Observations and numerical simulations of gradual SEP events with Ulysses and ACE

L.-L. Lian[1], G. Qin[1], Y. Wang[1], S.-W. Cui[2]

[1]Institute School of Science, Harbin Institute of Technology, Shenzhen 518055,PR China
qingang@hit.edu.cn

[2]Hebei Normal University, Shijiazhuang 050024, PR China
cuisw@hebtu.edu.cn

July 5, 2021

Outline

Solar energetic particle (SEP) event

Solar energetic particle (SEP) event

The particles observed in interplanetary space and near Earth are commonly referred to as solar energetic particles or SEPs: those accelerated at flares are known as impulsive SEP events, and particle populations accelerated by near-Sun CME-shocks are termed as gradual SEPs.

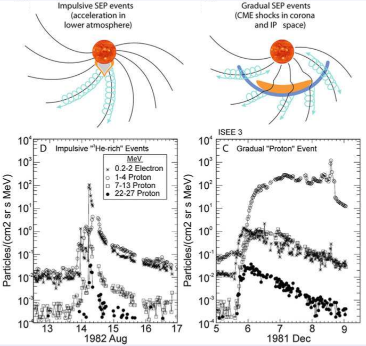

Figure 1: Impulsive (left) and gradual (right) classes of SEP events are distinguished by the probable sources of particle acceleration in each case (Reames 1999).

Flare and CME

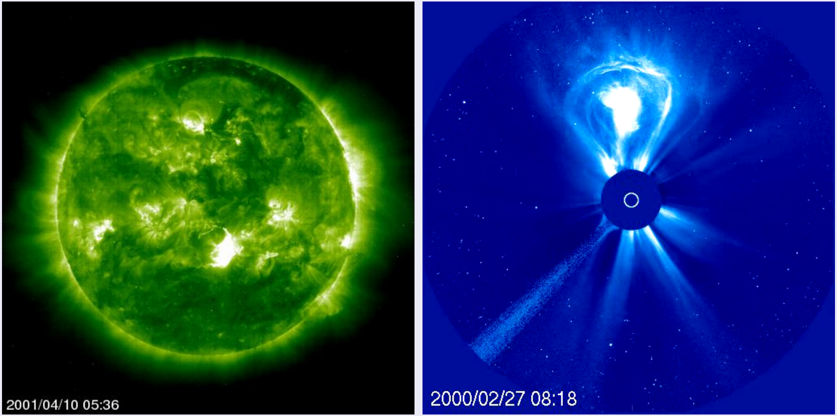

Figure 2: Flare (left) and Coronal Mass Ejection (CME) (right)

Spacecraft

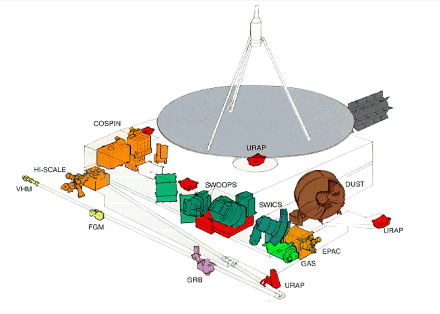

Figure 3: ACE (left) and Ulysses (right) spacecraft

Case I: 2000 June 10 event

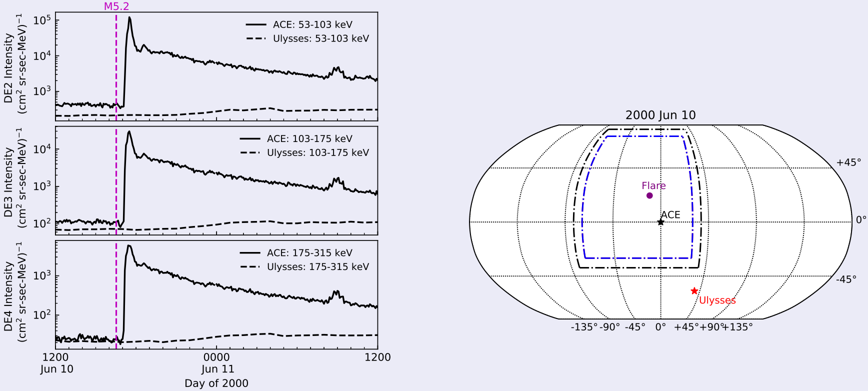

Figure 4: The left panels show the observation results of *ACE* (solid lines) and *Ulysses* (dashed lines) in DE2–DE4 energy channels, and the right panels shows the footpoints of *ACE* and *Ulysses*, as well as the flare, on the solar surface.

