
2005 Galactic Center Conference, KITP
Particle Acceleration in Solar Flares
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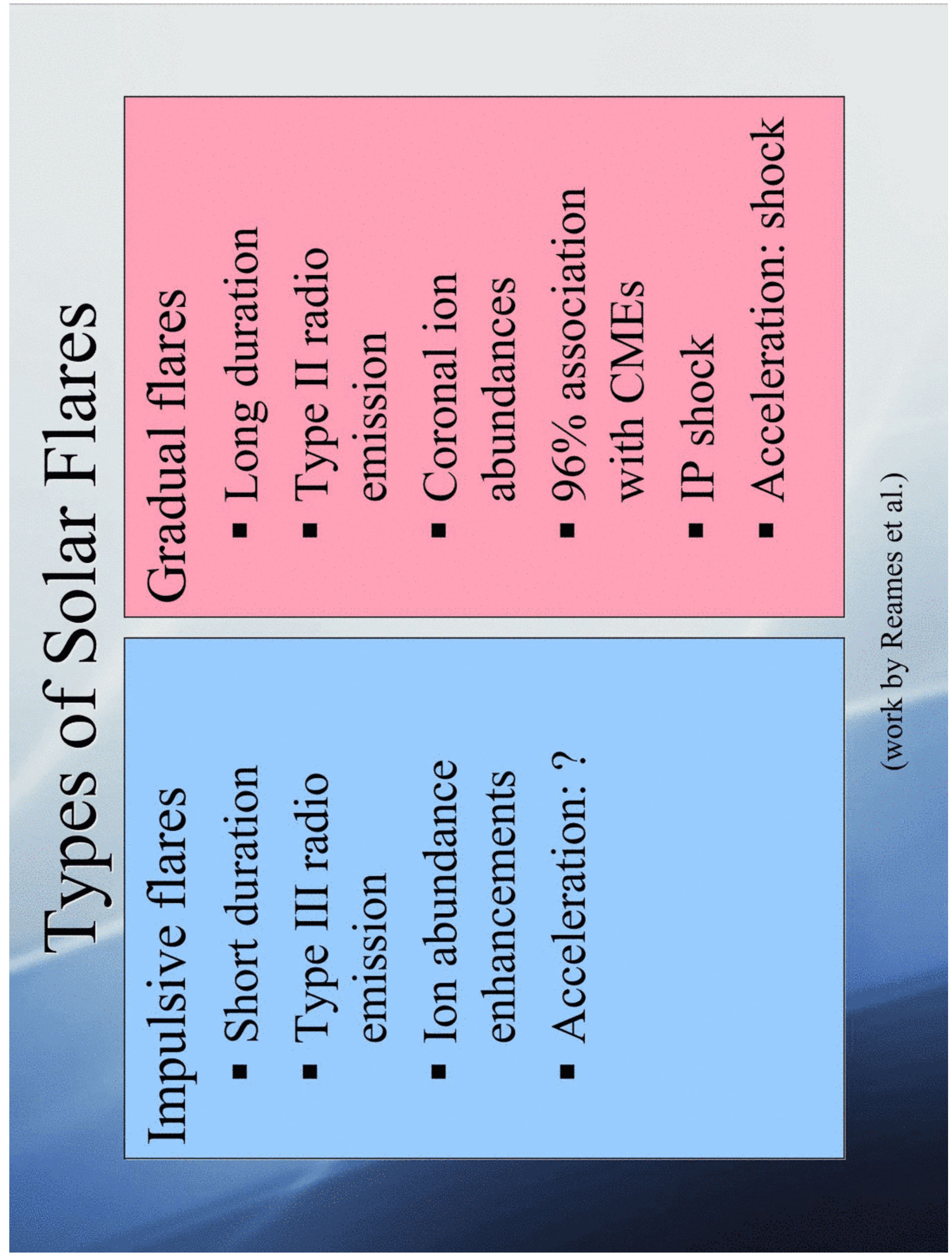
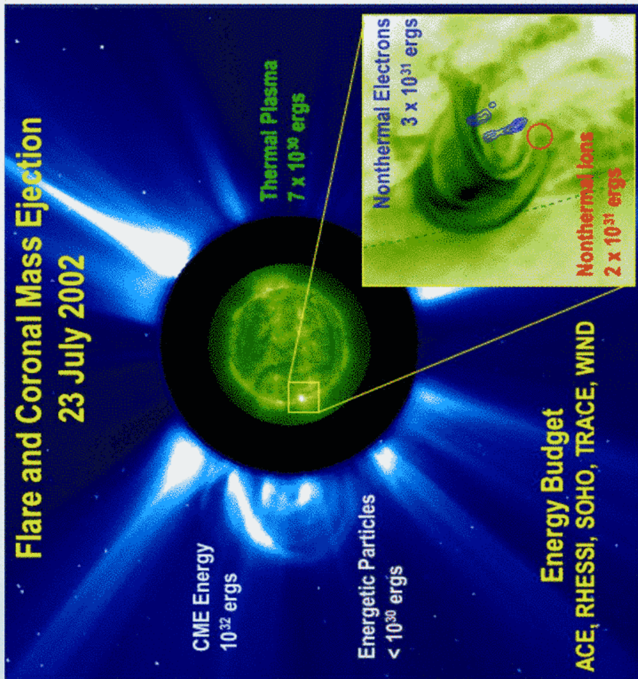
UAH


