Particle Acceleration in Solar Flares

Types of Solar Flares

**Impulsive flares**
- Short duration
- Type III radio emission
- Ion abundance enhancements
- Acceleration: ?

**Gradual flares**
- Long duration
- Type II radio emission
- Coronal ion abundances
- 96% association with CMEs
- IP shock
- Acceleration: shock

(work by Reames et al.)
...More or Less

- Large flares can sometimes occur with a CME

(Flare and Coronal Mass Ejection 23 July 2002)

(Emslie et al. 2004)

Impulsive Flare Geometry

(Yohkoh SXR image)
HE-Photon and Particle Spectra

(Murphy et al. 1997)

Current Missions

- Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)
  - Imaging germanium spectrometer
- Advanced Composition Explorer (ACE)
  - Interplanetary (SEP) ion distributions
- Transition Region and Coronal Explorer (TRACE)
- Solar and Heliospheric Observatory (SOHO)
- Wind
- Ground-based stuff (radio, Hα, …)

(Mason et al. 1999)
Basic Observations

Ions (large flare)
- $10^{35}$ p s$^{-1} > 1$ MeV
- for $\sim 100$ s
- 1 GeV maximum
- $3 \times 10^{31}$ ergs > 1 MeV/n
- Energy equipartition
- Simultaneous with electrons
- Acceleration from thermal distribution
- Abundance enhancements
- Replenishment

Electrons (large flare)
- $10^{37}$ e s$^{-1} > 20$ keV
- for $\sim 100$ s
- 100 MeV maximum
- $3 \times 10^{31}$ ergs > 20 keV
- Energy equipartition
- Simultaneous with ions
- Acceleration from thermal distribution
- Replenishment

(work by Ramaty et al., Share et al.)

(work by Emslie, Dennis, Lin, SMM/GRO Group, e.g.)

Abundance Enhancements

<table>
<thead>
<tr>
<th>Ion</th>
<th>Ambient Abundance Relative to H</th>
<th>Mass Number A</th>
<th>Charge-to-mass Ratio Q/A</th>
<th>Observed Enhancement in SEPs Relative to Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$^3$He</td>
<td>$\approx 5 \times 10^{-4}$</td>
<td>3</td>
<td>0.67</td>
<td>$\approx 2000$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>0.036</td>
<td>4</td>
<td>0.5</td>
<td>normal</td>
</tr>
<tr>
<td>C</td>
<td>$2.96 \times 10^{-4}$</td>
<td>12</td>
<td>0.5</td>
<td>normal</td>
</tr>
<tr>
<td>N</td>
<td>$7.90 \times 10^{-5}$</td>
<td>14</td>
<td>0.5</td>
<td>normal</td>
</tr>
<tr>
<td>O</td>
<td>$6.37 \times 10^{-4}$</td>
<td>16</td>
<td>0.5</td>
<td>normal</td>
</tr>
<tr>
<td>Ne</td>
<td>$9.68 \times 10^{-5}$</td>
<td>20</td>
<td>0.40</td>
<td>$\approx 3$</td>
</tr>
<tr>
<td>Mg</td>
<td>$1.25 \times 10^{-4}$</td>
<td>24</td>
<td>0.42</td>
<td>$\approx 3$</td>
</tr>
<tr>
<td>Si</td>
<td>$9.68 \times 10^{-5}$</td>
<td>28</td>
<td>0.43</td>
<td>$\approx 3$</td>
</tr>
<tr>
<td>Fe</td>
<td>$8.54 \times 10^{-5}$</td>
<td>56</td>
<td>0.23</td>
<td>$\approx 10$</td>
</tr>
<tr>
<td>Kr</td>
<td>$1.41 \times 10^{-8}$ (mean)</td>
<td>85 (mean)</td>
<td>0.13</td>
<td>$\approx 100$</td>
</tr>
<tr>
<td>Xe</td>
<td>$8.66 \times 10^{-10}$ (mean)</td>
<td>128 (mean)</td>
<td>0.11</td>
<td>$\approx 1000$</td>
</tr>
</tbody>
</table>

(work by Reames et al.)
1. Sub-Dreicer Electric Fields

- Uses: Long ($\sim 10^9$ cm) weak ($< 10^{-4}$ V cm$^{-1}$) fields
- Geometry: B-field aligned (or anti-aligned) in the loop
- Mechanism: Runaway acceleration (Dreicer 1960; Knoepfel & Spong 1979)
- Conclusion: Worthless (can’t account for anything except maybe low-energy electrons)

2. Super-Dreicer Electric Fields

- Uses: Long ($\sim 10^9$ cm) strong ($>> 1$ V cm$^{-1}$) fields
- Geometry: Large (thin!… aspect ratio $10^7$) current sheet above and normal to an arcade of loops
- Mechanism: Direct acceleration with drift escape
- Conclusion: No good (can’t do ions, high-energy electrons, abundance enhancements)
3. Shocks

- The mechanism for gradual events; prime importance at astrophysical sites
- Uses: Large-scale (Ellison & Ramaty 1985) or an ensemble of smaller shocks (Anastasiadis & Vlahos 1991)
- Geometry: In or around the loop(s)
- Mechanism: Diffusive, shock drift, KOLSDBSCEMS (Roth 2005, Chandran 2004)
- Conclusion: Last one is promising (stay tuned), forget the others

