Particle Acceleration in Astrophysics

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Cosmic ray spectrum observed at the Earth

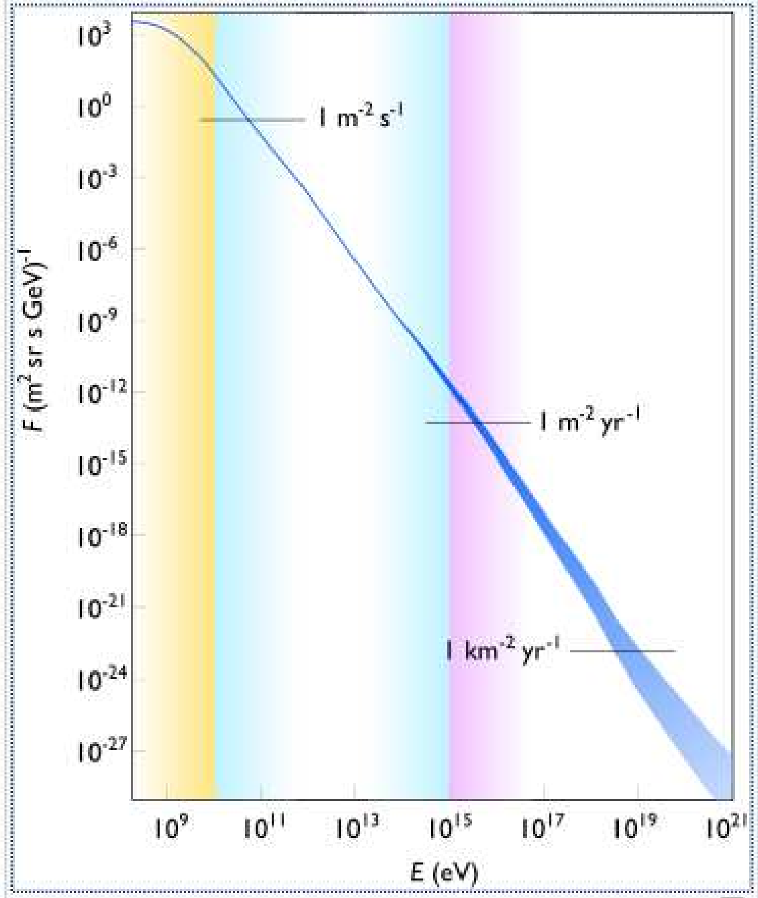


Figure 1: These are clearly accelerated particles

Motivation

- Particle acceleration is pretty ubiquitous in Astrophysics
- e.g., boundary of Earth's magnetosphere, Solar coronal mass ejections, Solar flares, pulsar magnetospheres, supernovae, supernova remnants, active galactic nuclei, extended radio sources
- Not to mention cosmic rays observed at the Earth!
- Accelerated particles are either detected by particle detectors (e.g., cosmic rays)
- or detected indirectly via the emission they produce (nonthermal radiation)