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.)

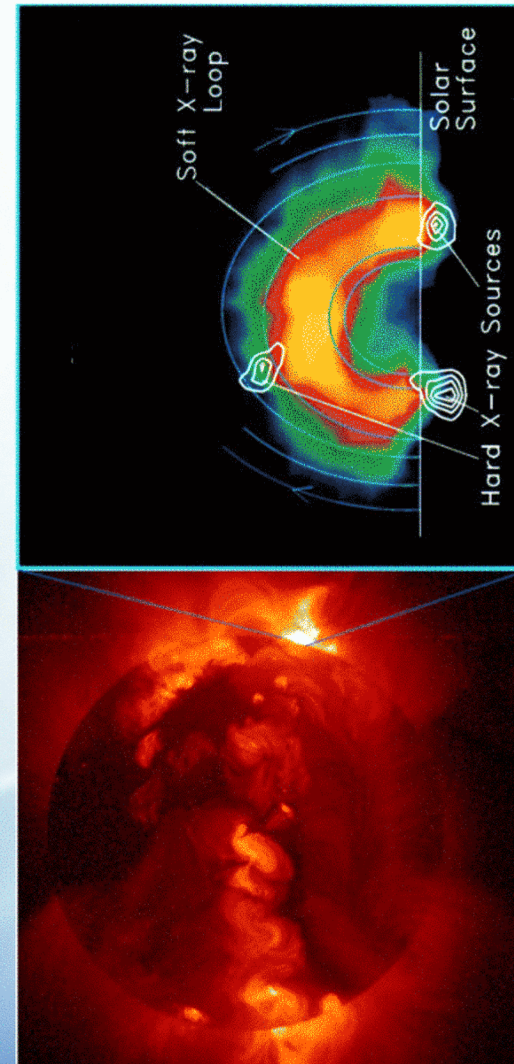
…More or Less

- Large flares can sometimes occur with a CME



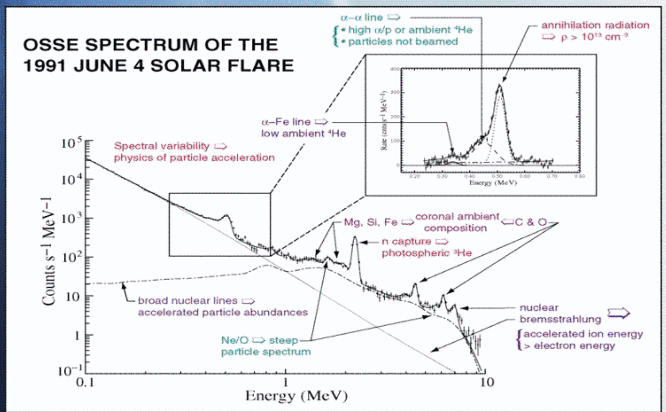
(Emslie et al. 2004)

