Particle Transport (and a little Particle Acceleration)

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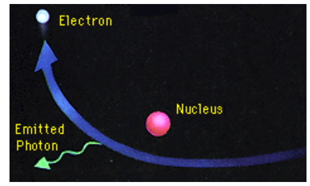
Evidence for Energetic Particles

- Particles escaping into interplanetary space
- Hard X-ray emission (electrons)
- Gamma-ray emission (electrons and ions)
- Radio emission (electrons)

- ***Will focus mostly on electrons in this talk***

Bremsstrahlung Process



Inversion of Photon Spectra

$$I(\varepsilon) = K \int_\varepsilon^\infty F(E)\, \sigma(\varepsilon,E)\, dE$$

$$\sigma(\varepsilon,E) = \kappa/\varepsilon E$$

$$J(\varepsilon) = \varepsilon\, I(\varepsilon) = \kappa K \int_\varepsilon^\infty G(E)\, dE$$

$$G(E) = -(1/\kappa K)\, dJ(\varepsilon)/d\,\varepsilon$$

$$G(E) \sim J(\varepsilon)$$

Key point!

Emission process is straightforward, and so it is easy to ascertain the number of electrons from the observed number of photons!

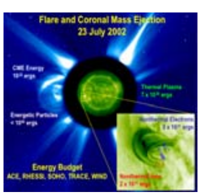
Required Particle Fluxes/Currents/Powers/Energies

(Miller et al. 1997; straightforwardly proportional to observed photon flux)

Electrons
- 10^{37} s^{-1} > 20 keV
- 10^{18} Amps
- 3×10^{29} ergs s^{-1} for 100 s = 3×10^{31} ergs

Ions
- 10^{35} s^{-1} > 1 MeV
- 10^{16} Amps
- 2×10^{29} ergs s^{-1} for 100 s = 2×10^{31} ergs

Order-of-Magnitude Energetics



Electron Number Problem

10^{37} s^{-1} > 20 keV

Number of electrons in loop = nV ~ 10^{37}

All electrons accelerated in 1 second!

Need replenishment of acceleration region!

Electron Current Problem

Steady-state (Ampère):

$$B = \mu_o I/2\pi r \sim (10^{-6})(10^{18})/10^8 = 10^4\ \mathrm{T} = 10^8\ \mathrm{G}$$

$$(B^2/8\pi)\, V \sim 10^{41}\ \text{ergs!}$$

Transient (Faraday):

$$V = (\mu_o \ell)\, dI/dt = (10^{-6})(10^7)(10^{18})/10 \sim 10^{18}\ \text{V!!}$$

So either
(1) currents must be finely filamented; or
(2) particle acceleration is in random directions

An Acceleration Primer

$\mathbf{F} = q\mathbf{E}_{part}$; $\mathbf{E}_{part} = \mathbf{E}_{lab} + \mathbf{v}_{part} \times \mathbf{B}$

- $\mathbf{E}_{part}$ large-scale → *coherent* acceleration
- $\mathbf{E}_{part}$ small-scale → *stochastic* acceleration

Acceleration by Large-Scale Electric Fields

$m\, dv/dt = q\, E_{part} - m\, \nu\, v$

- Suppose $\boxed{\nu \sim v^{n-1}}$

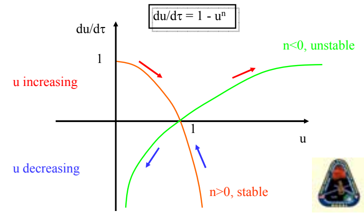
$dv/dt = (q/m)\, E_{part} - v^n = a - v^n$

Let $\boxed{v_c = a^{1/n};}$ $u = v/v_c$; $\tau = at/v_c$

$\boxed{du/d\tau = 1 - u^n}$

- For air drag, $\nu \sim v$ ($n = 2$)
- For electron in plasma, $\nu \sim 1/v^3$ ($n = -2$)