4a. Stochastic Acceleration: Fermi

- Uses: Large-amplitude ($\delta B/B \approx 1$) plasma waves, or magnetic “blobs”
- Geometry: Waves distributed throughout the loop(s), on both open and closed field lines.
- Mechanism: Adiabatic collisions with moving scattering centers (Fermi 1949; Davis 1956; Parker & Tidman 1958)
- Conclusion: Had its run, but no good (self-consistent model not possible)
4b. Stochastic Acceleration: Resonant

- Uses: low-amplitude ($\delta B / B \ll 1$) plasma waves
- Geometry: Waves distributed throughout the loop, on both open and closed field lines
- Mechanism: Resonance with either the transverse wave E-field (cyclotron) or the parallel B-field (Landau or Cherenkov)
- Conclusion: This is the one, in the proper model
Resonant Stochastic Acceleration

- General property of near-integrable Hamiltonian systems
- *Destruction of the last KAM surface between primary period-1 and period-2 island chains*
- In practice: *Overlap of primary period-1 islands*
  - Chirikov (1979)
  - Very conservative condition

An Example: Fast Mode Waves

\[ \vec{A}_0 = -yB_0 \hat{x} \]
\[ \vec{A}_w = \sum_{i=1}^{N} \hat{y} \frac{cE_i}{\omega_i} \sin(k_{\perp i}x + k_{\parallel i}z - \omega_i t) \]

Particle Motion \[ H = \left[ \left( \frac{p - q \vec{A}}{c} \right)^2 + m^2 c^4 \right]^{1/2} \]
Equation of Motion

- Guiding-Center/Action-Angle transformation
- expansion of H
- expansion of the forcing function
- keeping only the l=0 resonance (i.e.,
  transit-time acceleration) ⇒

\[
\begin{align*}
\dot{p}_z &= \frac{mc^2}{\gamma} \left( \frac{p_\perp}{mc} \right) \sum_{i=1}^{N} \varepsilon_i k_{\perp i} J_0(k_{\perp i} \rho) \cos(k_{\perp i} z - \omega_i t) \\
\dot{z} &= \frac{p_z}{m\gamma}
\end{align*}
\]

Transition to Global Stochasticity

Equations of Motion

\[
\begin{align*}
\hat{x}_{m+1} &= \hat{x}_m + \hat{v}_m \pmod{i} \\
\hat{v}_{m+1} &= \hat{v}_m + 2\pi \varepsilon^2 \sin(2\pi \hat{x}_{m+1})
\end{align*}
\]

- Regular motion, except near separatrices
- Stochastic regions isolated by KAM surfaces
- No net energy gain
Transition to Global Stochasticity

- Stochastic layers grow and thicken
- KAM surfaces still separate primary period-1 island chains
- particles are confined to the vicinity of an island chain
- No net energy gain

Transition to Global Stochasticity

- KAM surfaces are destroyed between primary period-1 island chains
- Secondary islands being emitted during bifurcation
- Particles sample most of phase space
- Can use Fokker-Planck theory now
Yes!

- Note the regions of regular trajectories separated from the stochastic regions by KAM surfaces
- Initial location of the particles = □

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**Does it Exist in Flares?**

- Absolutely!
- Required for \(^3\)He enhancements
- Need waves around \(\Omega_3\) (Fisk 1978)

Electron-beam model (Temerin & Roth 1992; Miller & Vinas 1993)

Electron-firehose model (Benz & Paesold 2002)
Cascading Turbulence Model

1. Alfvén and fast mode waves generated at large scales (assumption)
2. Cascade to higher wavenumbers (e.g., Zhou & Matthaeus 1989)
3. Fast mode waves energize electrons via transit-time acceleration (e.g., Miller 1997)
4. Alfvén waves energize ions via gyroresonant acceleration (e.g., Miller & Roberts 1995)
   - Both species accelerated by MHD turbulence in a 2-parameter model

Stochastic Acceleration Successes

- Accounts for the bulk observations of electron and ion acceleration
- Naturally yields replenishment of the acceleration region
- Naturally yields equipartition between electrons and ions
- Has significant predictive capability
- subMeV/nucleon ions (to be verified)
- Different locations for ion and electron acceleration (predicted and verified...)
Prediction: Different locations for Gamma-Ray and HXR emission

![Graph showing proton and electron rates](image)

(Miller 1998; Emslie, Miller, & Brown 2004)

Verification: 2002 July 23 Flare et al.

⇒ Ion acceleration occurs on longer (and/or different) loops
SEP Distributions

- 2-parameter fit (191 erg cm\(^{-3}\) s\(^{-1}\) at 10\(^8\) cm)
- Relative normalization is from the simulation!
- Typical energy-integrated abundances are produced for a range of parameter values

(Mason et al. 2003)

Summary

- Traditional resonant stochastic acceleration very successful for solar flares
  - Most successful (cascading-turbulence) model has only 2 parameters
  - Has been merged with a hydrodynamic code for atmospheric evolution
- Narrow EM shocks need to be considered
- Other forms of stochastic acceleration (Arnold diffusion, “surfatron”) also may have limited applicability
  - Very interesting nonlinear dynamics anyway