Impulsive Flare Geometry

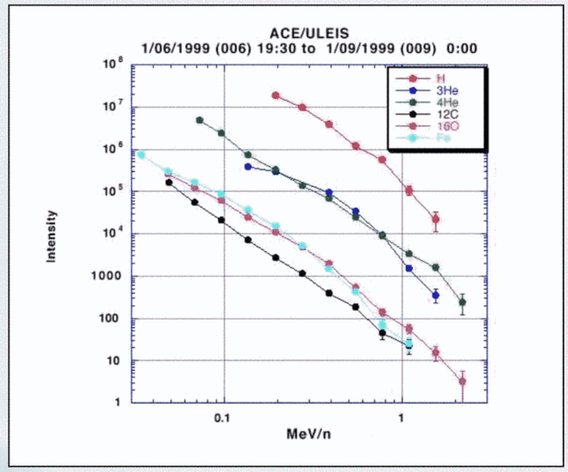


(Yohkoh SXR image)

HE-Photon and Particle Spectra



(Murphy et al. 1997)



(Mason et al. 1999)

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, …)

Basic Observations

Ions (large flare)

- 10^{35} p s^{-1} > 1 MeV
- for ~ 100 s
- 1 GeV maximum
- 3×10^{31} ergs > 1 MeV/n
- Energy equipartition
- Simultaneous with electrons
- Acceleration from thermal distribution
- Abundance enhancements
- Replenishment

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

Electrons (large flare)

- 10^{37} e s^{-1} > 20 keV
- for ~ 100 s
- 100 MeV maximum
- 3×10^{31} ergs > 20 keV
- Energy equipartition
- Simultaneous with ions
- Acceleration from thermal distribution
- Replenishment

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

Abundance Enhancements

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

(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

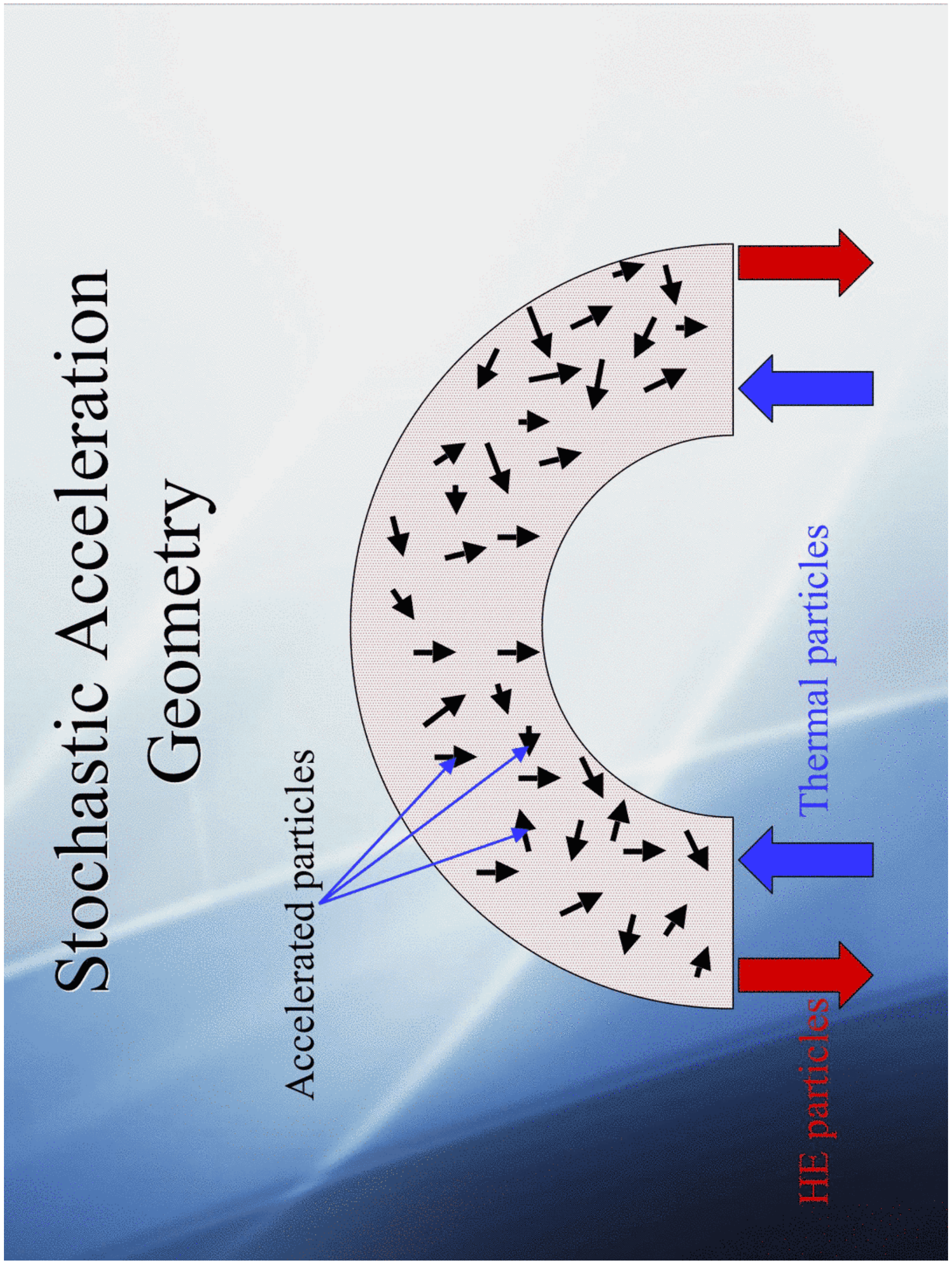
- Uses: Long ($\sim 10^9$ cm) strong ($>>1$ V cm^{-1}) fields
- Geometry: Large (thin!… aspect ratio 10^7) current sheet above and normal to an arcade of loops
- Mechanism: Direct acceleration with drift escape
- Conclusion: No good (can't do ions, high-energy electrons, abundance enhancements)