Acceleration Trajectories



The Dreicer Field

- Recall

$v_c = a^{1/n} \sim E_{part}^{-1/2}$

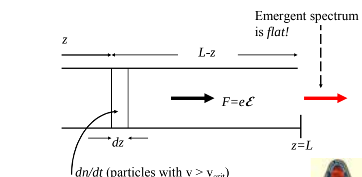
- If $v_c = v_{th}$, $E_{part} = E_D$ – the *Dreicer field*

($E_D \sim 10^{-8}\, n(\mathrm{cm}^{-3})/T(\mathrm{K})\ \mathrm{V\ cm}^{-1} \sim 10^{-4}\ \mathrm{V\ cm}^{-1}$)

$v_c = v_{th}(E/E_D)^{-1/2}$

- If $E < E_D$, $v_c > v_{th}$ – *runaway tail*
- If $E > E_D$, $v_c < v_{th}$ – *bulk energization*

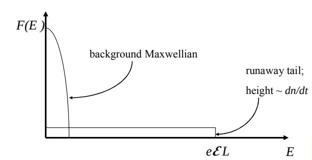
Sub-Dreicer Acceleration



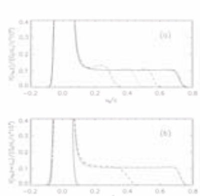
$E = e\mathcal{E}(L-z)$; $dE = e\mathcal{E}dz$; $F(E)dE = (dn/dt)dz$

→ $F(E) = (1/e\mathcal{E})(dn/dt)$

Accelerated Spectrum

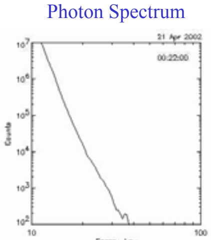


Computed Runaway Distributions



(Sommer 2002, Ph.D. dissertation, UAH)

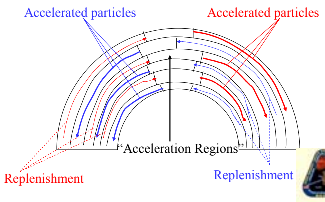
Photon Spectrum



Accelerated Spectrum

- Predicted spectrum is *flat*
- Observed spectrum is ~ power law
- Need many concurrent acceleration regions, with range of $\mathcal{E}$ and L

Sub-Dreicer Geometry



~10^{12} acceleration regions required!

Current closure mechanism?

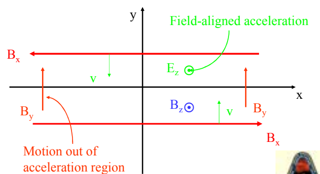
Sub-Dreicer Acceleration

- Long (~10^9 cm) acceleration regions
- Weak (< 10^{-4} V cm^{-1}) fields
- Small fraction of particles accelerated
- Replenishment and current closure are challenges
- Fundamental spectral form is flat
- Need large number of current channels to account for observed spectra and to satisfy global electrodynamic constraints

Super-Dreicer Acceleration

- Short-extent (~10^5 cm) strong (~1 V cm^{-1}) fields in large, thin (!) current sheet

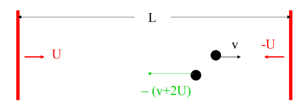
Super-Dreicer Acceleration Geometry



Super-Dreicer Acceleration

- Short (~10^5 cm) acceleration regions
- Strong (> 10 V cm^{-1}) fields
- Large fraction of particles accelerated
- Can accelerate both electrons and ions
- Replenishment and current closure are straightforward
- No detailed spectral forms available
- Need very thin current channels – stability?

(First-order) Fermi Acceleration



$dv/dt \sim \Delta v/\Delta t = 2U/(L/v) = (2U/L)v$

$\boxed{v \sim e^{(2U/L)t}}$

(requires v > U for efficient acceleration!)

Second-order Fermi Acceleration

- Energy gain in head-on collisions
- Energy loss in "overtaking collisions"

BUT number of head-on collisions exceeds number of overtaking collisions

→ Net energy gain!