Solar flare

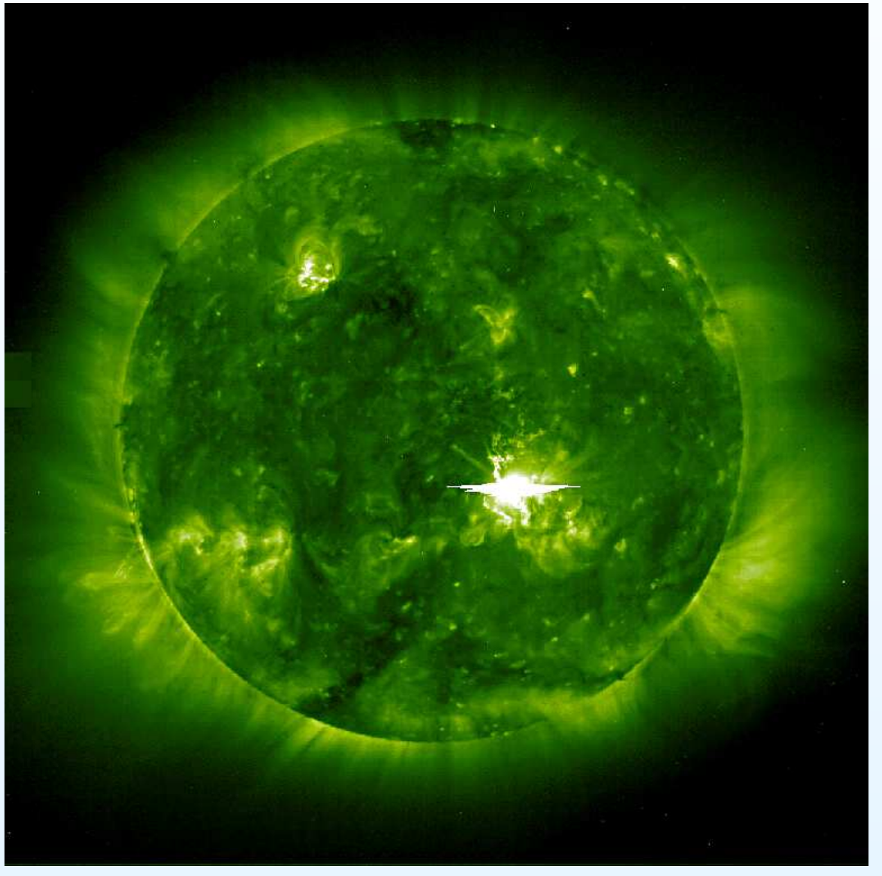


Figure 2: These too involve particle acceleration

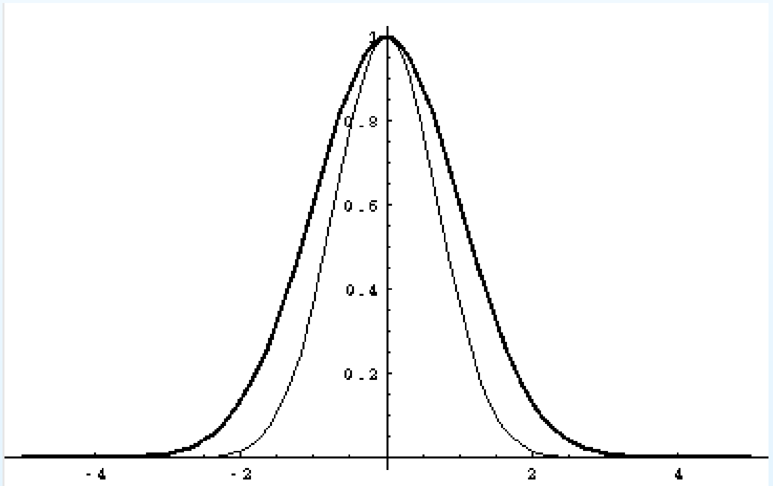
Outline

- Particle acceleration: what does it mean? (how is it different from heating?)
- Modeling particle acceleration: the Liouville/Vlasov formalism, the Fokker-Planck formalism, Fermi acceleration mechanisms
- Observational signatures of accelerated particles; how can you make out if the particle distribution is a thermal or a nonthermal one?

Thermal (i.e., Maxwellian) particle distribution

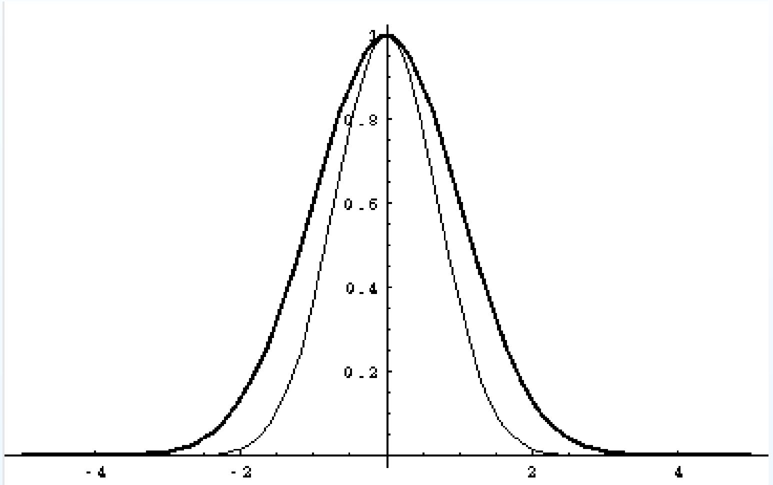
Let's first remind ourselves of the familiar thermal particle distribution:

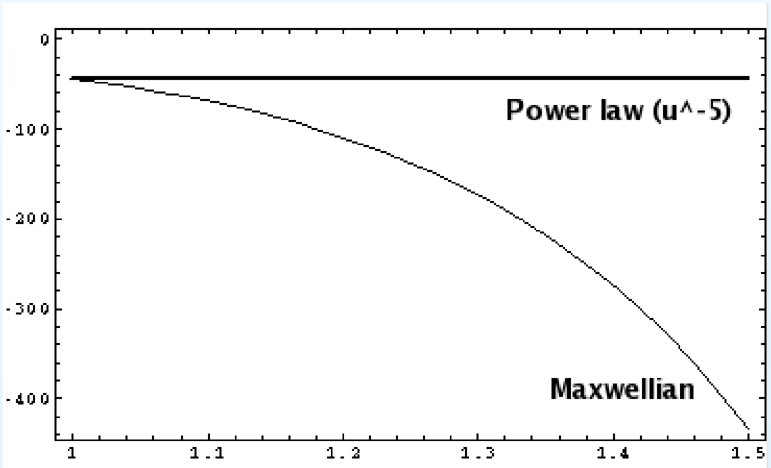
$$f(\mathbf{u}) = n \left(\frac{m}{2\pi kT} \right)^{3/2} \exp\left(- \frac{m\,\mathbf{u}^2}{2kT} \right), \quad n = \int d^3u\, f(\mathbf{u})$$



A thermal particle distribution emits blackbody radiation that is defined by the temperature T.

Nonthermal (accelerated) particle distribution





Where does the Maxwellian distribution come from? I

Consider first the collisionless Boltzmann equation

$$\frac{Df}{Dt} = \dot{f} + \dot{\mathbf{x}}\,\nabla f + \dot{\mathbf{u}}\,\nabla_u f = 0$$

The distribution function f represents the probability of finding a given particle in a given element of position-velocity phase space $d^3x\,d^3u$. The total number of particles is

$$n = \int f\,d^3x\,d^3u$$

$\dot{f} \rightarrow$ the creation/destruction of particles, $\dot{\mathbf{x}} \rightarrow$ the time evolution of the space-coordinate and $\dot{\mathbf{u}} \rightarrow$ the time evolution of the velocity-coordinate. The collisionless Boltzmann eq simply says that the number of particles in an elemental volume of phase space $d^3x\,d^3u$ (even as its deformed with time) is conserved.

Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq = 0. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian
- Even if the RHS were not 0; i.e., if there were collisions that take particles in and out of an elemental phase space volume,
  - for a given number, momentum and energy, the Maxwellian distribution occupies the maximum phase space volume
  - Generalized entropy argument: $H = \int f \ln f d^3u$ always $\downarrow$ with time, and the minimum is achieved by the Maxwellian
- So any distribution eventually relaxes to a Maxwellian.