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)



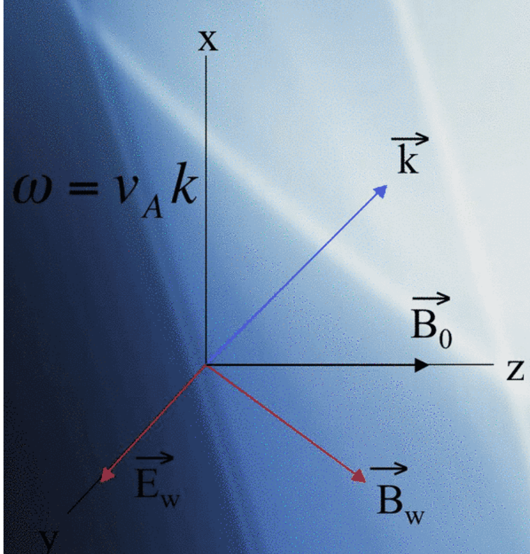
4b. Stochastic Acceleration: Resonant

- Uses: low-amplitude ($\delta B / B << 1$) 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



$$\vec{A}_0 = -yB_0\hat{x}$$

$$\vec{A}_w = \sum_{i=1}^{N} \hat{y}\,\frac{cE_i}{\omega_i}\sin(k_{\perp i}x + k_{zi}z - \omega_i t)$$

Particle Motion ⇔

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

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) ⇒

$$\dot{p}_z = \frac{mc^2}{\gamma}\left(\frac{p_\perp}{mc}\right)\sum_{i=1}^{N}\varepsilon_i k_{zi} J_0'(k_{\perp i}\rho)\cos(k_{zi}z - \omega_i t)$$