$V_{\mathrm{ACE}}^{\mathrm{SW}}$	$V_{\mathrm{Uly}}^{\mathrm{SW}}$	R_{Uly}	Ulysses loc	Flare site	Flare class
505 km/s	475 km/s	3.37 au	S58E87	N22W38	M5.2

Case II: 2001 December 26 event

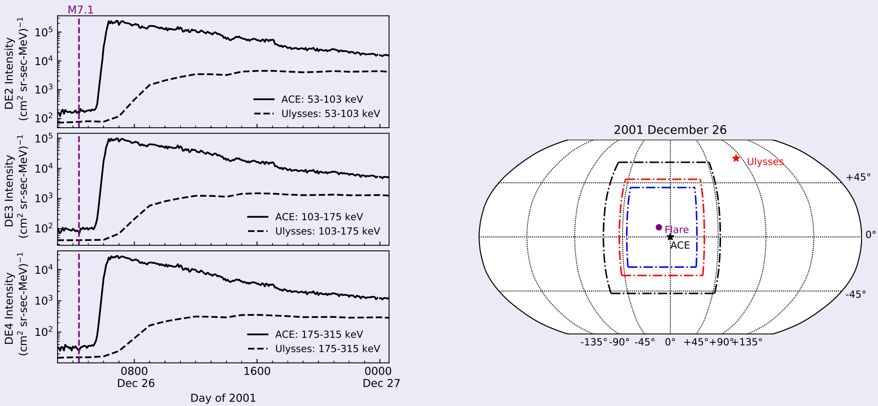

Figure 5: Same as Figure 4, except that it is for the event of 2001 December 26.

$V_{\mathrm{ACE}}^{\mathrm{SW}}$	$V_{\mathrm{Uly}}^{\mathrm{SW}}$	R_{Uly}	Ulysses loc	Flare site	Flare class
380 km/s	575 km/s	2.54 au	N67W39	N08W54	M7.1

Transport equation

Fokker-Planck Equation (Skilling 1971; Schlickeiser 2002; Qin et al. 2006; Zhang et al. 2009)

$$\frac{\partial f}{\partial t} + \left(v\mu\hat{\boldsymbol{b}} + \boldsymbol{V}^{sw}\right) \cdot \nabla f - \nabla \cdot (\kappa_\perp \cdot \nabla f) - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \frac{dp}{dt}\frac{\partial f}{\partial p} + \frac{d\mu}{dt}\frac{\partial f}{\partial \mu} = 0 \tag{1}$$

where

$$\frac{dp}{dt} = -p\left[\frac{1-\mu^2}{2}\left(\nabla \cdot \boldsymbol{V}^{sw} - \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{V}^{sw}\right) + \mu^2 \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{V}^{sw}\right] \tag{2}$$

$$\frac{d\mu}{dt} = \frac{1-\mu^2}{2}\left[-\frac{v}{L} + \mu\left(\nabla \cdot \boldsymbol{V}^{sw} - 3\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{V}^{sw}\right)\right] \tag{3}$$

Diffusion Coefficients

The model of pitch angle diffusion coefficient is set as the QLT (Jokipii 1966; Beeck & Wibberenz 1986)

$$D_{\mu\mu}(\mu) = \left(\frac{\delta B_{slab}}{B_0}\right)^2 \frac{\pi(s-1)}{4s} \frac{v}{l_{slab}} \left(\frac{R_L}{l_{slab}}\right)^{s-2} (\mu^{s-1} + h)(1-\mu^2) \tag{4}$$

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

The perpendicular mean free path is from NLGC (Matthaeus et al. 2003) with analytical approximations (Shalchi et al. 2004, 2010):

$$\lambda_\perp = \left[\left(\frac{\delta B_{2D}}{B_0}\right)^2 \sqrt{3\pi} \frac{s-1}{2s} \frac{\Gamma\left(\frac{s}{2}+1\right)}{\Gamma\left(\frac{s}{2}+\frac{1}{2}\right)} l_{2D}\right]^{2/3} {\lambda_\parallel}^{1/3} \tag{6}$$

Particle source

Source of SEP events:

$$f_b(z \leq 0.05\,\mathrm{AU}, \mathrm{E_k}, \theta, \varphi, \mathrm{t}) = \frac{\mathrm{a}}{\mathrm{t}} \cdot \frac{\mathrm{E_k}^{-\gamma}}{\mathrm{p}^2} \cdot \exp\left(-\frac{\tau_\mathrm{c}}{\mathrm{t}} - \frac{\mathrm{t}}{\tau_\mathrm{l}}\right) \tag{7}$$

- τ_c and τ_l(in Units of Days) are the rise and decay timescales of source injection profile, respectively.

