Study of solar energetic particle event timescales associated with ICMEs with numerical simulations

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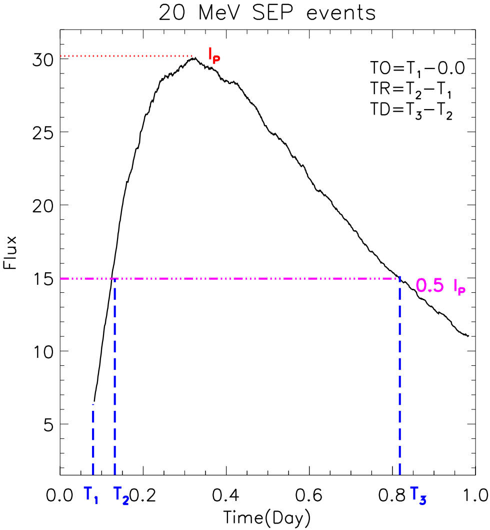
Outline

SEP timescales with ICMEs

- Definition of SEP events timescales (Kahler 2013):



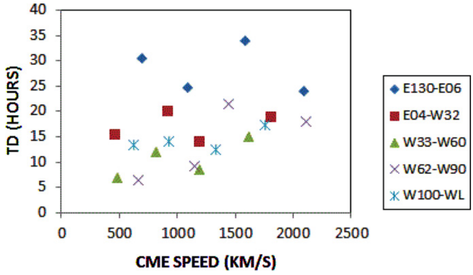
- TO–The onset time from CME launch to SEP onset;
- TR–The rise time from onset to half the peak intensity ($0.5I_p$);
- TD–The duration of the SEP intensity above $0.5I_p$.

Research interests

- Works of Kahler (2013):
  - The relationship between the EPACT/ Wind 20 MeV SEP events timescales and their associated CME speeds (V_{CME}) or widths (W_{CME}) observed by LASCO/SOHO.
- Our numerical simulations:
  - To compare with the conclusions of observation data analysis, we make numerical simulations with the same data.

Analysis methods of observation data

- Correlations of TD versus V_{CME}/ W_{CME}:



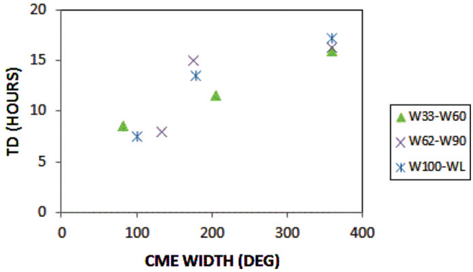


Figure: Methods of Kahler (2013)

- Divide 217 SEP-CME events into 5 solar-source longitude ranges;
- Arrange the events with V_{CME} ascending order;
- Divide the events evenly into 4 groups of about 11 events each;
- Pick up the median values as typical values;
- Obtain typical V_{CME} and SEP timescales typical values;
- Typical W_{CME} and SEP timescales typical values can get similarly.

Conclusions of observation data analysis

- Conclusions of Kahler (2013):
  - V_{CME} and W_{CME} are of significant correlation which renders interpretation of the timescale results uncertain;
  - TD increase with both V_{CME} and W_{CME};
  - Faster (and wider) CMEs drive shocks and accelerate SEPs over longer times to produce the longer TR and TD SEP timescales.

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):

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

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

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

Our Models: The diffusion coefficients

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

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

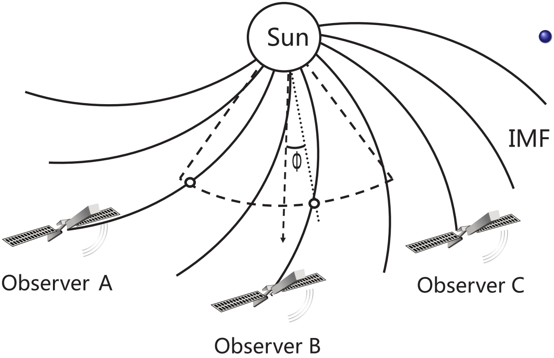
$$\lambda_{\parallel} = \frac{3v}{8} \int_{-1}^{+1} \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}} d\mu$$