Collisions

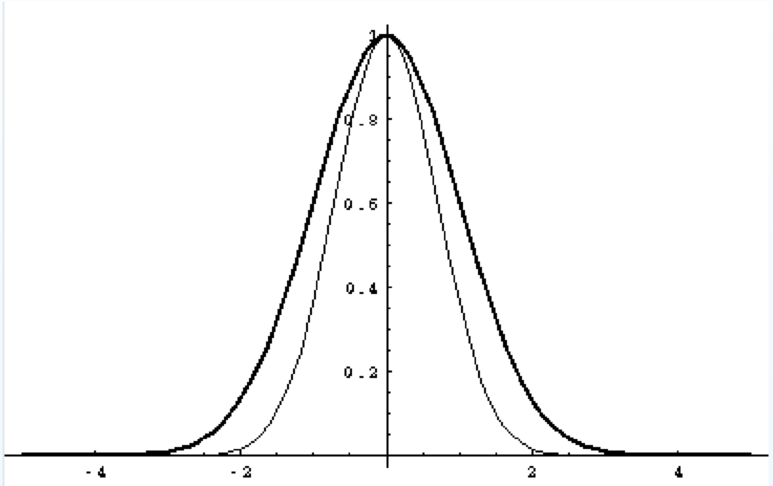
- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$. The RHS (the collision operator) is an integral over velocities which involves the distribution function

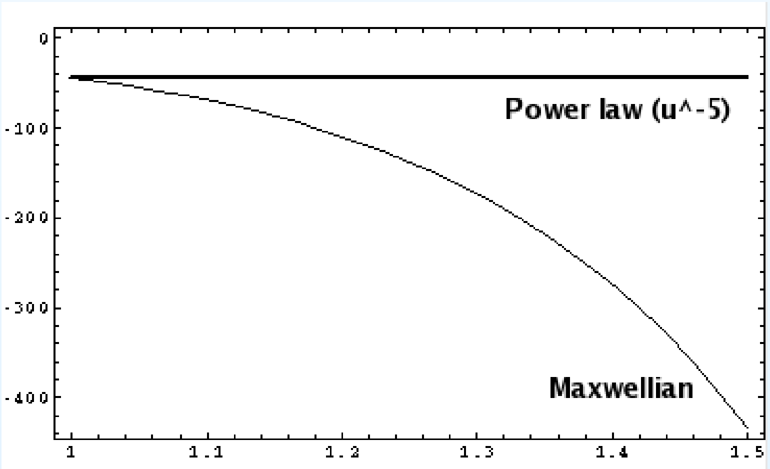
- When the collisions are Coulomb in nature, a Maxwellian f makes the RHS = 0

- Coulomb collisions $\rightarrow$ heating ; T $\uparrow$ leads to $\uparrow$ in width (variance) of Maxwellian

- With non-Coulomb collisions, non-Maxwellian distributions eventually relax to a Maxwellian, provided there's enough time. Else, the distribution could be non-thermal/accelerated.

Nonthermal particle distributions





The “collisional” Boltzmann equation

$$\frac{Df}{Dt} = -C_{\rm out} + C_{\rm in} = \frac{\partial f}{\partial t}\Big|_{\rm c}$$

If the cumulative effect of small collisions/deflections is dominant, the RHS integral (collision term) can be Taylor expanded to first order to yield the Fokker-Planck form (“friction” $+$ diffusion in velocity space)

$$\frac{\partial f}{\partial t}\Big|_{\rm c} = -\frac{\partial}{\partial u}\Big(Af\Big) + \frac{1}{2}\frac{\partial^2}{\partial u^2}\Big(Bf\Big)$$

The Fokker-Planck form

- The Fokker-Planck form of the collision integral can also be heuristically derived by considering a particle in a *dilute* gas that experiences a large number of small amplitude, stochastic “kicks”

- Random walk of tip of velocity (or momentum) vector represents “diffusion” in velocity/momentum space

- Drag due to motion through dilute gas $\rightarrow$ “friction” term.

$$\left.\frac{\partial f}{\partial t}\right|_{\rm c} = -\frac{\partial}{\partial u}\left(Af\right) + \frac{1}{2}\frac{\partial^2}{\partial u^2}\left(Bf\right)$$

The “friction” term

$$\frac{\partial f}{\partial t} = -A \frac{\partial f}{\partial u}$$

Solution:

$$f \propto \exp\left[-(u - At)^2\right]$$

- Mean increases/decreases linearly with time; hence “friction”
- First order acceleration/deceleration.
- Relevant for situation where scattering centers move systematically e.g., converging/diverging flows.

