Scattering and transport of energetic electrons in solar flares

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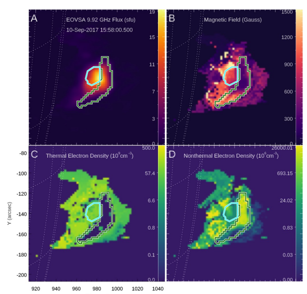
Overview

The role of whistler waves in scattering energetic electrons as they undergo acceleration during magnetic energy release in solar flares is explored with particle-in-cell (PIC) simulations and in the development of a transport model. Energetic electrons accelerated in flares reach relativistic velocities. The transit time of these energetic electrons across the energy release region in flares (< 0.1s) is much shorter than the energy gain time of these electrons (~10s). This disparity in time scales is associated with the fact that the Alfvén speed in the corona is much smaller than the velocity of light. Strong pitch-angle scattering can potentially lead to self-confinement of energetic electrons undergoing acceleration.

Flare observations related to transport

- The decay time of hard X-ray emission from flares exceeds the transit time of energetic electrons across the source by two orders of magnitude (Masuda et al. 1994; Krucker et al. 2007, 2010).
- RHESSI spacecraft observations suggest that the electron energy flux in the source regions of flares can exceed that measured at the chromosphere by up to an order of magnitude (Simões et al. 2013).
- EOVSA observations suggest that non-thermal electrons accelerate and self-confine in localized regions in the corona (Fleishman et al. 2021)



Whistler wave basics

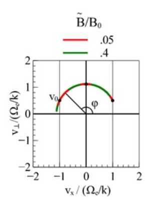
- Whistlers are dispersive waves that rotate in the electron direction around the ambient magnetic field

$$\omega = \frac{k_{\|} k d_e^2}{1 + k^2 d_e^2}\Omega_e$$

- Phase speed peaks around the electron Alfven speed V_{Ae} for $kd_e \sim 1$ with d_e the electron skin depth.
- Oblique propagation introduces resonances at multiple harmonics of the electron cyclotron frequency

$$\omega - k_{\|} v_{\|} - n\Omega_e = 0$$

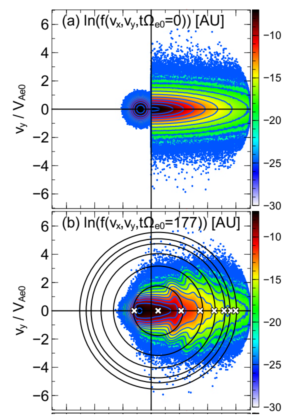
- For large amplitude waves the resonances overlap, causing electron pitch angle scattering



$$L_0 \sim \frac{V_0}{v_w} \sim \frac{V_{Ae}}{V_0} L << L$$

Whistler heat flux instability

- Whistlers scatter electrons in pitch angle in the whistler wave frame
  - The electron energy in the plasma frame is reduced, driving whistlers unstable
- PIC simulation with an anisotropic κ distribution drives oblique whistlers
  - Relevant for energetic electrons – powerlaw distribution
  - Energetic electrons also scattered through the n=1,0,-1,-2,-3, … resonances



Transport equations for energetic electrons in flares – Basic assumptions

- The scattering mean-free-path of electrons by whistlers is short compared with gradient scale lengths of energetic electrons

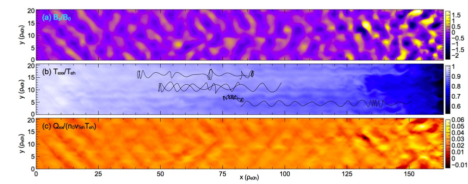
  ⇒ Pitch angle anisotropy of electrons is weak
- Describe whistler scattering by a pitch angle scattering operator in the whistler wave frame
  - Assume that the whistlers can scatter electrons over the full range of pitch angles

  ⇒ To be tested with PIC simulations
- The whistler phase speed V_{Ae} is small compared with the characteristic velocity V_0 of energetic electrons

  ⇒ enables an order-by-order expansion of the electron distribution function

Challenges with modeling electron scattering in flares

- PIC simulations on energetic electron scattering to date have been based on transient systems with specified initial κ distributions
  - Solution – carry out simulations with energetic electrons injected from boundaries and run to steady state (Roberg-Clark+ 2018)



- PIC simulations are limited to unrealistically small systems with the result that the energy fluxes of the energetic electrons that drive whistlers are too large and produce unrealistically strong whistlers
  - Solution – develop a set of transport equations that parallel those used in describing cosmic ray transport (Kulsrud & Pearce 1969, Zweibel 2013)

Overview of transport equations

- A complete set of coupled transport for energetic electrons limited by self-driven whistler waves has been developed.
  - Whistlers are driven unstable by the energy flux of energetic electrons
  - The scattering rate ν_w of electrons is calculated self-consistently by balancing whistler drive with collisionless damping.
  - The resulting electron mean-free-path L_0 is short compared with the gradient scale length L of the energetic electrons

$$L_0 \sim \frac{V_0}{v_w} \sim \frac{V_{Ae}}{V_0} L << L$$

  with V_0 the characteristic velocity of energetic electrons associated with their energy $W = mV_0^2/2$
  - Because of the short mean-free-path, electrons remain nearly omni-directional