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

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

Our Methods

- Simulating CME by our shock model :

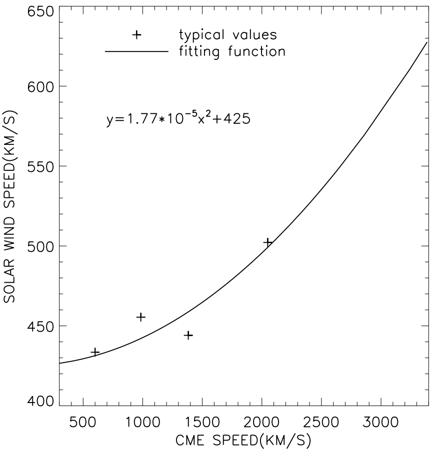


Wang et al. (2012)

- Assumptions:
  - $V_{Shock} = V_{CME}$;
  - $W_{Shock} = W_{CME} + 90°$, $(W_{CME} \leq 270°)$;
  - $W_{Shock} = 360°$, $(W_{CME} > 270°)$;
  - shock nose direction — source location;

Some parameters

- Solar wind speed:



- V_{SW} and V_{CME}: positive correlation
- Correlation of V_{SW} with V_{CME}:

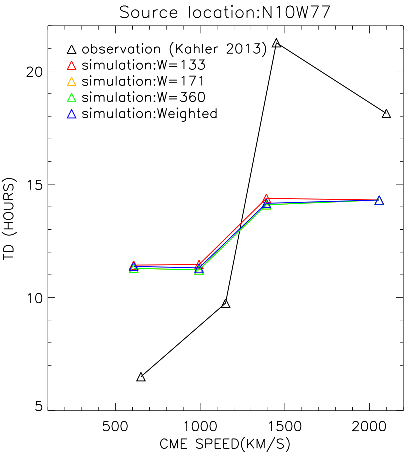
$$V_{SW} = 1.77 \times 10^{-5} {V_s}^2 + 425$$

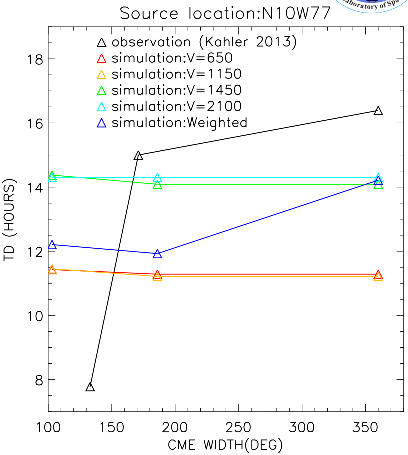
Some parameters

- Turbulence level:
  - Strong event arouse high speed shock, and make a high level of magnetic turbulence.
  - V_{SW} and V_{CME} are positive correlation.
  - Turbulence level can be reprsented by solar wind speed like this:

  $$\frac{\delta B}{B_0} = 0.001387 V_{sw} + 0.6124$$

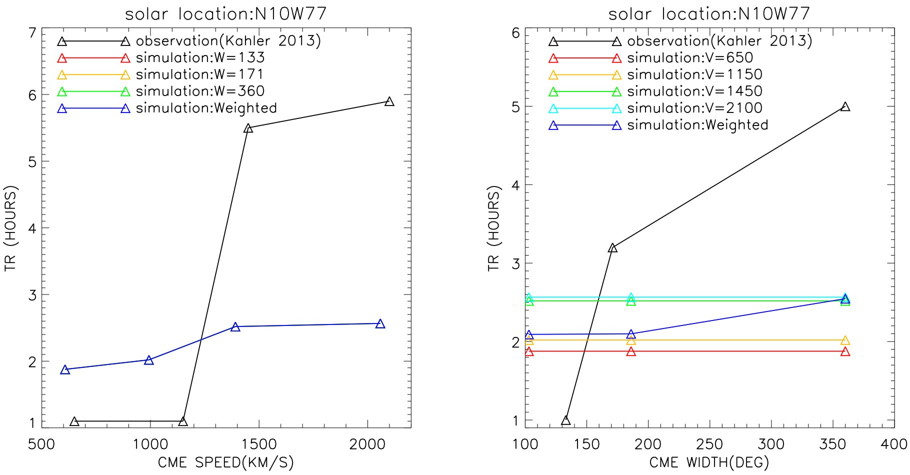
Comparision of simulation with observation



