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

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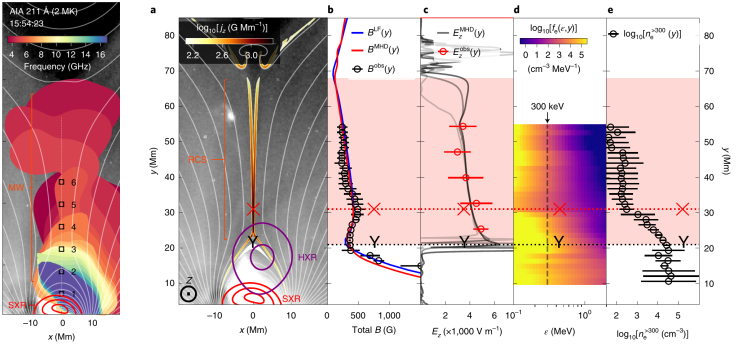
Outline

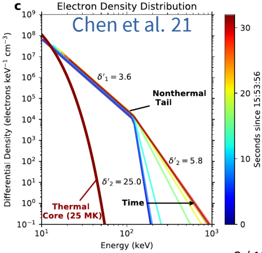
1. Introduction to the macroscopic energetic-particle model
2. Two applications
3. Conclusions

Rich observations of flare-accelerated electrons and associated emissions



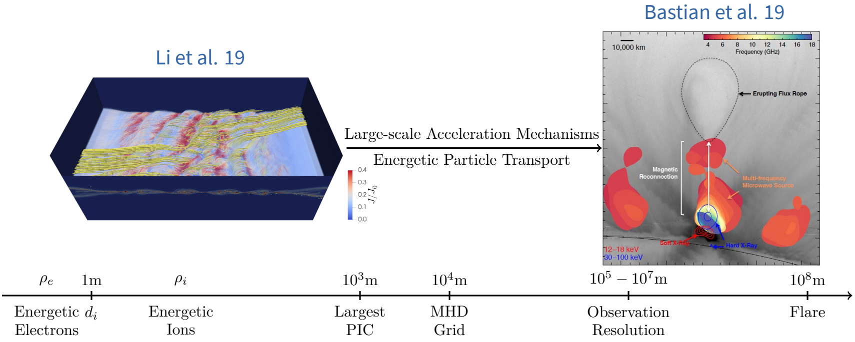
Chen et al. 20, Nature Astronomy

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



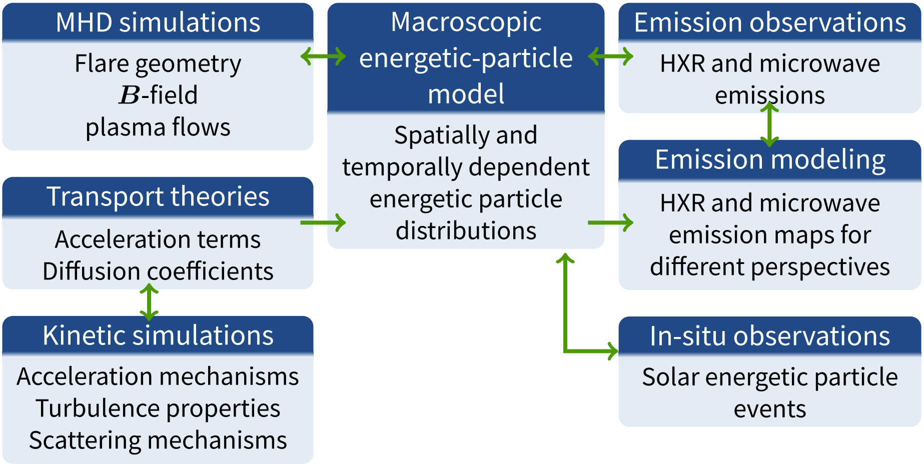
Chen et al. 21

Challenges and opportunties 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)



Rest of this talk

MHD simulations

Flare geometry
$\boldsymbol{B}$-field
plasma flows

→

Macroscopic energetic-particle model

Spatially and temporally dependent energetic particle distributions

↔

Emission observations

HXR and microwave emissions

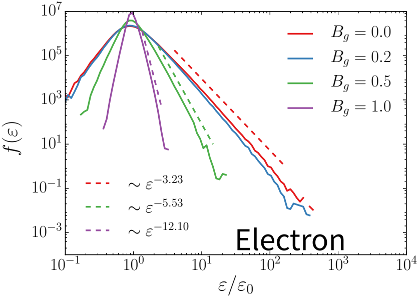
- MHD simulations provide plasma flows and B-field.
- The model-generated nonthermal electron distributions will be compared with those derived from nonthermal emissions.

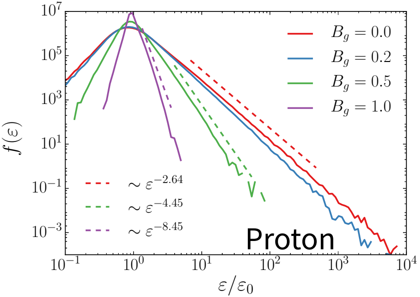
The macroscopic model

$$
\begin{aligned}
\frac{\partial f}{\partial t} = & -(U_i + V_{d,i})\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] && \text{spatial transport} \\
& + \frac{p}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) && \text{acceleration} \\
& + Q && \text{source term} \\
& + \ldots
\end{aligned}
$$

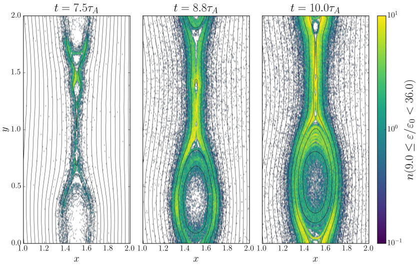
- Assumptions (supported by kinetic simulations)
  - f is nearly isotropic due to pitch-angle scattering by reconnection-driven turbulence (e.g., Dahlin et al. 17, Li et al. 19)
  - 1st-order acceleration due to flow compression ⇔ acceleration associated with drift motions (e.g., le Roux et al. 15, Li et al. 18).
- κ_{ij} and D_{pp} are calculated using quasi-linear theory for now.
- Solved using stochastic integration: `https://git.io/fxQY1`.