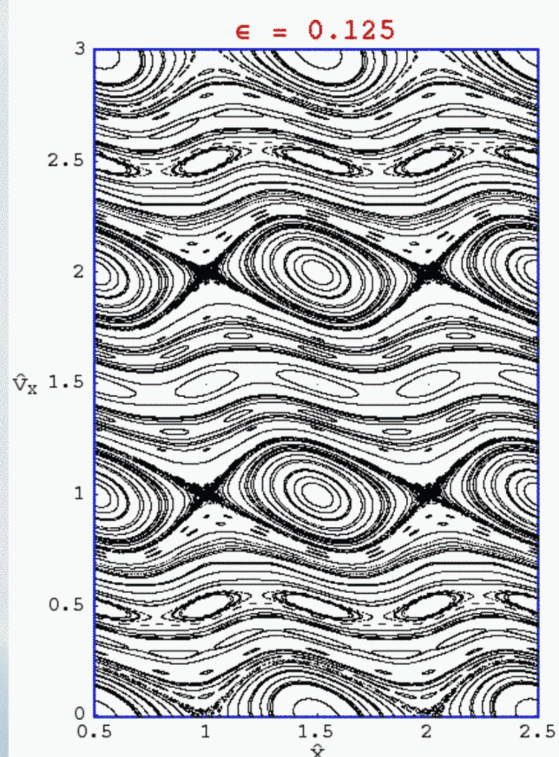
$$\dot{z} = \frac{p_z}{m\gamma}$$

Transition to Global Stochasticity

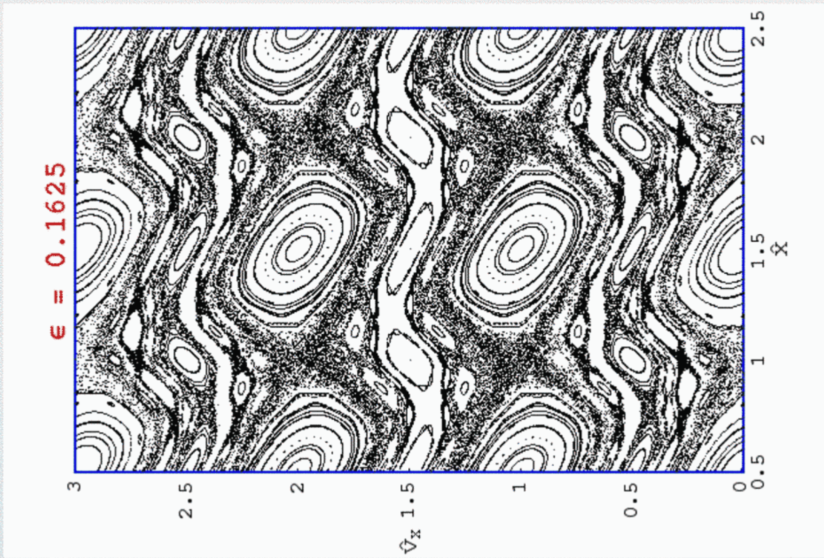
Equations of Motion
⇔
Standard Mapping

$$\hat{x}_{m+1} = \hat{x}_m + \hat{v}_m \quad (\mathrm{mod}\ i)$$
$$\hat{v}_{m+1} = \hat{v}_m + 2\pi\varepsilon^2 \sin(2\pi\hat{x}_{m+1})$$

