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AN EFFECT OF PERPENDICULAR DIFFUSION ON THE ANISOTROPY OF SOLAR ENERGETIC PARTICLES FROM UNCONNECTED SOURCES

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ABSTRACT

Recently, Tan and coworkers studied the 2001 September 24 solar energetic particle (SEP) event observed by the *Wind* spacecraft at 1 AU and found that there is a counter-streaming particle beam with a deep depression of flux at 90° pitch angle during the beginning of the event. They suggested that it is a result of a reflecting boundary at some distance outside of 1 AU. While this scenario could be true under some specific configuration of an interplanetary magnetic field, in this paper we offer another possible explanation. We simulated the SEP event by solving the five-dimensional focused transport equation numerically for 40 keV electrons with perpendicular diffusion. We find that a counter-streaming particle beam with deep depression at 90° pitch angle can form on Parker magnetic field lines that do not directly connect to the main particle source on the Sun in the beginning of an SEP event. It can happen when a significant number of observed particles come from adjacent field lines through parallel transport to large radial distance first, hopping across field lines through perpendicular diffusion, and then getting scattered back to 1 AU, where they combine with the particles directly coming from the Sun to form a counter-streaming beam.

Key words: diffusion – interplanetary medium – Sun: flares – Sun: particle emission

1. INTRODUCTION

As suggested by a number of authors, (e.g., Tan et al. 1992, 2007, 2008; Bieber et al. 2002; Reames & Ng 2002), an enhanced interplanetary magnetic field (IMF) in the outer heliosphere can act as a reflecting boundary or a diffusion barrier to solar energetic particles (SEPs) coming from coronal mass ejection (CME) shocks or solar flares. It can contain the particles long enough to form a nearly uniform distribution in the entire inner heliosphere and particles of all energies then dissipate at the same rate through adiabatic cooling, a phenomenon commonly known as the reservoir effect of SEPs. Recently, Tan et al. (2009) studied the 2001 September 24 SEP event and claimed that the counter-streaming particle beam with a deep depression of flux at 90° pitch angle observed during the beginning of this event is consistent with an outer reflecting boundary beyond 1 AU.

According to the quasi-linear theory for cosmic ray diffusion (Jokipii 1966), the perpendicular diffusion coefficient is usually much smaller than the parallel diffusion coefficient. It is usually ignored in many numerical studies of SEP transport in interplanetary space. However, McKibben (1972) and McKibben et al. (2003) noticed that SEP fluxes observed at very different locations in the inner heliosphere often become equalized and they attributed it to an effective cross-field diffusion that can distribute the SEPs uniformly. Furthermore, Dwyer et al. (1997) and Zhang et al. (2003) reported that in some circumstances perpendicular diffusion could be considerable relative to parallel diffusion. Numerical simulations of test particle propagation in model solar wind turbulence (Qin et al. 2002; Qin 2007) showed that perpendicular diffusion coefficients generally disagree with quasi-linear theory. Furthermore, Matthaeus et al. (2003), Shalchi et al. (2004), and Qin (2007) provided nonlinear guiding center theories to account for perpendicular and parallel diffusion coefficients from the test particle simulation results.

Many works were done to describe the SEP intensity with the focused Fokker–Planck transport equation (Parker 1963; Roelof 1969; Earl 1976; Kallenrode 1993; Dröge 1994; Ng & Reames 1994; Ruffolo 1995; Kallenrode & Wibberenz 1997; Qin et al. 2005, 2006). Recently, Zhang et al. (2009) presented a more complete model of SEP transport in three-dimensional interplanetary magnetic fields with consideration of both parallel and perpendicular diffusion. In addition, by numerically solving the SEP transport model it is showed that even weak perpendicular diffusion can have an important effect on propagation of SEPs in three-dimensional interplanetary magnetic fields (Zhang et al. 2009; He et al. 2011). The simulations in Zhang et al. (2009) showed that the observed SEP reservoir phenomenon is a robust result of SEP propagation with an enhanced "communication" across latitude and longitude. More recently, Qin et al. (2011) demonstrated that perpendicular diffusion also causes particles accelerated at interplanetary shocks to behave like the reservoir phenomenon. The three-dimensional SEP model with both parallel and perpendicular transport has provided us tools to better understand the propagation of SEPs.

