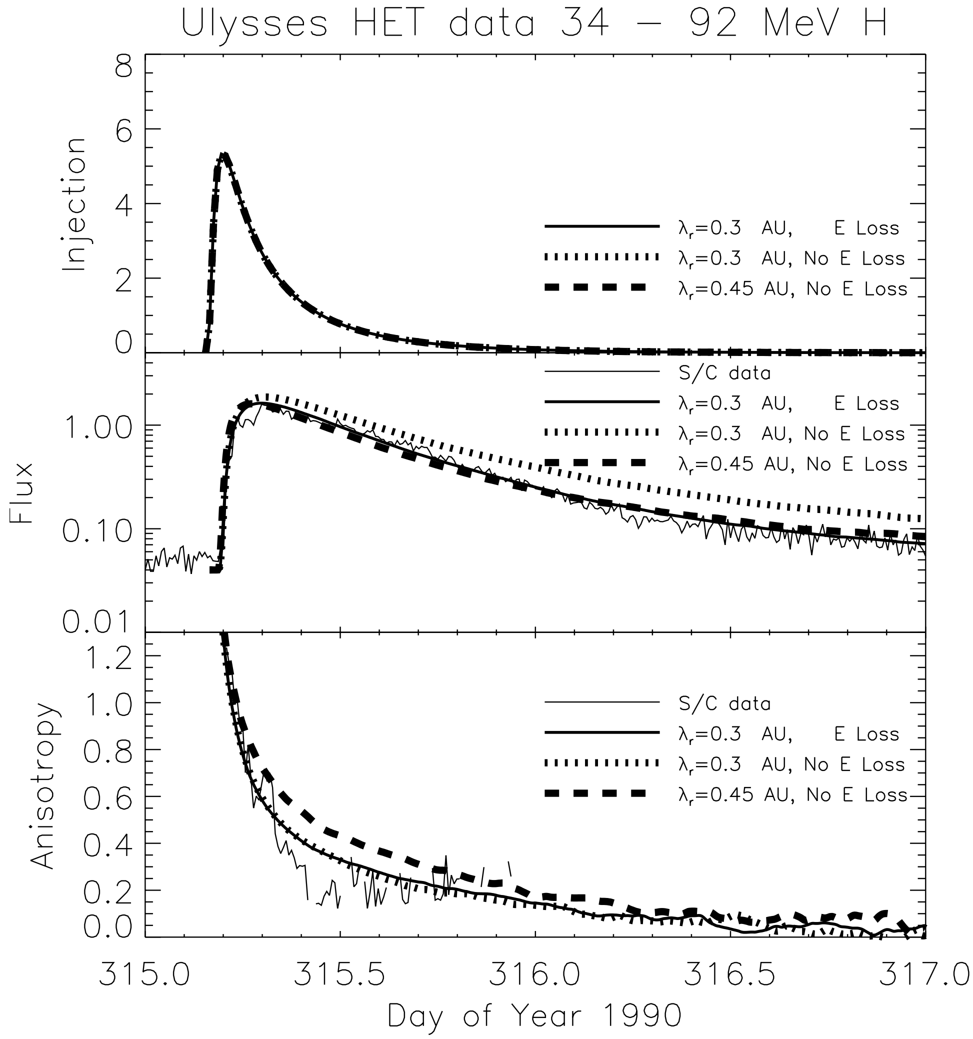

Figure 1. Fits to the time-intensity and anisotropy profiles of 34–92 MeV protons observed on Ulysses during the 1990, day 315 event.

adiabatic cooling (No E loss) but with a larger mean free path, λ_r = 0.45 AU.

[14] The top panel of the Figure 1 indicates the injection profile at the source. The middle panel indicates the flux observed at the spacecraft. In the panel during the initial phase all three of the simulations agree with spacecraft data well. However, immediately after the peak time, the dotted curve does not agree with spacecraft data, while both of the thick solid and dashed curves still agree with spacecraft data well for several days. The bottom panel indicates the anisotropy profile. In the panel at times t < 315.2 and t > 316 days the spacecraft anisotropy data curve is not shown since there is no significant anisotropy. Comparing our modeled anisotropy profile, we can see both of the thick solid and dotted curves agree with the spacecraft data very well. However, the dashed curve does not agree with the spacecraft data during the first day.

[15] From Figure 1 we can see both the simulations with and without adiabatic cooling effects with radial mean free path λ_r = 0.3 AU fit to the spacecraft data very well in the initial phase, however, after that, while the simulation with adiabatic cooling effects still agrees with spacecraft data very well, the one without adiabatic cooling effects does not, because it dissipates much slower than the spacecraft data. Using the model without adiabatic cooling, when we increase the mean free path to λ_r = 0.45 AU, the flux profile agrees with spacecraft data for the entire event, but the anisotropy profile becomes unacceptable 0.2 days after the initial phase.