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

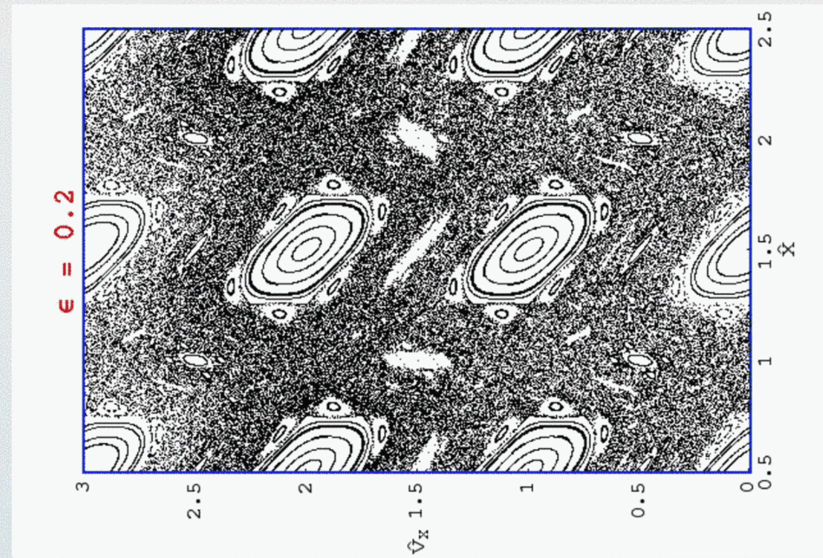


Transition to Global Stochasticity



- 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

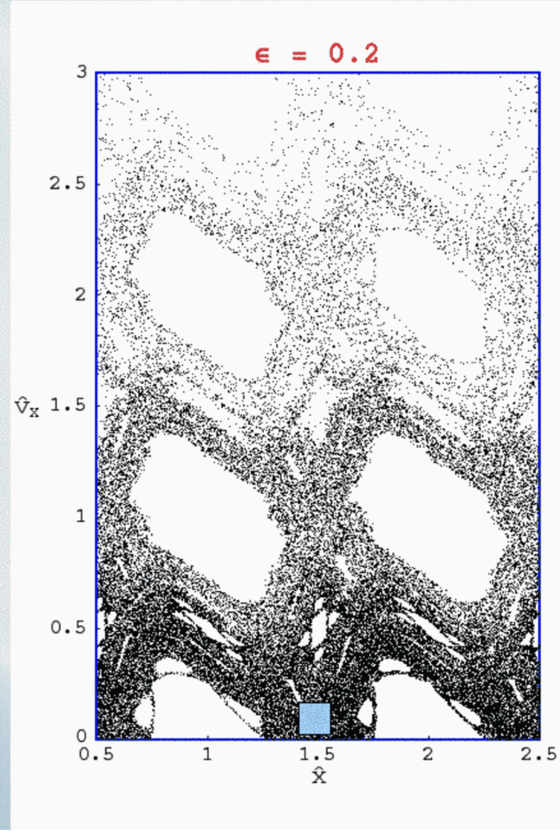


- KAM surfaces are destroyed between primary period-1 island chains
  - Secondary islands being emitted during bifurcation
- Particles sample most of phase space
- Acceleration
- Can use Fokker-Planck theory now

Acceleration? Really?

Yes!

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

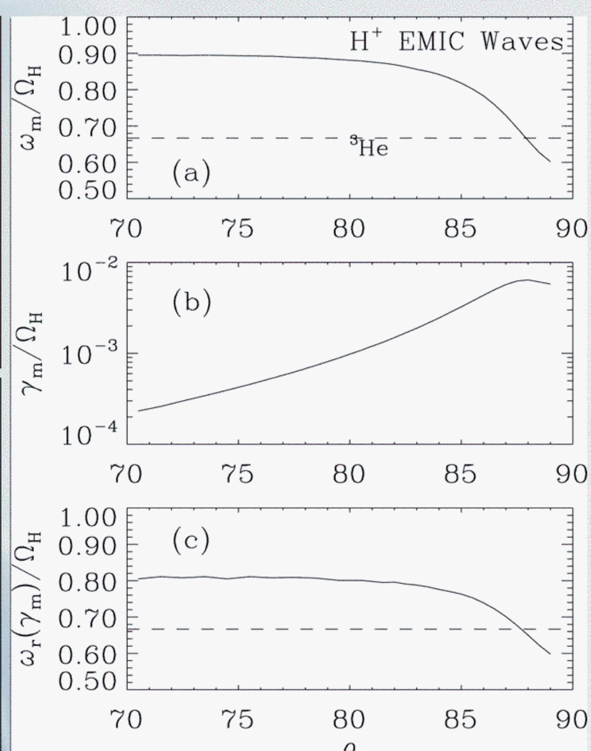


Does it Exist in Flares?

- Absolutely!
- Required for ^{3}He enhancements
- Need waves around Ω_3 (Fisk 1978)

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

Electron-firehose model (Benz & Paesold 2002)



Cascading Turbulence Model

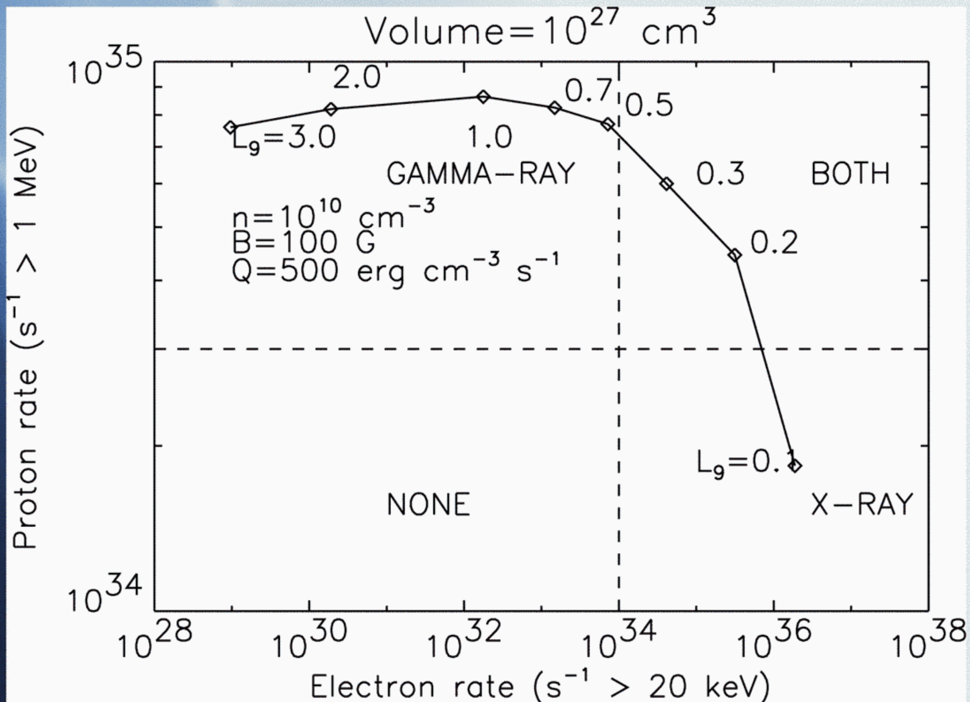
1. Alfven and fast mode waves generated at large scales (assumption)
2. Cascade to higher wavenumbers (e.g., Zhou & Matthaeus 1989)
3. Fast mode waves energize electrons via transit-time acceleration (e.g., Miller 1997)
4. Alfven waves energize ions via gyroresonant acceleration (e.g., Miller & Roberts 1995)