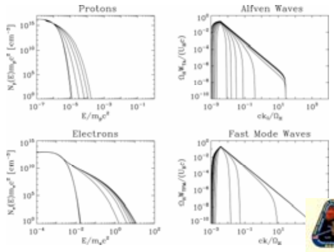
Stochastic Fermi Acceleration (Miller, LaRosa, Moore)

- Requires the injection of large-scale turbulence and subsequent cascade to lower sizescales
- Large-amplitude plasma waves, or magnetic "blobs", distributed throughout the loop
- Adiabatic collisions with converging scattering centers give 2nd-order Fermi acceleration (*as long as v > U!*)

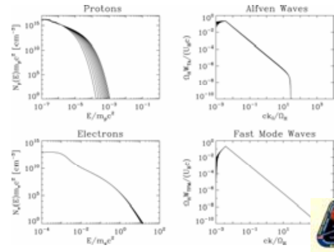
Stochastic Fermi Acceleration

- Thermal electrons have $v>v_A$ and are efficiently accelerated immediately
- Thermal ions take some time to reach v_A and hence take time to become efficiently accelerated

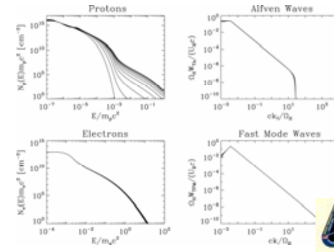
Stochastic Acceleration



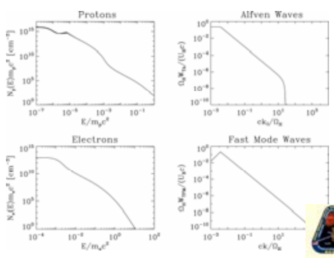
t = 0 – 0.1 s



t = 0.1 – 0.2 s



t = 0.2 – 1.0 s



T = 2 – 4 s ➔ Equilibrium

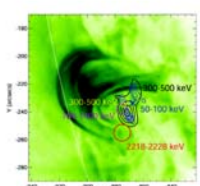
Stochastic Acceleration

- Accelerates both electrons and ions
- Electrons accelerated immediately
- Ions accelerated after delay, and only in long acceleration regions
- Fundamental spectral forms are power-laws

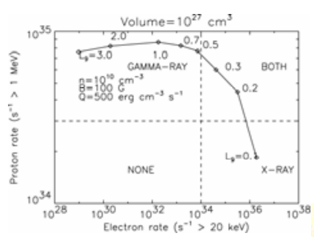
Electron vs. Ion Acceleration and Transport

- If ion and electron acceleration are produced by the same fundamental process, then the gamma-rays produced by the ions should be produced in approximately the same location as the hard X-rays produced by the electrons

Observations: 2002 July 23 Flare



Ion acceleration favored on longer loops!



Particle Transport

Cross-section

$$\frac{dE}{dt} = \sigma\, n\, v\, E$$

erg s^{-1} cm^{2} cm^{-3} cm s^{-1} erg

Coulomb collisions

- $\sigma = 2\pi e^4 \Lambda / E^2$;
  - Λ = "Coulomb logarithm" ~ 20)
- $dE/dt = -(2\pi e^4 \Lambda/E)\, nv = -(K/E)\, nv$
- $dE/dN = -K/E$; $dE^2/dN = -2K$
- $E^2 = E_o^2 - 2KN$

Spectrum vs. Depth

- Continuity: $F(E)\, dE = F_o(E_o) dE_o$
- Transport: $E^2 = E_o^2 - 2KN$; $E\, dE = E_o\, dE_o$
- $F(E) = F_o(E_o)\, dE_o/dE = (E/E_o)\, F_o(E_o)$
- $F(E) = (E/\, ([E^2 + 2KN]^{1/2}) F_o([E^2 + 2KN]^{1/2})$