We apply the time-backward Markov stochastic process method (Zhang (1999) and Qin et al. (2006).)

Simulation results I: 2000 June 10

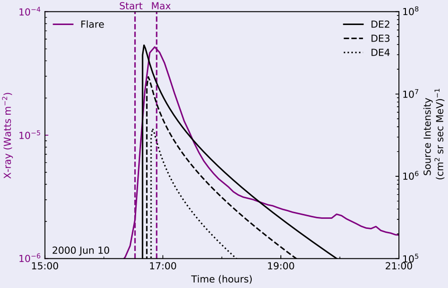

Figure 6: Particle source profiles in DE2 –DE4 and associated SXR flare for the event of 2000 June 10.

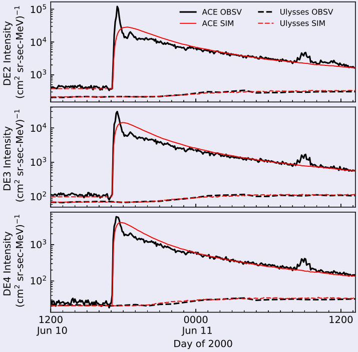

Figure 7: Comparison of the observations of electron intensities and the simulation results

Event Date	$\frac{\delta B}{B_0}$	Channel	$\lambda_\parallel$ (au)	$\frac{\kappa_\perp}{\kappa_\parallel}$	τ_c	τ_L	$\Delta\theta$	I_{max}	ΔT_1
2000 Jun 10	0.353	DE2	0.220	0.023	0.002	0.05	60	3.92 E+07	6.32
		DE3	0.245	0.021	0.002	0.05	53	1.61 E+07	10.64
		DE4	0.273	0.020	0.002	0.05	53	3.47 E+06	14.96

Simulation results II: 2000 June 10

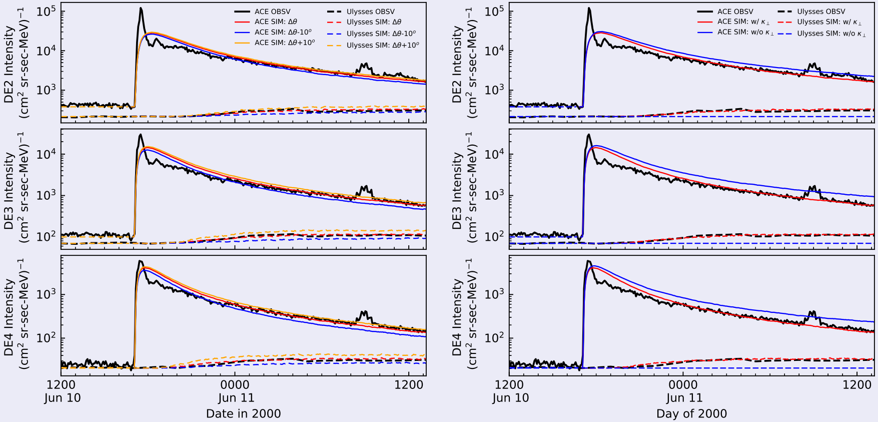

Figure 8: Similar as Figure 7 except that simulation results with different half width of particle source (left), and without perpendicular diffusion (right) are added additionally.

Simulation results I: 2001 December 26

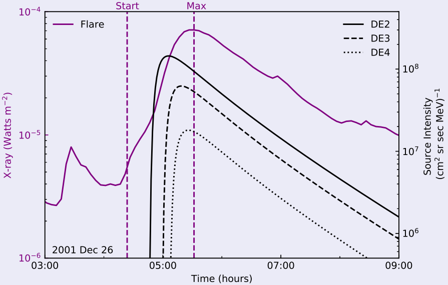

Figure 9: Particle source profiles in DE2 –DE4 and associated SXR flare for 2001 December 26 SEP event

