Estimation of the release time of solar energetic particles near the Sun

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Velocity Dispersion Analysis method

- The Velocity Dispersion Analysis (VDA) method has been used widely to investigate the SEP acceleration and transport process (Krucker et al. 1999; Krucker and Lin 1999; Reames 2009; Li et al. 2013).
- This method assumes that the first arriving particles move along the magnetic field lines, and the path length traversed is indepndent with energy. With these assumptions, the SEP release time near the Sun and the interplanetary path length can be determined by using the onset time of different energy particles.
- In this talk, we study how different source models and perpendicular diffusion affects the VDA results.

The transport model of SEPs

A three-dimensional focus transport equation (Skilling 1971 ; Schlickeiser 2002 ; Qin et al. 2006 ; Zhang et al. 2009; He et al. 2011, Wang et al. 2012, Zuo et al. 2013, Qin et al. 2013):

$$\frac{\partial f}{\partial t} = \nabla \cdot \kappa_{\perp} \cdot \nabla f - (v\mu \hat{b} + V^{sw}) \cdot \nabla f + \frac{\partial}{\partial \mu}(D_{\mu\mu}\frac{\partial f}{\partial \mu})$$

$$+p\left[\frac{1-\mu^2}{2}\left(\nabla \cdot V^{sw} - \hat{b}\hat{b} : \nabla V^{sw}\right) + \mu^2 \hat{b}\hat{b} : \nabla V^{sw}\right]\frac{\partial f}{\partial p}$$

$$-\frac{1-\mu^2}{2}\left[-\frac{v}{L} + \mu\left(\nabla \cdot V^{sw} - 3\hat{b}\hat{b} : \nabla V^{sw}\right)\right]\frac{\partial f}{\partial \mu}$$

In our simulations, we use a time-backward Markov stochastic process method to solve the transport equation (Zhang 1999; Qin et al. 2006). The interplanetary field is Parker field, and the solar wind speed is set to 400 km/s.

Diffusion coefficients

The relationship of the $D_{\mu\mu}$ and parallel mean free path $\lambda_{\parallel}$ is written as (Jokipii, 1966; Hasselmann, 1968; Earl 1974)

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

We follow the model of pitch angle diffusion coefficient from (Beeck and Wibberenz 1986),

$$D_{\mu\mu} = D_0 \upsilon p^{q-2} \left\{ |\mu|^{q-1} + h \right\} \left(1 - \mu^2\right), \tag{2}$$

The perpendicular diffusion coeffeint is proportional to parallel one,

$$\kappa_{\perp} = a \kappa_{\parallel} \tag{3}$$

where we set $a = 0.01$ in our simulations.

Different source model

We use boundary values to model the particle injection from the source, and the boundary condition is chosen as the following form

$$f_b(z \leq 0.05\mathrm{AU}, E_k, \theta, \varphi, t) = a\frac{E_k^{-\gamma}}{p^2}\xi\left(t, \theta, \varphi\right), \tag{4}$$

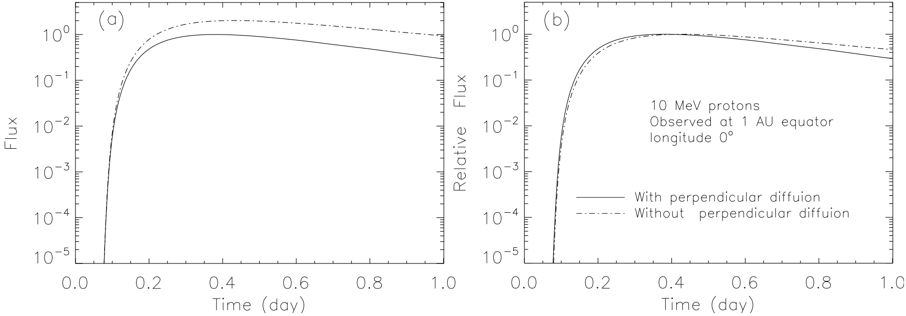
$$\xi\left(t,\theta,\varphi\right) =$$
$$\begin{cases} \frac{1}{t}\exp\left[-\frac{t_c}{t} - \frac{t}{t_l}\right] H\left(\phi_s - \left|\phi\left(\theta,\varphi\right)\right|\right) & \text{Case1}, \\ \left\{\frac{1}{t}\exp\left[-\frac{t_c}{t}\left(\frac{\phi_s}{\phi_0}\right)^2 - \frac{t}{t_l}\right] H\left(\phi_s - \left|\phi\left(\theta,\varphi\right)\right|\right) + \right. & \\ \left. \frac{1}{t}\exp\left[-\frac{t_c}{t}\left(\frac{\phi(\theta,\varphi)}{\phi_0}\right)^2 - \frac{t}{t_l}\right]\left[1 - H\left(\phi_s - \left|\phi\left(\theta,\varphi\right)\right|\right)\right]\right\} & \text{Case2}, \end{cases}$$

ϕ_s is set to 15^o.