Spectrum vs. Depth

$F(E) = (E/\, ([E^2 + 2KN]^{1/2}) F_o([E^2 + 2KN]^{1/2})$

(a) $2KN \ll E^2$

$F(E) \sim F_o(E)$

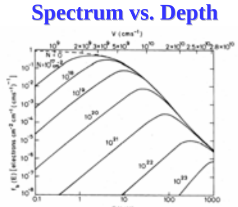
(b) $2KN \gg E^2$

$F(E) \sim (E/[2KN]^{1/2})\, F_o([2KN]^{1/2}) \sim E$

Also,

$v\, f(v)\, dv = F(E)\, dE \rightarrow f(v) = m\, F(E)$

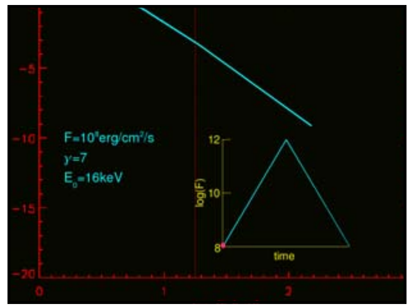
Spectrum vs. Depth



Resulting photon spectrum gets harder with depth!

Return Current

- $dE/ds = -e\mathcal{E}$, $\mathcal{E}$ = electric field
- Ohm's Law: $\mathcal{E} = \eta\, j = \eta e \mathcal{F}$, $\mathcal{F}$ = particle flux
- $dE/ds = -\eta e^2 \mathcal{F}$
- dE/ds independent of E: $E = E_o - e^2 \int \eta\, \mathcal{F}\, ds$
  - note that $\mathcal{F} = \mathcal{F}[s]$ due to transport and $\eta = \eta(T)$

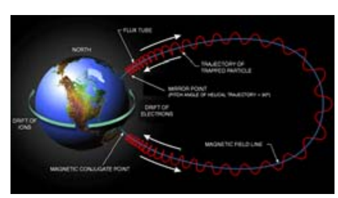


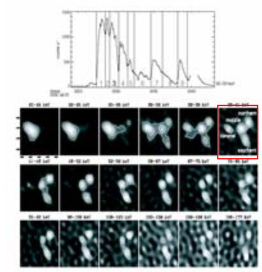
Return Current

- $dE/ds = -\eta e^2 \mathcal{F}$
- Penetration depth $s \sim 1/\mathcal{F}$
- Bremsstrahlung emitted $\sim \mathcal{F} \times (1/\mathcal{F})$ – independent of $\mathcal{F}$!
- Saturated flux limit – very close to observed value!

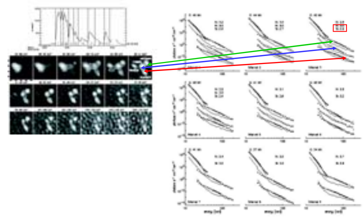
Magnetic Mirroring

- $F = -\mu\, dB/ds$; μ = magnetic moment
- Does not change energy, but causes redirection of momentum
- Indirectly affects energy loss due to other processes, e.g.
  - increase in pitch angle reduces flux $\mathcal{F}$ and so electric field strength $\mathcal{E}$
  - Penetration depth due to collisions changed

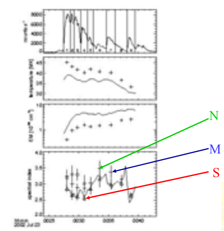




Feature Spectra



Temporal Trends



Implications for Particle Transport

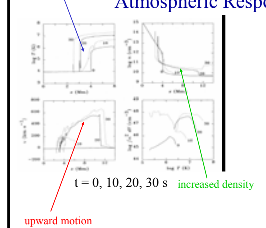
- Spectrum at one footpoint (South) consistently harder
- This is consistent with collisional transport through a greater mass of material!

Atmospheric Response

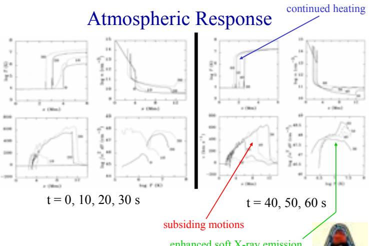
- Collisional heating → temperature rise
- Temperature rise → pressure increase
- Pressure increase → mass motion
- Mass motion → density changes

- “Evaporation”

Atmospheric Response



Atmospheric Response



The “Neupert Effect”