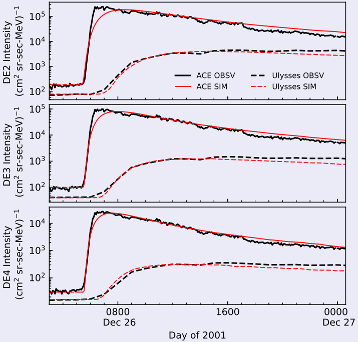

Figure 10: Electrons fluxes of the observations and simulations in DE2–DE4

Event Date	$\frac{\delta B}{B_0}$	Channel	$\lambda_\parallel$ (au)	$\frac{\kappa_\perp}{\kappa_\parallel}$	τ_c	τ_L	$\Delta\theta$	I_{max}	ΔT_1
2001 Dec 26	0.533	DE2	0.097	0.069	0.02	0.05	55	1.45 E+08	20.08
		DE3	0.108	0.064	0.02	0.05	40	6.22 E+07	33.04
		DE4	0.120	0.060	0.02	0.05	33	1.81 E+07	40.24

Simulation results II: 2001 December 26

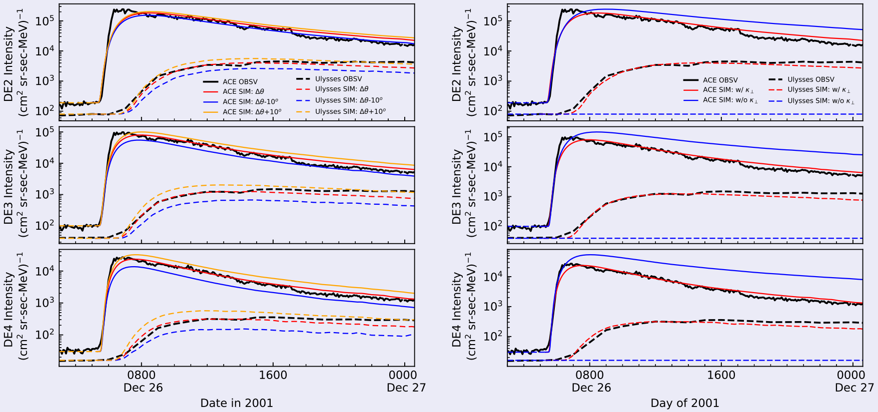

Figure 11: Similar as Figure 10 except that simulation results with different half width of particle source (left), and without perpendicular diffusion (right) are added additionally.

The theoretical models

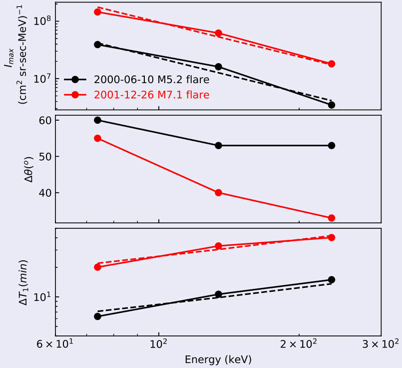

Figure 12: From top to bottom: the maximum value of particle source intensity $I_{\max}$, the half width of particle source $\Delta\theta$, and the time interval from the onset time of the flare to the peak time of the particle source, ΔT_1, with different energy for the two SEP events.

$$I_{\max} = \frac{G F_{\mathrm{SXR}} \Delta T_{\mathrm{d}}}{E^2}, \tag{8}$$

where, $G = 2.07 \times 10^{-3}$ (s sr)$^{-1}$, F_{SXR} is the SXR peak intensity, and ΔT_d is the time interval from the SXR initial time to the peak time.

$$\Delta T_1 = H p \Delta T_{\mathrm{d}}, \tag{9}$$

where, $H = 3.41 \times 10^{11}$ (GeV/c)$^{-1}$, p is the particle momentum.

Conclusion

1. The different of SEP flux between ACE and Ulysses probably caused by the significant difference between the two events.
2. The effect of perpendicular diffusion plays an important role in the propagation of particles, especially when the spacecraft's footpoint is not directly connected to the particle source.
3. The start times and peak times of the particles source are between the onset and peak times of flare in DE2–DE4 energy channels.
4. The peak value of the source intensity $I_{\max}$ is a function of the peak intensity ($F_{\rm SXR}$) and rise time ($\Delta T_{\rm d}$) of the flare and the particle energy (E).
5. The best fit half width of particle source $\Delta\theta$ decreases with the increasing of energy.
6. The time interval from the onset time of the flare to the peak time of the particle source ΔT_1 increases as the increasing of the momentum (p) and the rise time of SXR ($\Delta T_{\rm d}$).

Thank you !