[16] For all other channels without anisotropy data we only fit simulation results to their flux profile. For each channel we fit the entire event with and without energy loss to get two mean free path values for the two models. Although for other channels we do not fit simulations to anisotropy data from spacecraft observation, from the results in Figure 1 we assume that without adiabatic cooling, the simulations that fit the flux profile for the entire event can also fit the anisotropy data for a short time period; therefore we consider the mean free paths obtained from such simulations as the mean free paths fitted without energy loss. Figure 2 shows particles' mean free path as a function of their rigidity for all the energy channels consid-

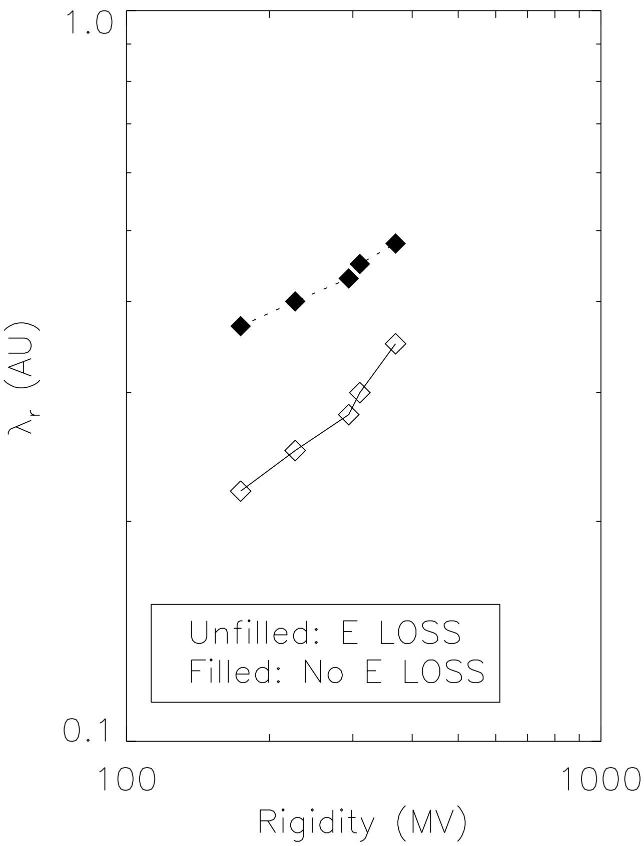

Figure 2. Rigidity dependence of particles' radial mean free path.

ered. The filled symbols indicate results without energy loss, but the unfilled symbols indicate that with energy loss. Note that when considering the effect of adiabatic cooling, SEP's mean free paths obtained from fitting numerical results to the spacecraft data is always smaller than that without energy loss.

4. Discussion

[17] In many models studying SEP's transport by numerically fitting spacecraft data with simulations, adiabatic cooling effects are ignored, and the fits are usually done over short time intervals, generally immediately after onset [e.g., *Bieber et al.*, 1994; *Dröge*, 2000]. Moreover, at later times in the event, there usually are discrepancies between flux profiles of spacecraft data and simulations, i.e., the simulation results dissipate slower than the spacecraft data. In our study, we find that to fit both time profile of flux and anisotropy of gradual events simultaneously, simulations without adiabatic cooling could only fit spacecraft data in a short time range (the initial phase). After the peak time, the simulation's dissipation is much slower than that of the spacecraft data. However, simulations with adiabatic cooling can fit the entire several-day-long event very well. Moreover, to fit time profile of flux for the entire event, the simulation without adiabatic cooling has to increase the mean free path about 50%. However, such increase of mean free path makes the anisotropy profile only acceptable for a short time period after the peak time. The result suggests that we must include the adiabatic cooling in order to model the SEP events correctly because this affects the derivation of mean free path using gradual SEP events.

[18] The well-accepted 80% two-dimensional (2-D) and 20% slab composite turbulence geometry is originally suggested by *Bieber et al.* [1994] to solve the mean free paths' "too small" problem; however, the transport equation considered did not include the adiabatic cooling effects. From Figure 2 we can see with adiabatic cooling effect the fitting results of particles' mean free paths are always smaller than that without adiabatic cooling effect. Therefore including the adiabatic cooling effects moves the fitting results in the same direction as the QLT expectations. In the future we plan to work on gradual SEP events with wider rigidity range. We will also compare our fitted mean free paths with the quasi-linear theory results with the real solar wind data to check how well including adiabatic cooling effects can fix the above SEPs parallel mean free paths' "too small" problem. It is possible that the discrepancy can not be accounted entirely to adiabatic cooling effect, and other effects still need to be considered, e.g., spectral anisotropy with weaker contribution from 2-D components [*Qin et al.*, 2006]. In this work we do not have information for source of the gradual SEPs and we choose the injection function as a simple Reid-Axford profile with flux spectrum $\gamma_0 = -3$ for the entire gradual event, while the realistic one could be rather complicated. The injection function we choose is helpful for us to obtain good fit to the observations we study. Regarding to the main purpose of this article, we do not try to investigate the realistic source of the SEP event. However, as one of our future tasks, we can further verify the injection function by fitting the energy spectrum of spacecraft data. To get time propagation of energy spectrum we have to fit flux and anisotropy time profiles for different energy SEPs simultaneously. By doing so, we can also examine the rigidity dependance of SEP's transport coefficients.

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