Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks

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Outline

1. Overview
2. SEP Transport
3. SEP Acceleration
Overview of observations [Bryant et al. 1962]

[Graphs showing particle counts over time for different energy levels.]
<table>
<thead>
<tr>
<th>Solar energetic particles</th>
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- $^3$He enhanced, electron-rich, high ion Q
- Up to high E, dispersive onset
- At low E, non-dispersive peak
- (stochastic acceleration) (shock acceleration)
Solar energetic particles

- Impulsive flares
- CME shocks (gradual events)
- near Sun
- interplanetary

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Precision modeling $\rightarrow$ Transport $\rightarrow$ Injection

(stochastic acceleration) (shock acceleration)

\[
\frac{\partial F(t, \mu, z, p)}{\partial t} = -\frac{\partial}{\partial z} \mu v F(t, \mu, z, p) \quad \text{(streaming)}
\]

\[- \frac{\partial}{\partial z} \left(1 - \mu^2 \frac{v^2}{c^2}\right) v_{sw} \sec \psi F(t, \mu, z, p) \quad \text{(convection)}
\]

\[- \frac{\partial v}{\partial \mu} \frac{v}{2L(z)} \left[1 + \mu \frac{v_{sw}}{v} \sec \psi - \mu \frac{v_{sw} v}{c^2} \sec \psi \right] \cdot (1 - \mu^2) F(t, \mu, z, p) \quad \text{(focusing)}
\]

\[+ \frac{\partial}{\partial \mu} v_{sw} \left(\cos \psi \frac{d}{dt} \sec \psi\right) \mu (1 - \mu^2) \cdot F(t, \mu, z, p) \quad \text{(differential convection)}
\]

\[+ \frac{\partial \varphi(\mu)}{\partial \mu} \frac{\partial}{\partial \mu} F(t, \mu, z, p) \quad \text{(scattering)}
\]

\[+ \frac{\partial}{\partial p} p v_{sw} \left[\sec \psi \frac{d}{dt} (1 - \mu^2) + \cos \psi \frac{d}{dt} \sec \psi \mu^2 \right] \cdot F(t, \mu, z, p). \quad \text{(deceleration)}
\]
Simulation of interplanetary transport

- Specify magnetic field configuration
- Solve PDE
- Runs in a few minutes [Nutaro et al., Comp. Phys. Comm. ‘01]

Fitting SEP data

- Simultaneous fit to intensity vs. time
  anisotropy vs. time
- Optimal piecewise linear injection (least squares)
- Optimal scattering mean free path, \( \lambda \)

[DR, Khumlumlert, & Youngdee, JGR ‘98]
Easter 2001

- Ground Level Enhancement (GLE)
- Observed by neutron monitors (high statistics, precise directionality)
- We can accurately fit the intensity & anisotropy
- Precise timing results (will show shortly)

GLE of Bastille Day 2000: Initial Fit ...

- **intensity (ความหนาแน่นอนุภาค)**
  - เวลา vs. ความหนาแน่นอนุภาค

- **anisotropy (อัตราไหลออก – อัตราไหลเข้า)**
  - เวลา vs. อัตราไหลเข้า-ออก
Magnetic bottleneck in space
Thus we have convincing evidence for interplanetary magnetic mirroring of energetic particles.

Closed magnetic loop?

Help! We’ve been swallowed by a magnetic cloud!
Oct. 28, 2003

- Solar neutrons: from interacting SEP
- Mysterious fast peak
- Slow decay implies loop geometry
- Timing of main peak of escaping SEP: onset at soft X-ray maximum (like Easter 2001)

[Bieber et al., sub. to GRL]
## Comparison with EM timing

<table>
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<tr>
<th>EMISSION</th>
<th>APR. 15, 2001</th>
<th>OCT. 28, 2003</th>
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<tr>
<td></td>
<td>START</td>
<td>PEAK</td>
</tr>
<tr>
<td>Type III radio burst</td>
<td>13:36</td>
<td>13:38</td>
</tr>
<tr>
<td>CME liftoff*</td>
<td>13:24-31</td>
<td></td>
</tr>
<tr>
<td>Type II radio burst</td>
<td>13:40</td>
<td>13:47</td>
</tr>
<tr>
<td>Type IV radio burst</td>
<td>13:44</td>
<td>14:57</td>
</tr>
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* Linear - quadratic fits  ** Sudden onset of intense emission

All times are “Solar Time” or UT minus 8 min. for EM emissions
How accurate is the injection timing derived from linear fits to onsets?

\[ t_{\text{onset}} = \frac{\text{path}}{v} + t_0 \]

[Sáiz, Evenson, & DR, in preparation]
There is some spread in the injection start times and pathlengths derived from straight-line fits, depending on the mean free path and duration of injection:

- Injection timing: several minutes
- Pathlength: ~ 50 %
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Difficult to separate acceleration & transport
Saturation, composition changes [Ng et al. ’99]
Seed population, local accelerated spectrum (stochastic acceleration)
Transport parallel or perpendicular to the mean magnetic field

Turbulent magnetic field deviates from mean field

field line random walk

Δx vs. z
Perpendicular transport: Recent ideas

- Dynamical turbulence [Bieber & Matthaeus 1997]
- MC simulations [Giacalone & Jokipii 1999]
- Second diffusion: Nonlinear guiding center theory [Qin et al. 2003]
- Trapping by topology of turbulence [DR, Matthaeus, & Chuychai 2003]
“halo” of low SEP density over wide lateral region

“core” of SEP with dropouts

[DR, Matthaeus, & Chuychai 2003]
Acceleration of particles by shocks
Following collision with a scattering center: lose energy
Head-on collision with a scattering center: gain energy
Since $u_1 > u_2$ there is a net gain in energy
Solar wind & IP shock abundances

Mass/Charge (AMU e⁻¹)

Upstream & IP shock abundances

Mass/Charge (AMU e⁻¹)

Spectra and abundances for Sep. 7 2002 IP shock

Why do the spectra roll over at ~ 0.1 - 10 MeV/n?
(data - see also: Gosling et al. 1981; van Nes et al. 1985)

Possible mechanisms suggested by Ellison & Ramaty (1985)

- shock thickness $\sim \kappa/u \rightarrow$ energy is too low
- drift over shock width $\rightarrow$ rollover at $\sim 100$ MeV/Q
- finite time for shock acceleration $\rightarrow$ considered here

(see also: Klecker et al. 1981; Lee 1983)
Finite-Time Shock Acceleration

- Probability approach (like Bell 1978, Drury 1983)
- Acceleration rate, \( r = \frac{1}{t_{\text{acc}}} \)
- Escape rate, \( \varepsilon \)
- Time at present (age of shock), \( t \)
- No. of acceleration events, \( n \)
- \( r, \varepsilon \) constant w/ energy - combinatorial model
- \( r, \varepsilon \) varying - ODE (analytic, numerical)
- Acceleration at interplanetary shocks
Rollover energy \((E_c / A)\) 
(well above injection energy)

\[ \lambda = \text{const.} \]
\[ E_c / A \propto t^2, \text{ independent of } Q/A \]

\[ \lambda \propto P^\alpha \]
\[ E_c / A \propto t^{2/(\alpha+1)} \left( Q/A \right)^{2\alpha/(\alpha+1)} \]
We welcome foreign students!