Spectral Single and Double Power-law Formation by Sequential Particle Acceleration in Flux Ropes

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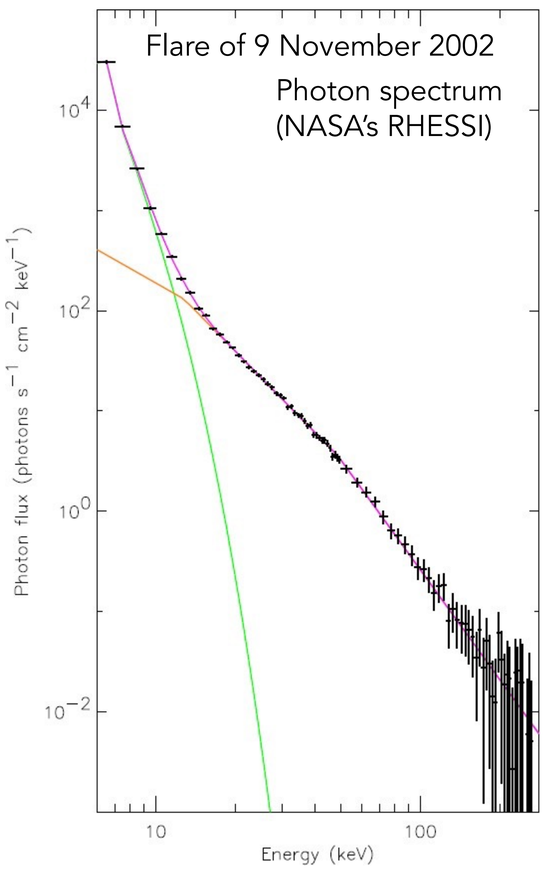
Abstract: Spectral single and double power laws are common in high-energy phenomena such as solar flares and solar energetic particles, including ground level enhancement events. It is not clear what physical processes determine the energy breaks and spectral indexes of these power laws. Here, we describe a first-principles model of pitch-angle and energy distribution-function evolution, which produces power laws and provides a physical interpretation for such spectral features (Guidoni et al. 2022, ApJ). In this model, a prescribed fraction of particles sequentially "hops" between shrinking flux ropes (accelerators) formed by flare reconnection. Each accelerator increases particle energies by a modest amount, but particles must visit only a few accelerators to increase their energies by orders of magnitude. The energy gain in each accelerator is derived using data from global magnetohydrodynamic simulations of an eruptive flare/coronal mass ejection as ambient conditions for the evolving particle distributions. We also describe our fully analytic method for forming and interpreting power laws, which requires only two constrained physical parameters of the acceleration region and is independent of the acceleration model, as well as preliminary results extending the analytical model to the formation of double power laws.

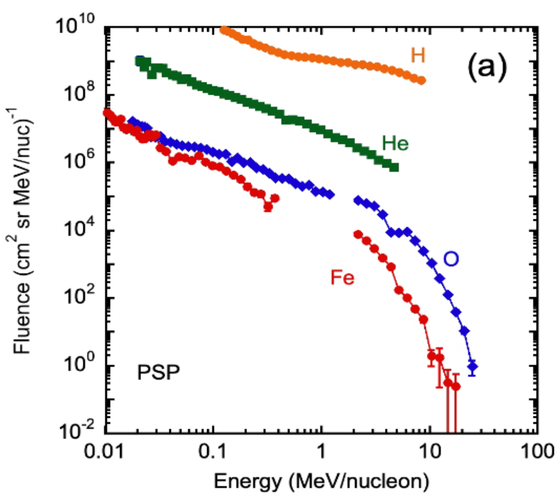
Motivation: Explain High-Energy Observations, e.g., X-ray Flare Spectra, Solar Energetic Particles (SEPs)

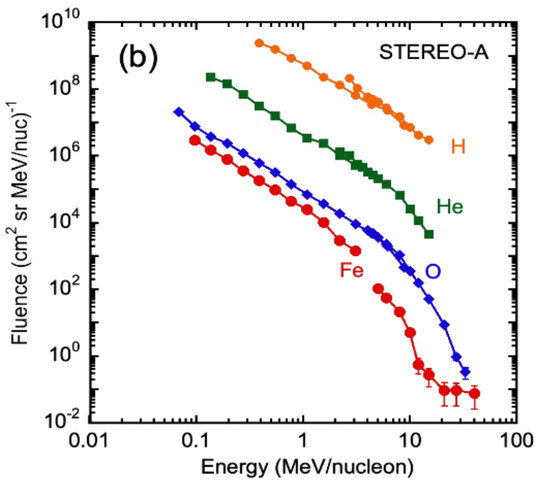


Benz, *Living Reviews in Solar Physics* (2008)

Electrons that produce the above photon distributions have single or double power law distributions

SEP observations (fluence spectra), 29 November 2020

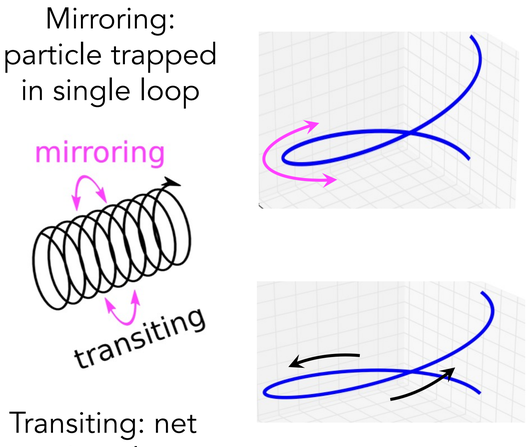




Mason et al., Astronomy & Astrophysics 2021

Particle Trajectories (gyromotion not shown)

