The 23 July 2012 SEP event numerical simulation with multi-spacecraft observation data

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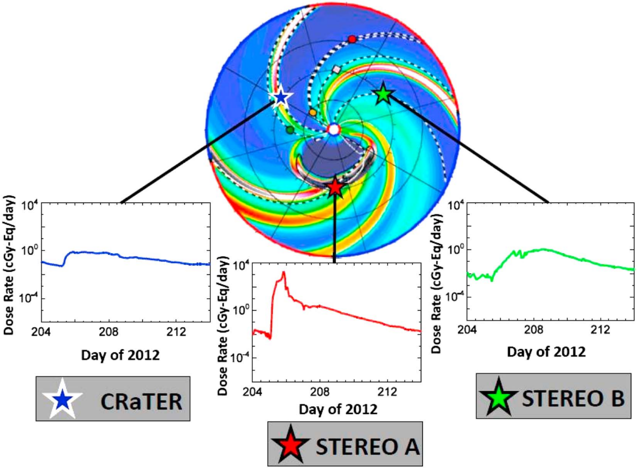
Outline

The 2012.07.23 SEP event

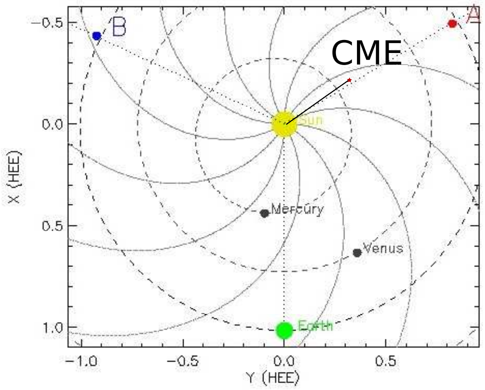


(C. T. Russell et al. (2013))

- time: 2012.07.23
- The Magnetic field109nT

The 2012.07.23 SEP event

- Orbit of the spacecraft and the CME bursted direction

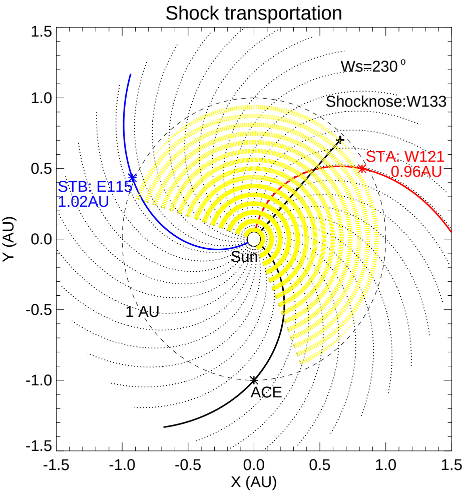


- STEREO A: W121.3°S0.07°
- STEREO B: E115.2°S0.16°
- Flare: S15°W133° (NOAA 11520)

http://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where_gif

The 2012.07.23 SEP event

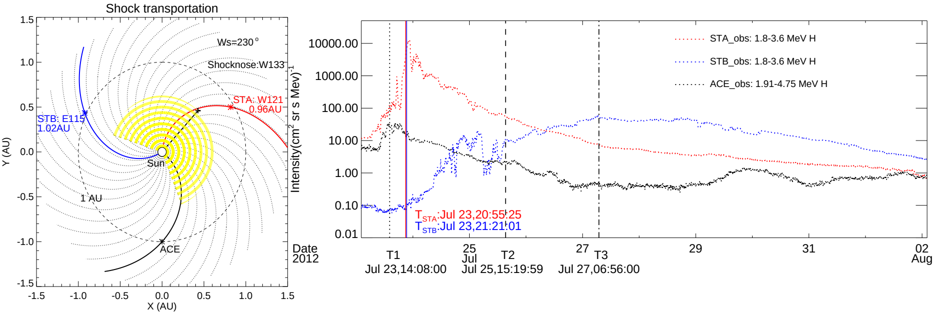
- The relationship between the shock width and the spacecraft locations



- STEREO A: The shock was detected at 20:55:25UT
- STEREO B: The shock was detected at 21:21:01UT
- ACE: No shock was detected
- Half of the shock $W_s/2$shuld be around $\frac{W_s}{2} \in (\angle ShockSunSTB, \angle ShockSunACE$ so $W_s \in (224^\circ, 266^\circ)$