In this paper, we study a peculiar anisotropy of solar energetic electrons sometimes observed by spacecraft. We simulate an SEP event by numerically solving the Fokker–Planck focused transport equation in a three-dimensional Parker interplanetary magnetic field without an artificial outer reflecting boundary. Our results show that particle perpendicular diffusion can offer a new explanation to the counter-streaming particle beam observed by *Wind*/3DP instrument during the beginning of the 2001 September 24 SEP event. In Section 2, we describe Tan et al.'s (2009) observation and explanation of 2001 September 24 event. In Section 3, we describe our model used to simulate SEP transport. In Section 4, we show an effect of perpendicular diffusion on the anisotropy of SEP electrons that can also be used to explain the *Wind* observations.

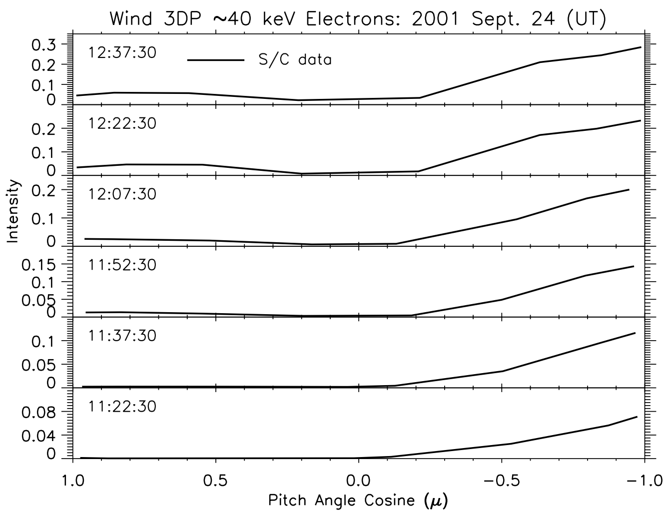

Figure 1. Five second interval 40 keV electrons intensity as a function of μ for different time in the 2001 September 24 event as measured by the *Wind*/3DP instrument. The panels from bottom to the top show increasing time.

2. Tan et al.'s (2009) EXPLANATION OF 2001 SEPTEMBER 24 EVENT

Tan et al. (2009) studied the pitch-angle distribution of solar energetic electrons observed by the three-dimensional plasma and energetic particles (3DP) instrument (Lin et al. 1995) on the *Wind* spacecraft for the 2001 September 24 event. Figure 1 shows several pitch-angle distributions of ∼40 keV electrons at 15 minute intervals near the beginning of the event. The increasing time displayed in each of the panels from bottom to the top shows when the data were measured. The angular distribution is obtained from sectored measurements of eight directions. Each of the sector measurements has an accumulation time of 5 s. The data shown in Figure 1 are similar to the lower panels of Figure 2 in Tan et al. (2009), except the accumulation time. Following Tan et al. (2009) the coordinates is set up in such a way that $\mu = \cos(\theta) = -1$ corresponds to particles moving away from the Sun.

As shown by Tan et al. (2009) and in Figure 1 of this paper, in the beginning of the event, non-zero flux only appears at $\mu \lesssim -0.2$, indicating that all particles are moving away from the Sun. About 30 minutes later, electrons of $\mu \gtrsim 0.7$ begin to appear but $\mu \sim 0$ electrons were still absent. Tan et al. (2009) suggested that there is no scattering of incident electrons because of the zero flux at $\mu \sim 0$ so that the electron increase at $\mu \sim 0.7$ is mainly formed by electrons reflected from a stronger magnetic field beyond 1 AU.

3. OUR MODEL FOR SIMULATIONS

Here, we briefly describe the model we use to study SEP transport through the interplanetary field. For detailed description please refer to Qin et al. (2006) and Zhang et al. (2009). We use the focused transport equation to derive the gyrophase-averaged distribution function $f(\mathbf{x}, \mu, \mathbf{p}, \mathbf{t})$ of SEP (e.g., Skilling 1971; Schlickeiser 2002)

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \mathbf{V}^{sw}\cdot\nabla f + \dot{p}\frac{\partial f}{\partial p} + \dot{\mu}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) - \frac{\partial}{\partial x}\left(\kappa_{xx}\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial y}\left(\kappa_{yy}\frac{\partial f}{\partial y}\right) = Q(\mathbf{x}, p, t), \quad (1)$$

where $\mathbf{x}$ is particle's position, z is the coordinate along the magnetic field spiral, p is particle's momentum, μ is particle's pitch-angle cosine, t is time, v is the particle speed, $\mathbf{V}^{\mathbf{sw}}$ is the solar wind velocity, and Q is the source term. Here,

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

indicates particles momentum change due to the adiabatic cooling effect (Skilling 1971; Qin et al. 2004). We also consider particle pitch-angle variation because of magnetic focusing effect and the divergence of the solar wind flows (e.g., Roelof 1969; Isenberg 1997; Kóta & Jokipii 1997)

$$\dot{\mu} = \frac{1-\mu^2}{2}\left[-\frac{v}{B}\frac{\partial B}{\partial z} + \mu\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right] = \frac{1-\mu^2}{2}\left[\frac{v}{L} + \mu\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right], \quad (3)$$

where B is the background interplanetary magnetic field strength which is directed along the z-axis, and magnetic focusing length L is defined by $L = (\mathbf{z}\cdot\nabla\ln B)^{-1}$.