Mirroring: particle trapped in single loop



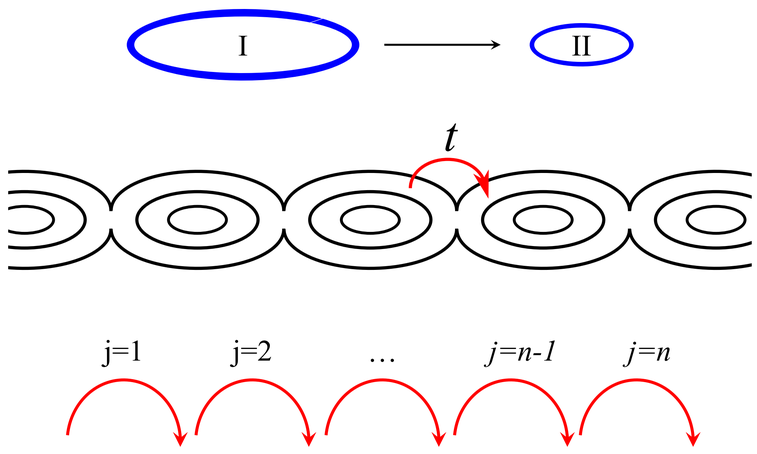
Transiting: net motion along axis of flux rope

r : average energy increase by each accelerator

t : average percentage of particles jumping between accelerators

n : average number of visited accelerators

Acceleration Region's Physical Parameters



Particle Adiabatic Invariants:

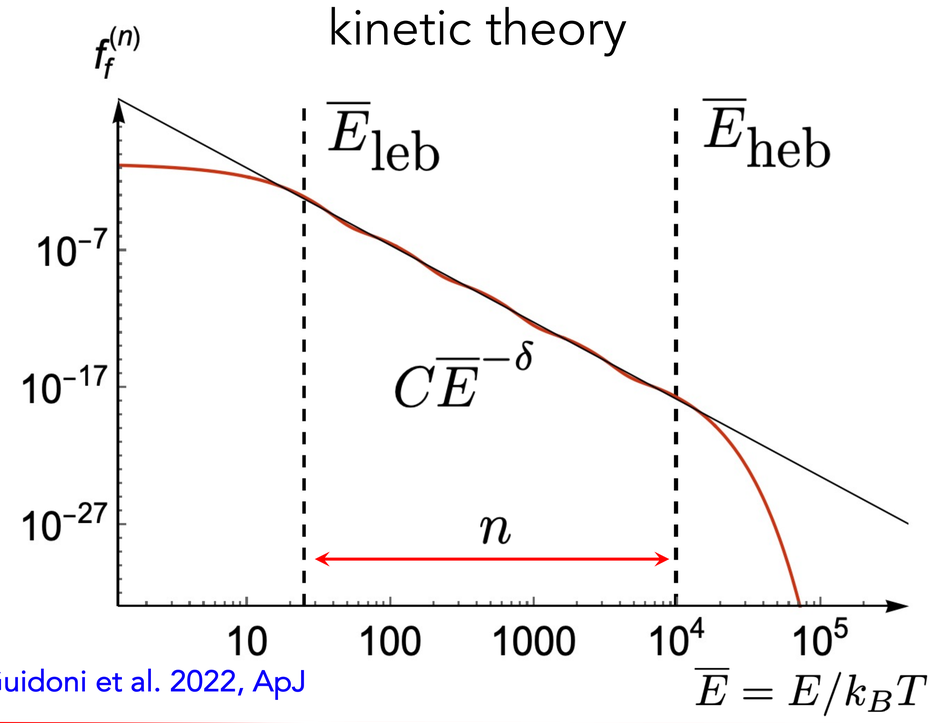
Magnetic moment $\longrightarrow \mu = \dfrac{v_\perp^2}{B}$

Parallel action $\longrightarrow J = \oint v_{||} ds$

$$E^2 = v_\perp^2 + v_{||}^2$$

Extract $\vec{B}$ from simulation (or observation) of flux ropes

We developed a first-principles, analytical model of single power-law formation that combines MHD and kinetic theory



Guidoni et al. 2022, ApJ

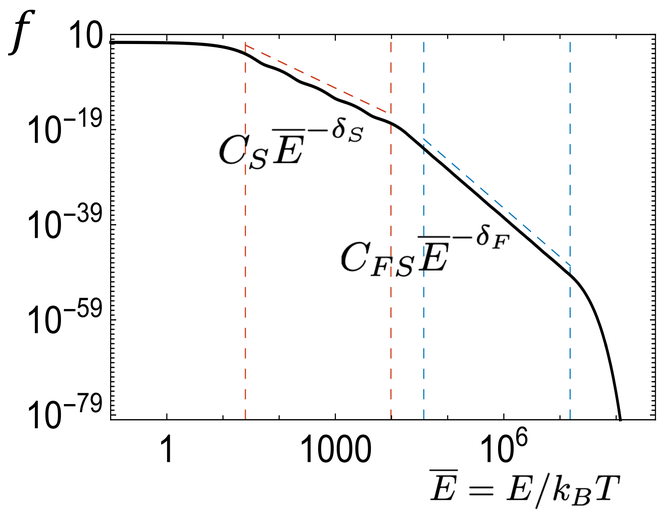
Simple analytical expressions of observables as function of physical parameters of the acceleration region:

- $\delta = 1 - (\log t / \log r)$
- $E_{\mathrm{leb}} = (\alpha + \delta) r$
- $E_{\mathrm{heb}} = (\alpha + \delta) r^n$

$\alpha \in (0,0.5)$: choose your acceleration mechanism

Analytical Model Easily Generalized to Double Power Laws

Guidoni et al., in preparation



Energy-pitch Angle Evolution