The 2012.07.23 SEP event

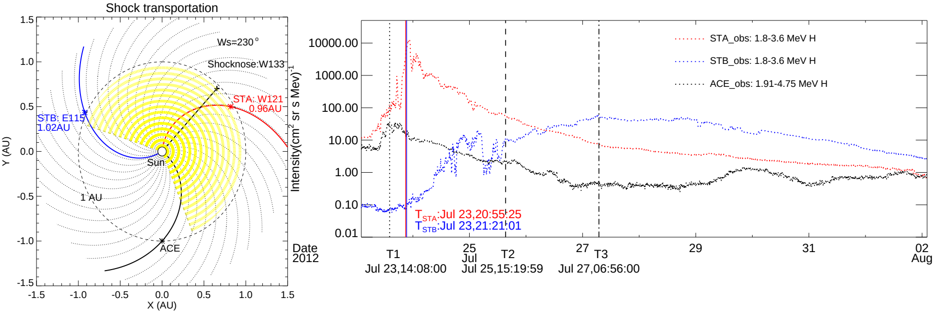
- Transport propagation-Parker field
  - T17.23,14:08:00



  - ACE:reach peakthen downward
  - STB:background value
  - STA:upward

The 2012.07.23 SEP event

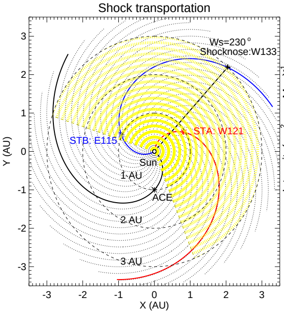
- Transport propagation-Parker field
  - T_{STA}7.23,20:55:25

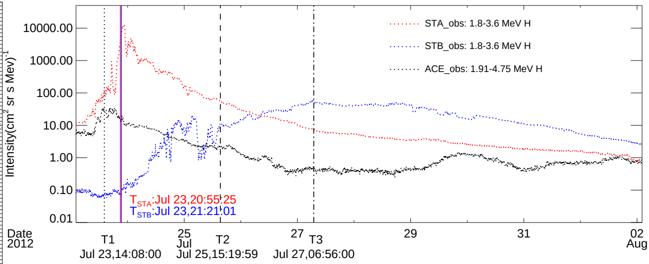


  - STAThe peak time was just at when the shock arrived, then downward
  - STBupward

The 2012.07.23 SEP event

- Transport propagation-Parker field
  - T27.25,15:19:59

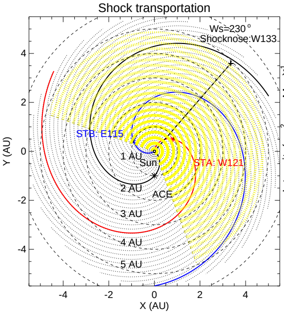


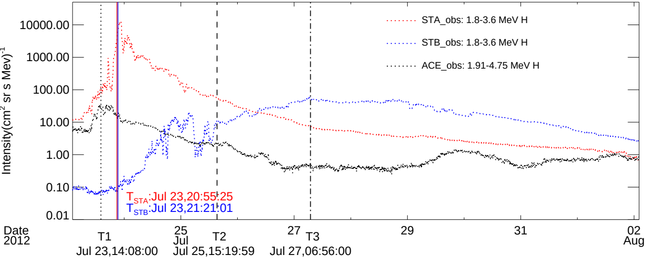


  - The nose of the shock passed through the magnetic field of STBproduces the most SEPs

The 2012.07.23 SEP event

- Transport propagation-Parker field
  - T37.27,06:56:00





  - When the most SEPs produced by the shock nose arrived at STB(the peak of the blue line in the right figure), the shock had been at the location shown in the left figure.

Our Models: The transport model of SEPs

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

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

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

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

- The shock was treated as a SEP source (Kallenrode et al. 1997):

$$Q = a\delta(r - v_s t) \left(\frac{r}{r_c} \right)^{\alpha(p, v_s)} \exp \left[-\frac{|\phi(\theta, \varphi)|}{\phi_c(p)} \right] p^{-\gamma}$$

Our Models: The simulation method

- We use a time-backward Markov stochastic process method to solve the transport Equation (Zhang 1999):

$$d\mathbf{x}(s) = \sqrt{2\kappa_\perp} \cdot d\mathbf{w}(s) + (\nabla \cdot \kappa_\perp - v\mu(s)\overset{\wedge}{\mathbf{b}} - \mathbf{v^s})ds$$

$$d\mu(s) = \sqrt{2D_{\mu\mu}}dw(s) + \left\{ \frac{\partial D_{\mu\mu}}{\partial \mu} - \frac{1-\mu^2}{2}\left[-\frac{v}{L} + \mu\left(\nabla \cdot \mathbf{v^s} - 3\overset{\wedge}{\mathbf{b}}\overset{\wedge}{\mathbf{b}} : \nabla \mathbf{v^s} \right) \right] \right\} ds$$

$$dp(s) = p(s)\left[\frac{1-\mu^2}{2}\left(\nabla \cdot \mathbf{v^s} - \overset{\wedge}{\mathbf{b}}\overset{\wedge}{\mathbf{b}} : \nabla \mathbf{v^s} \right) + \mu^2 \overset{\wedge}{\mathbf{b}}\overset{\wedge}{\mathbf{b}} : \nabla \mathbf{v^s} \right] d(s)$$

Our Models: The diffusion coefficients

- The model of pitch angle diffusion coefficient is set as the following (Jokipii 1966, Teufel and Schlickeriser 2003):

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

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

- The perpendicular mean free path is set as (Matthaeus et al. 2003; Shalchi et al. 2004, 2010):

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

The 2012.07.23 SEP event

Table: Model parameters independent of the particle species used in the calculations.