Parallel mean free path $\lambda_\parallel$ can be derived from the pitch-angle diffusion coefficient as (Jokipii 1966; Hasselmann & Wibberenz 1968, 1970; Earl 1974)

$$\lambda_\parallel = \frac{3v}{8}\int_{-1}^{+1}\frac{(1-\mu^2)^2}{D_{\mu\mu}}d\mu \quad (4)$$

under the condition that particles have a nearly isotropic pitch-angle distribution. In addition, following Bieber et al. (1994) we assume that the particle radial mean free path, defined by $\lambda_r \equiv \lambda_\parallel \cos^2\psi$, where ψ is the angle between the local magnetic field direction and the radial direction, is a constant throughout the heliosphere, reflecting the effect of magnetic turbulence power distribution over the radial distance.

We use a formula for the pitch-angle diffusion coefficient taken from a quasi-linear theory (Beeck & Wibberenz 1986; Qin et al. 2006)

$$D_{\mu\mu}^r = D_{\mu\mu}/\cos^2\psi = D_0 v R^{-1/3}\{|\mu|^{q-1} + h\}(1-\mu^2), \quad (5)$$

where the constant D_0 is to control the level of scattering due to the magnetic field fluctuations and R is the particle rigidity. To avoid the zero scattering problem at 90° pitch angle (or $D_{\mu\mu}(\mu = 0) = 0$) commonly seen in the standard quasi-linear theory, a constant h, which comes from the nonlinear effect of wave–particle interaction, is added to the equation for $D_{\mu\mu}$. If $h \gg 1$, the pitch-angle diffusion coefficient approaches the limit of isotropic form with a strong scattering at $\mu = 0$. From simulations (Qin & Shalchi 2009) we can see that in medium- to high-level magnetic turbulence (as observed in solar wind), there is strong nonlinear effect so the scattering at $\mu = 0$ is strong. Therefore, a relatively higher $h = 0.2$ is set in our simulation. Note that, in this work if resonance broadening is neglected, i.e., $h = 0$, the simulation results will be changed to some extent, but the conclusions will not change. The constant $q = 5/3$ is related to the power spectrum of magnetic field turbulence in inertial range, which we choose to be a Kolmogorov spectrum.

A source term with a power-law spectral index γ is specified at the inner boundary $r < 0.01$ AU to have a Reid–Axford time profile (Reid 1964)

$$Q(z < 0.01\,\mathrm{AU}, |\theta - \theta_0| \leqslant \Delta\theta, |\phi - \phi_0| \leqslant \Delta\phi, E_k, t) = \frac{C}{t-t_0}\frac{E_k^{-\gamma}}{p^2}\exp\left(-\frac{\tau_c}{t-t_0} - \frac{t-t_0}{\tau_L}\right), \quad (6)$$

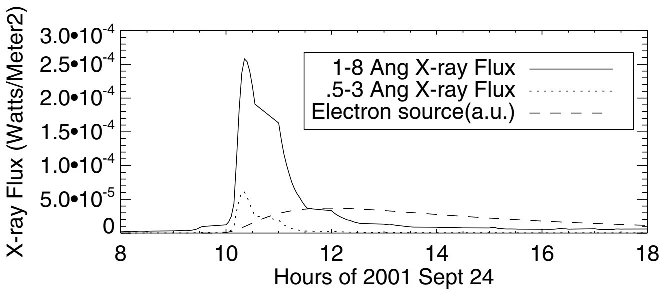

Figure 2. 1–8 Å (solid line) and 0.5–3 Å (dotted line) solar X-ray fluxes observed by GOES-8 Space Environment Monitor (5 minute averages). The dashed line is the time variation of solar energetic electron injection source in arbitrary units.

where E_k is the kinetic energy of the source particle, τ_c and τ_L are the time constants controlling the injection profile, (θ_0, ϕ_0) denotes the heliospheric latitude and longitude of the source center, and $\Delta\theta$ and $\Delta\phi$ are half widths of SEP sources in latitude θ and longitude ϕ, respectively. We set SEP source with limited coverage of 33° in latitude and 66° in longitude, which is roughly a typical size of SEP sources (CMEs or flares) (Hundhausen 1993; Maia et al. 2001; Wang et al. 2006). Furthermore, an outer escape boundary is set at a large enough radial distance of $r = 50$ AU, and the SEP source energy spectrum index γ is set to be $\gamma = 3.0$ in Equation (6).

