Modeling Large-scale Electron Acceleration and Transport Associated with Magnetic Reconnection

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Outline

1. Introduction to the macroscopic energetic-particle model
2. Two applications
3. Conclusions
Rich observations of flare-accelerated electrons and associated emissions

- EOVSA, RHESSI, Solar Orbiter/STIX, PSP, and many others
- Accurate flare geometry, magnetic profile, nonthermal emissions, and nonthermal electron distributions.
Challenges and opportunities for modeling

The scale separation is enormous in solar flares.
- Acceleration and transport occur at global scales.
- A large number of particles are accelerated.
- The flare geometry and dynamics are complex.
- Kinetic physics is essential for electron scattering and transport.
- Reconnection is complicated, especially in 3D.
A framework to bridge simulations and observations (modeling-centric)

- **MHD simulations**
  - Flare geometry
  - $B$-field
  - Plasma flows

- **Transport theories**
  - Acceleration terms
  - Diffusion coefficients

- **Kinetic simulations**
  - Acceleration mechanisms
  - Turbulence properties
  - Scattering mechanisms

- **Macroscopic energetic-particle model**
  - Spatially and temporally dependent energetic particle distributions

- **Emission observations**
  - HXR and microwave emissions

- **Emission modeling**
  - HXR and microwave emission maps for different perspectives

- **In-situ observations**
  - Solar energetic particle events
MHD simulations provide plasma flows and $B$-field.

- The model-generated nonthermal electron distributions will be compared with those derived from nonthermal emissions.
The macroscopic model

\[
\frac{\partial f}{\partial t} = - (U_i + V_{d,i}) \frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \kappa_{ij} \frac{\partial f}{\partial x_j} \right] + \frac{p}{3} \frac{\partial U_i}{\partial x_i} \frac{\partial f}{\partial p} + \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial f}{\partial p} \right) + Q + \ldots
\]

- Assumptions (supported by kinetic simulations)
  - \( f \) is nearly isotropic due to pitch-angle scattering by reconnection-driven turbulence (e.g., Dahlin et al. 17, Li et al. 19)
  - 1st-order acceleration due to flow compression \( \leftrightarrow \) acceleration associated with drift motions (e.g., le Roux et al. 15, Li et al. 18).
- \( \kappa_{ij} \) and \( D_{pp} \) are calculated using quasi-linear theory for now.
Application 1: a local reconnection layer

- The electron spectra are similar to $k_{\text{global}}$ model with feedback (Arnold et al. 21, PRL).

Spatially and temporally dependent maps of energetic electrons (Li et al. 18).
The spectra are roughly consistent with the observations.
Application 2: case 1 (maps of energetic electrons)

- High-energy electrons can fill the flare reconnection region.
- High-energy electron flux peaks at the looptop region.
Application 2: case 2 (with plasmoid)

- The spectra are also consistent with the observations.
Application 2: case 2 (maps of energetic electrons)

- High-energy electron flux peaks when two islands merge.
Conclusions

• We solved a macroscopic model with background MHD simulations of solar flares. We showed that electrons are accelerated to hundreds of keV and develop nonthermal power-law distributions, both of which are consistent with the observations.

• Reconnection exhaust, magnetic islands, and flare looptop regions are all possible electron acceleration sites. The island mergers are highly efficient in accelerating electrons due to strong compression.

• To explain some of the observations, additional acceleration mechanisms (stochastic acceleration and termination shocks) might be required.