Parameter	Physical meaning	Value
v_s	shock speed	2003 km s^{-1}
W_s	shock width	230°
V^{SW}	solar wind speed	450 km s^{-1}
r_O	Observer solar distance	1 au
Δr	Shock space interval between two fresh injections	0.001 au
r_c	Radial normalization parameter	0.05 au
r_{b0}	Inner boundary	0.05 au
r_{b1}	Outer boundary	50 au
D^p_{slab}	Constant for proton parallel diffusion	0.063
D^e_{slab}	Constant for electron parallel diffusion	0.0252
D^p_{2D}	Constant for proton perpendicular diffusion	0.3
D^e_{2D}	Constant for electron perpendicular diffusion	0.402

The 2012.07.23 SEP event

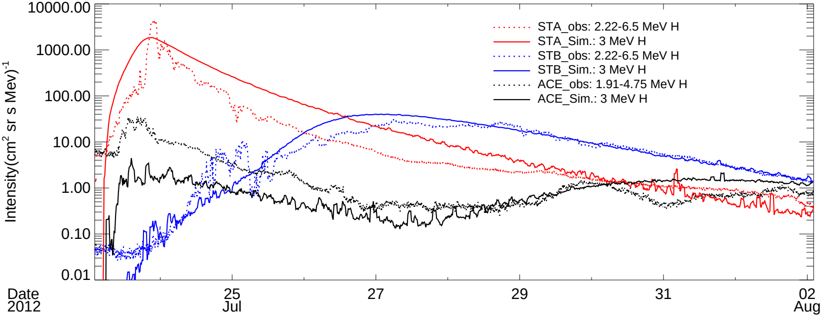
Table: Model parameters depending on particle species used in simulations.

Particle Type	Energy (MeV)	α	ϕ_c	γ	$\lambda_{\parallel}$ [1] (au)	$\kappa_{\perp}/\kappa_{\parallel}$ [1]
Protons	3	-2	3	-2.5	0.18	4.4%
Electrons	0.2	-3	2	-6.5	0.082	10%

[1] For particles in the ecliptic at 1 au.

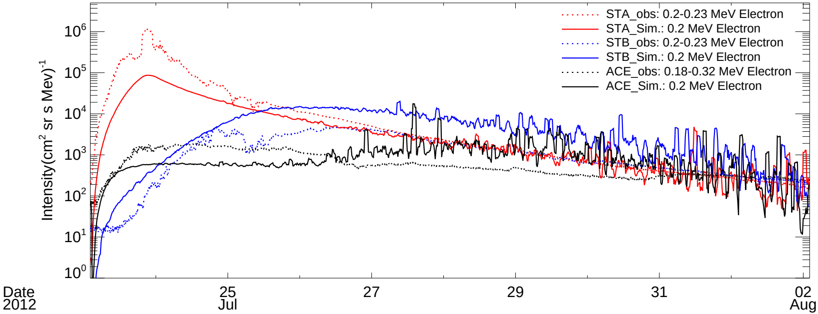
Simulation results

- Comparison of 3MeV Proton simulation and observation



Simulation results

- Comparison of 0.2MeV Electron simulation and observation



Conclusions

- We qualitatively analyze the relationship between the propagation of the CME-driven shock in the interplanetary space and the associated SEP flux observed by the multiple spacecraft.
- We simulated the SEP event by numerically solving the three-dimensional focused transport equation of SEPs considering the shock as the moving source of energetic particles. The simulations and observations approximately agree for the three spacecraft, especially in terms of the timing for the start and peak of SEP flux.

Table: Peak values of observations and simulations.

Particle	Energy (MeV)	Data Type	*STEREO-A* $(\mathrm{cm^2 sr\ s\ Mev})^{-1}$	*STEREO-B* $(\mathrm{cm^2 sr\ s\ Mev})^{-1}$	*ACE* $(\mathrm{cm^2 sr\ s\ Mev})^{-1}$
Protons	3	obs	4.6×10^3	3.1×10^1	3.5×10^1
		sim	4.7×10^3	1.1×10^2	2.2×10^1
Electrons	0.2	obs	1.2×10^6	4.7×10^3	1.9×10^3
		sim	1.4×10^5	8.5×10^4	1.9×10^3

Thank You