We solve the focused transport equation (1) by tracing SEPs using time-backward Markov stochastic processes back to their injection time (Zhang 1999). The method can deal with expanded source energy spectrum easily. Note that only those particles traced back to the source region near the initial injection time may contribute significantly to the statistics. The detailed numerical method is described in Qin et al. (2006) and Zhang et al. (2009). To get a time profile of SEP flux at any one location and energy, we typically calculate 1.5×10^7 stochastic trajectories on a parallel super-computer running with message passing interface (MPI).

4. RESULTS AND DISCUSSION

We try to simulate the electrons seen by the *Wind*/3DP instrument in the 2001 September 24 SEP event. The solar flare associated with this event occurred at S16E23 which started at 09:32 UT, reached optical emission maximum at 10:38 UT, and ended at 11:09 UT. The solar X-ray flux observed by GOES-8 Space Environment Monitor (5 minute averages) is shown in Figure 2. The 1–8 Å X-ray flux and 0.5–3 Å X-ray flux are shown with solid and dotted lines, respectively. To simulate the ∼40 keV SEP electron transport in interplanetary space, we set the onset time for the SEP injection to the starting time of the solar flare, or $t_0 = 9.57$ hr on 2001 September 24. The other two timescales in the SEP source function equation (6) are $\tau_c = 3.30$ hr and $\tau_L = 6.74$ hr. The time variation of our model solar energetic electrons source in arbitrary units is plotted in Figure 2 with dashed line. From the figure, we can see that both the peak time and the beginning of the decay phases are later than the duration of solar flare. This is a typical setting for SEP source from a gradual SEP event (e.g., Qin et al. 2006), because it takes time for CME shocks to propagate through the corona and accelerate particles. Since we use the Parker spiral model (Parker 1963) as an interplanetary magnetic field and set a constant solar wind velocity $V^{sw} = 450\,\mathrm{km\,s^{-1}}$, the footpoint of the interplanetary magnetic field line connecting the *Wind* spacecraft with the Sun was at ∼50.°4 W in longitude. The

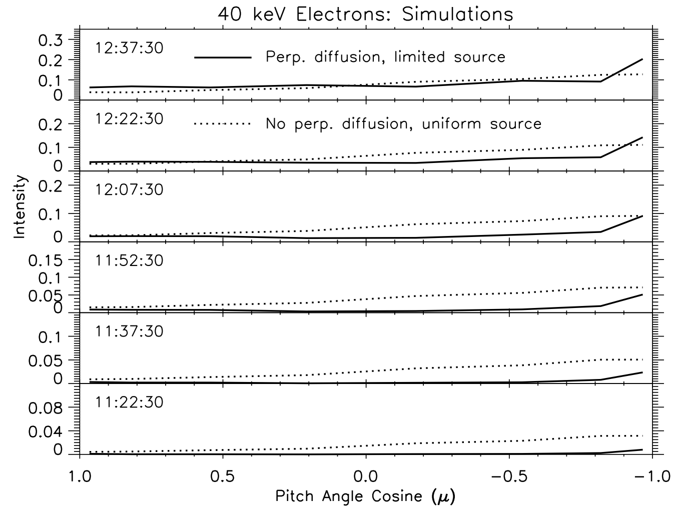

Figure 3. Simulation results for intensity as a function of μ for different time in the 2001 September 24 event. The panels from bottom to the top show increasing time. Solid and dotted lines indicate simulation results at each time with and without perpendicular diffusion considered, respectively.

heliographic latitude of field line footpoint to the spacecraft at that time is ∼7.°0 N. The solar flare location (S16E23) separated from the field line footpoint ∼73.°4 in longitude and ∼23.°0 in latitude. In addition, we set constant radial mean free path $\lambda_r = 0.15$ AU (or parallel mean free path $\lambda_\parallel = 0.34$ AU at 1 AU) and perpendicular mean free paths $\lambda_x = \lambda_y = 0.03$ AU for 40 keV electrons of the SEP event. According to observations, the mean free paths of energetic electrons in solar wind could vary in a large range (Bieber et al. 1994; Dröge 2000). Here, we use some typical values to demonstrate a case study.