→ Both species accelerated by MHD turbulence in a <u>2-parameter model</u>

Stochastic Acceleration Successes

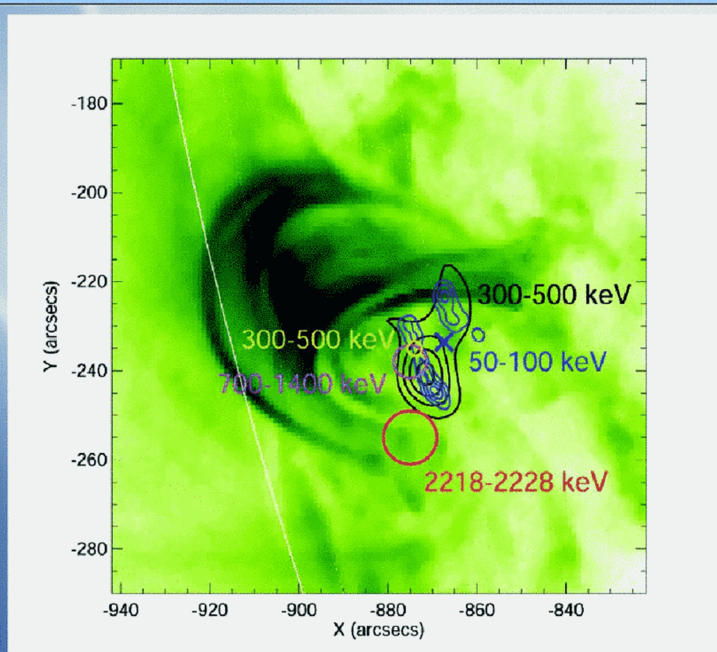
- Accounts for the bulk observations of electron and ion acceleration
- Naturally yields replenishment of the acceleration region
- Naturally yields equipartition between electrons and ions
- Has significant predictive capability
  - subMeV/nucleon ions (to be verified)
  - Different locations for ion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

Prediction: Different locations for Gamma-Ray and HXR emission



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

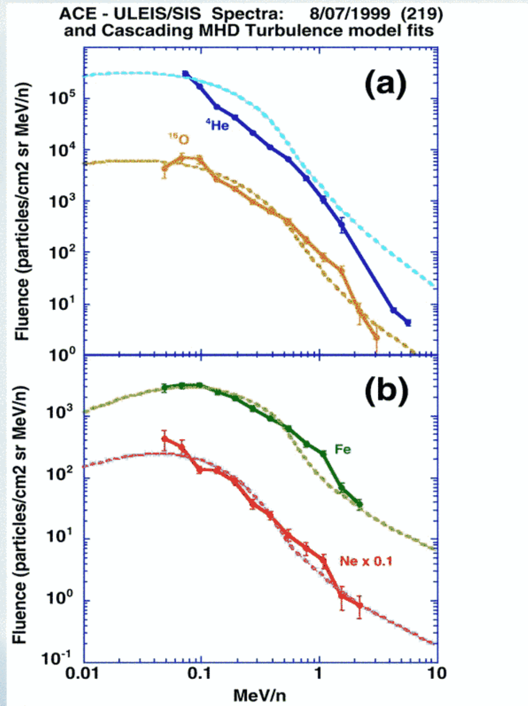
Verification: 2002 July 23 Flare et al.



⇒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