Some definitions

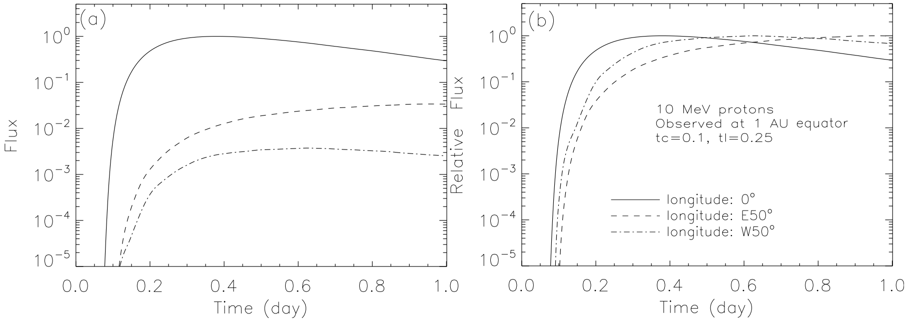
- We set parallel mean free paths $\lambda_{\parallel} = 0.126$ AU for 10 MeV protons as strong scattering, and set $\lambda_{\parallel} = 0.3$ AU protons as weak scattering.
- We set $t_c = 0.02$ day (0.48 hour) and $t_l = 0.05$ day (1.2 hours) as a short duration, and set $t_c = 0.1$ day (2.4 hours) and $t_l = 0.25$ day (6 hours) as a long duration case.
- We choose the background level as a constant fraction A of the maximum intensity. In each energy channel, we set the background fraction A as 10^{-5}, 10^{-3}, and 10^{-1}, corresponding to a low background level, middle background level, and high background level, respectively.

With and without perpendicular diffusion



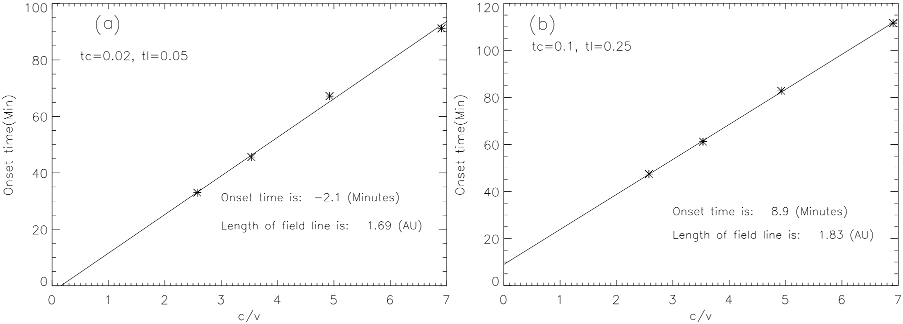
Comparison of 10 MeV proton fluxes with perpendicular diffusion (solid line) and without perpendicular diffusion (dash-dotted line). The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{\|}$ is set to 0.126 AU for 10 MeV particles.

Observed at different locations



Comparison of 10 MeV proton fluxes observed at different locations. The E50° is short for 50° east, and W50° is short for 50° west. The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.126 AU for 10 MeV particles.

Velocity Dispersion Analysis (VDA) method



The results of using the VDA method to calculate the SEP release time and path length. The source model is set to be case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to be 15^o. $\lambda_{||}$ is set to be 0.126 AU for 10 MeV particles.

Results of VDA method with strong scattering

Case	Duration	Background	Location	t_i (min)	L (AU)
1	Short	Low	Center	-2.1	1.69
			W50	-12	2.42
			E50	-18	2.51
2	Short	Middle	Center	-1.7	1.86
			W50	-8.3	2.38
			E50	-18	2.68
3	Short	High	Center	-0.98	2.34
			W50	-23	3.95
			E50	-43	4.83

The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.126 AU for 10 MeV particles. We set $t_c = 0.48$ hour and $t_l = 1.2$ hours as a short duration.