- Hard X-ray (and microwave) emission proportional to injection rate of particles (“power”)
- Soft X-ray emission proportional to accumulated mass of high-temperature plasma (“energy”)
- So, we expect

$$I_{SXR} \sim \int I_{HXR}\, dt$$

Inference of transport processes from observations

The Continuity Equation

$$\frac{d}{dz}\int_{E_1(z)}^{E_2(z)} F(E,z)\,dE = \int_{E_1}^{E_2}\frac{\partial F(E,z)}{\partial z}\,dE + F(E_2,z)\frac{dE_2}{dz} - F(E_1,z)\frac{dE_1}{dz} = 0\,, \qquad (3.1)$$

which can be written

$$\int_{E_1}^{E_2}\left\{\frac{\partial F(E,z)}{\partial z}+\frac{\partial}{\partial E}\left[F(E,z)\frac{dE}{dz}\right]\right\}dE = 0\,. \qquad (3.2)$$

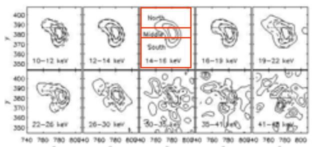
Since this is true for an arbitrary energy interval, the integrand must vanish, so that

$$\frac{\partial F(E,z)}{\partial z}+\frac{\partial}{\partial E}\left[F(E,z)\frac{dE}{dz}\right] = 0\,. \qquad (3.3)$$

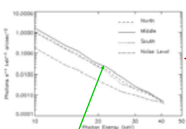
Using Spatially Resolved Hard X-ray Data to Infer Physical Processes

- Electron continuity equation:
  $\partial F(E,N)/\partial N + \partial/\partial E\,[F(E,N)\,\mathbf{dE/dN}] = 0$
- Solve for dE/dN:
  $\mathbf{dE/dN} = -[1/F(E,N)]\int[\partial F(E,N)/\partial N]\,dE$
- So observation of F(E,N) gives ***direct*** empirical information on physical processes (**dE/dN**) at work

April 15, 2002 event



Subsource Spectra



Photon

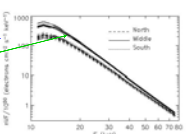
Electron

'Middle' region spectrum is softer

Spectrum reminiscent of collisional variation

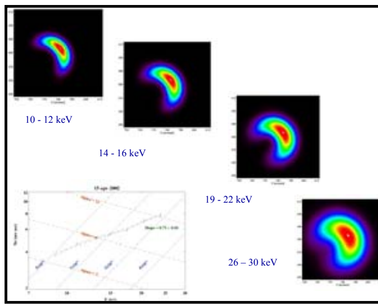
But

$dE/dN = -[1/F(E,N)]\int[\partial F(E,N)/\partial N]\,dE$?

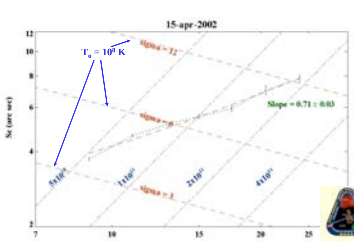


Variation of Source Size with Energy

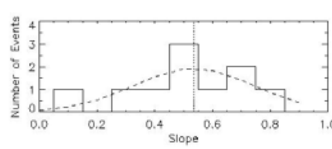
- Collisions: $dE/ds \sim -n/E \rightarrow L \sim \varepsilon^2$
  In general, L *increases* with ε
  (increased penetration of higher energy electrons)
- General: $dE/ds \sim -n/E^{\alpha} \rightarrow L \sim \varepsilon^{1+\alpha}$
- Thermal: $T \sim T_o \exp(-s^2/2\sigma^2) \rightarrow L(\varepsilon, T_o, \sigma)$
  In general, L *decreases* with ε
  (highest-energy emission near temperature peak)



Source Size vs Energy



Histogram of Slopes



NOT compatible with slope of 2!

Significance of Observed Slope

- Collisions
  $dE/ds \sim -n/E^{\alpha}$, $\alpha=1$, slope $= 1 + \alpha = 2$
- Observed mean slope $1 + \alpha \sim 0.5$
  $\alpha \sim -0.5$
  $\rightarrow dE/ds \sim -nE^{0.5} \sim -nv$ (??)