Application 1: a local reconnection layer



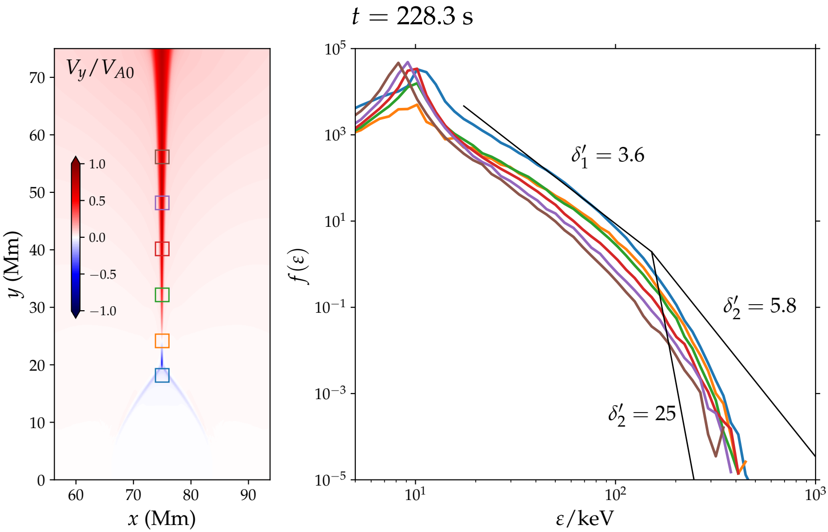


- The electron spectra are similar to `kglobal` model with feedback (Arnold et al. 21, PRL).



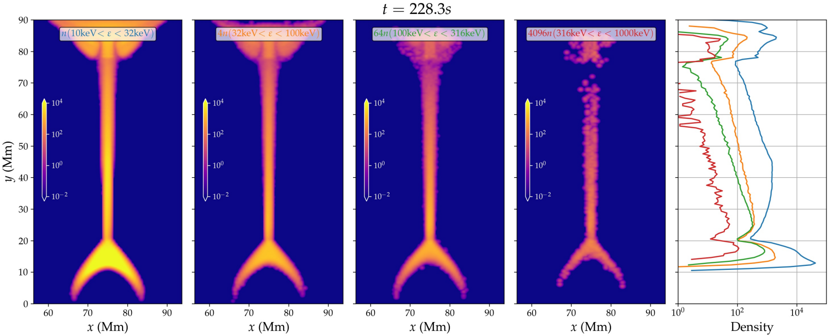
Spatially and temporally dependent maps of energetic electrons (Li et al. 18).

Application 2: Sep. 10th 2017 flare (early impulsive phase), case 1 (no plasmoid)



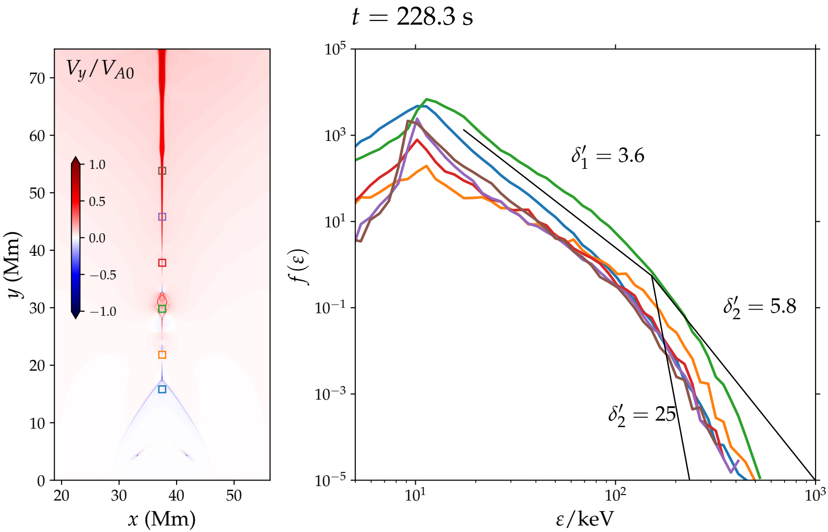
- The spectra are roughly consistent with the observations.

Application 2: case 1 (maps of energetic electrons)



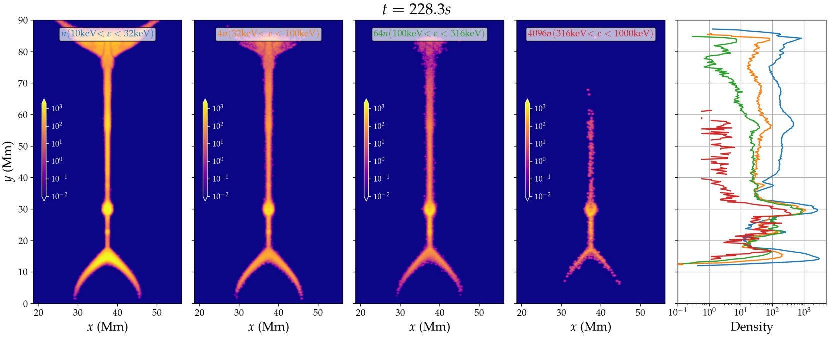
- High-energy elections can fill the flare reconnection region.
- High-energy electron flux peaks at the looptop region.

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.