The solid and dotted curves of Figure 3 show results from simulations with the focused transport equation in two scenarios, one with and one without the perpendicular diffusion, respectively. The simulation results shown in each panel are flux at the time displayed. The simulation with perpendicular diffusion (solid curves) has led to the following findings. In the beginning of the event, there were only electrons moving away from the Sun. Later, a flux peak of electrons at $\mu \sim 0.7$ was formed. With $\mu \sim 0$ particles still missing, both the fluxes of electrons moving away and toward the Sun increase with time. In the early stages during the event onset, our simulation of SEPs' transport with perpendicular diffusion shows a similar feature of a counter-streaming particle beam with a deep depression $\mu \sim 0$ as observed by *Wind*/3DP instrument. Eventually at a late stage (top two panels of Figure 3), the electron flux from simulations with perpendicular diffusion at $\mu \sim 0$ increases, similar to data observed by *Wind*/3DP (top two panels of Figure 1) did, although the increase of flux at $\mu \sim 0$ in the spacecraft data appears a little later. As a comparison, the dotted curves in Figure 3 show simulation without perpendicular diffusion with a uniform SEP source. From the figure we can see that for the whole time interval during the event onset, the electron flux in the simulation without perpendicular diffusion increases by decreasing μ, or there is no counter-streaming particle beam at any time. The comparison between the results of the two simulations (solid and dotted curves) shows that the perpendicular diffusion can cause counter-steaming particle beams with a deep depression of flux around $\mu \sim 0$.

After SEPs are produced near the surface of the Sun, they transport throughout the interplanetary magnetic field with fluctuations. Their transport in the heliospheric magnetic field can be parallel and perpendicular simultaneously. In the case we study, the distance between source center and observer footpoint is about 73°.4 in longitude and 23°.0 in latitude if we assume the interplanetary magnetic field is a Parker spiral. In order for particles to be detected by the observer, they have to travel both in parallel and perpendicular directions if the SEP sources are assumed to cover limited range of latitude and longitude on solar surface. In our model with perpendicular diffusion, we assume $\lambda_r = 0.15$ AU (or $\lambda_z = 0.33$ AU at 1 AU) and $\lambda_x = \lambda_y = 0.03$ AU. Since parallel mean free path is relatively large in the model and magnetic focusing tends to make particles more field aligned as they move out, after the energetic electrons are released from the solar source, the electrons will mostly move in the parallel direction to reach radial distances larger than 1 AU before they are scattered back. In the same time, perpendicular diffusion causes the particles to cross magnetic field lines, which happens more effective at larger radial distances. Because diffusive transport has random characteristics, for those particles detected by the observer, some have crossed the field lines at smaller radial distances $r \lesssim 1$ AU, while others may transport across to observer's field line at radial distances $r \gtrsim 1$ AU. Those transporting across at smaller radial distances are detected by the observer while moving away from the Sun in the parallel direction, but those that crossed the field lines at large radial distances can only be detected after they are scattered back toward the Sun. Therefore, according to our model, in the beginning of the initial event stage, a counter stream beam with deep depressed flux around $\mu \sim 0$ is formed. Afterward, particles with more and more scatterings are detected by the observer, so the flux around $\mu \sim 0$ begins to increase.

In this work, we use a simple model to study the transport of solar energetic electrons. For example, we adopt Parker spiral as a simple model for the interplanetary magnetic field with constant solar wind velocity $v_{\rm sw} = 450$ km s^{-1}. In addition, we assume constant radial mean free path $\lambda_r = 0.15$ AU and perpendicular mean free paths $\lambda_x = \lambda_y = 0.03$ AU. Another important assumption we make is the SEP source function in Equation (2). In order to fit observations more accurately, we may need to do a full parameter search with some more realistic diffusion coefficients. In addition, we could also adopt more realistic IMF and SEP sources. However, the main purpose of this work is not to accurately fit this particular observation with simulation. We just use a theoretical calculation with an idealized model to demonstrate that the perpendicular diffusion can cause counter-streaming particle beams similar to that observed by *Wind*/3DP instrument.

5. SUMMARY

Tan et al. (2009) showed a feature of counter-streaming particle beam with deep depression of flux around $\mu \sim 0$ in the beginning of an SEP event observed by the *Wind*/3DP instrument. They suggested that there might exist an outer reflecting boundary since there is no scattering of incident electrons. In this work, with a simulation of solar energetic electrons transport by solving the five-dimensional Fokker–Planck transport equation, we find that in some particular geometry at the beginning of a SEP event, the SEP transport with perpendicular diffusion can produce similar feature of a counter-streaming particle beam with a deep depression around $\mu \sim 0$. This explanation does not need to invoke a "hypothetical" outer reflecting boundary or magnetic mirror.

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