Results of VDA method with strong scattering

Case	Duration	Background	Location	t_i (min)	L (AU)
4	Long	Low	Center	8.9	1.84
			W50	1.5	2.39
			E50	-8.9	2.70
5	Long	Middle	Center	12	2.09
			W50	9.9	2.66
			E50	-7.7	3.34
6	Long	High	Center	26	2.98
			W50	26	4.65
			E50	-6.9	6.45

The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.126 AU for 10 MeV particles. We set $t_c = 2.4$ hours and $t_l = 6$ hours as a long duration.

Results of VDA method with weak scattering

Case	Duration	Background	Location	t_i (min)	L (AU)
1	Short	Low	Center	2.8	1.34
			W50	-1.3	1.60
			E50	2.1	1.39
2	Short	Middle	Center	2.6	1.46
			W50	6.1	1.52
			E50	4.0	1.41
3	Short	High	Center	6.8	1.70
			W50	6.9	1.87
			E50	6.0	1.84

The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.3 AU for 10 MeV particles. We set $t_c = 0.48$ hour and $t_l = 1.2$ hours as a short duration.

Results of VDA method with weak scattering

Case	Duration	Background	Location	t_i (min)	L (AU)
4	Long	Low	Center	11	1.48
			W50	13	1.57
			E50	14	1.43
5	Long	Middle	Center	16	1.61
			W50	17	1.78
			E50	20	1.63
6	Long	High	Center	38	1.90
			W50	44	2.16
			E50	42	2.67

The source model is set to case 1, and the particles are accelerated by a flare without source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.3 AU for 10 MeV particles. We set $t_c = 2.4$ hours and $t_l = 6$ hours as a long duration.

Results of VDA method with source diffusion

Case	Scattering	Background	Location	t_i (min)	L (AU)
1	Strong	Low	Center	-2.1	1.69
			W50	-0.91	1.91
			E50	-4.8	1.96
2	Strong	Middle	Center	0.41	1.82
			W50	-6.9	2.41
			E50	-5.9	2.31
3	Strong	High	Center	-0.88	2.38
			W50	2.8	3.29
			E50	-0.72	3.34

The source model is set to case 2, and the particles are accelerated by a flare with source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{\|}$ is set to 0.126 AU for 10 MeV particles. We set $t_c = 0.48$ hour and $t_l = 1.2$ hours.

Results of VDA method with source diffusion

Case	Scattering	Background	Location	t_i (min)	L (AU)
4	Weak	Low	Center	2.8	1.34
			W50	0.4	1.56
			E50	2.1	1.39
5	Weak	Middle	Center	3.5	1.45
			W50	4.6	1.63
			E50	3.9	1.51
6	Weak	High	Center	8.3	1.69
			W50	11	2.02
			E50	11	1.91

The source model is set to case 2, and the particles are accelerated by a flare with source propagation. ϕ_0 and ϕ_s are set to 15^o. $\lambda_{||}$ is set to 0.3 AU for 10 MeV particles. We set $t_c = 0.48$ hour and $t_l = 1.2$ hours.

Conclusions

- When the observer is connected to the source by interplanetary magnetic field, the effects of particles propagating in the solar atmosphere and perpendicular diffusion in the interplanetary space have little influence on the onset time of SEP fluxes and the VDA results.

Conclusions

- If SEPs accelerated by a solar flare can not propagate in the solar atmosphere, the SEP source region is approximate to the size of solar flare.
- When the observer is far from SEP source, the VDA method is valid in some cases of weak scattering. However, in the cases of strong scattering, the release time and the path length obtained from the VDA method are much different from the real values except some fortuitous cases.

Conclusions

- If SEPs accelerated by a solar flare can propagate in the solar atmosphere, the SEP source region should be larger than the size of solar flare as times go by.
- When the observer is far from SEP source, the VDA method is valid in some cases of particles effective propagation in the solar atmosphere.

Conclusions

- The VDA results are significantly influenced by the location and size of SEP source, the time profile of SEP source, particle mean free path, and background level.
- As a result, the VDA method is applicable in some SEP events which meet the following conditions, such as, short source duration, large mean free path, low background level, and good connection between the observer and the source.