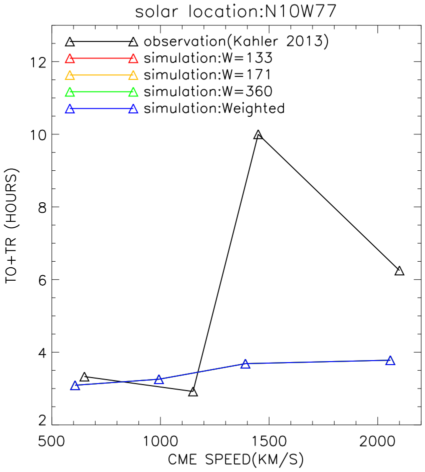


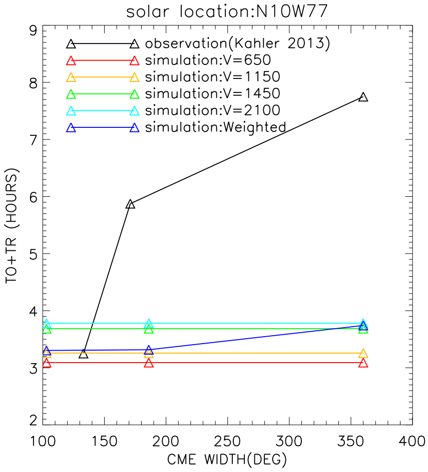
- When V_{CME} is fixed, TDs with different W_{CME}s are almost same;
- TD increase with V_{CME};
- TD is independent on W_{CME};
- TD is dependent directly on V_{CME}.

Comparision of simulation with observation

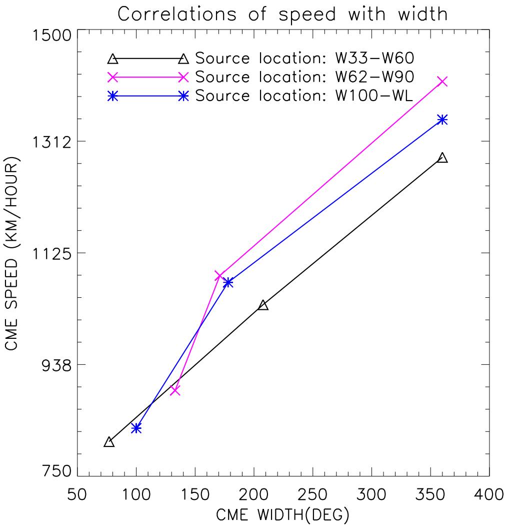


Comparision of simulation with observation





Correlations of V_{CME} with W_{CME}



- Source location cannot affect the correlation of V_{CME} and W_{CME};
- For one event, V_{CME} is larger, the probability of large W_{CME} is greater;
- The average W_{CME} of events with large V_{CME} is larger than that with little V_{CME}.

Conclusions

- Our simulations can fit conclusions of Kahler (2013):
  - TD increase with both V_{CME} and W_{CME};
  - V_{CME} and W_{CME} are of significant correlation.
- Our simulations can come to conclusions which analysis of observation data cannot:
  - TD is independent on W_{CME};
  - TD is dependent directly on V_{CME}.

Thank You!