The “diffusion” term

$$\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial v^2}$$

Solution (for constant D):

$$f = \left(\frac{D}{4\pi t}\right)^{1/2} \exp\left(-\frac{v^2}{4Dt}\right)$$

- Gaussian broadens and gets shallower with time $\rightarrow$ diffusion in velocity space.
- But mean velocity still increases! (why?)
- This is second order acceleration, typically due to stochastically moving scattering centers.

Nonthermal, power law spectrum: an example

Consider only the “diffusion” term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\,\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

with collisions that yield

$$\mathcal{D}(v) = D_0\,v^2\,,$$

where D_0 is a constant. The steady-state solution is $f \propto v^{\alpha}$; i.e., a power-law (clearly non-thermal) particle spectrum.

This is an example of a particular kind of second-order Fermi acceleration. So the name of the game would be to find physical situations that yield a particular form for the diffusion coefficient $\mathcal{D}(v)$.

Non-Coulomb collisions

- Concept of “scattering centers” (Fermi, 1949)
- Scattering centers move
  - systematically (first order Fermi acceleration), or
  - stochastically (second order Fermi acceleration).
- Scattering centers could be: turbulent eddies, magnetic field inhomogenieties, EM waves whose amplitudes vary stochastically with time (particles resonate w/ these waves)...

“Algorithm” - I

- Determine physically motivated form for various terms in the Fokker-Planck eq (e.g., A, B, escape timescale, source/sink terms)
- Try to see what kinds of solutions one can get for particle distribution (f); preferably analytical
- Get Green’s function (i.e., response to monoenergetic injection), then convolve with input distribution (to acceleration process) to get final overall particle distribution

“Algorithm” - II

- If the particles are directly detected (e.g., as with cosmic rays), things are a tad simpler; you can directly tell if the distribution is thermal/nonthermal
- Else, from the computed particle distribution, try to get the predicted observational signature (radiation)
- This involves radiation processes (e.g., synchroton, gyrosynchrotron, bremstrahhlung, air showers..)
- Often the equations for the particle distribution and radiation can be coupled (messy!)

Thermal/nonthermal radiation: how to tell? I

- If detailed multiwavelength radiation spectrum is available:
- Body in thermodynamic equilibrium (i.e., thermal/Maxwellian particle distribution) will emit a blackbody spectrum. The temperature of the emitting particles will be immediately obvious from the observed spectrum (e.g., the Sun's photosphere is 6000 K)
- If the underlying particle spectrum is nonthermal, one cannot define a temperature for the particles. The radiation spectrum will depend upon the specific emission process. But the spectrum will typically be a power law or so (not blackbody)

Thermal/nonthermal radiation: how to tell? II

- If radiation spectrum not available (as is often the case):
- Define a brightness temperature $T_b = (\lambda^2/2k\,\Omega)\ \times \mathrm{Observed\ Radiation\ Flux}$ (Rayleigh-Jeans part of blackbody spectrum)
- If the brightness temperature is rather high (regardless of whether or not the observed radiation is actually blackbody), the radiation is probably nonthermal
- For a self-absorbed source, its possible to relate the brightness temperature T_b of the observed radiation and the kinetic temperature T_e of the underlying particles: $T_e = (1/3k)\,\gamma\, m\, c^2 = T_b$

Pedagogical references

- High Energy Astrophysics - Longair (Cambridge U. Press)
- Plasma Physics for Atrophysics - Kulsrud (Princeton U. Press)
- An Introduction to the Theory of Astrophysical and Laboratory Plasmas - Sturrock (Cambridge U. Press)
- Acceleration and transport of energetic charged particles in space, J. R. Jokipii, 2001, *Astrophysics and Space Science*, vol. 277, pp. 15-26
- Acceleration mechanisms, D. B. Melrose, 2009, arXiv:0902.1803v1 (astro-ph.SR)

We next look at a couple of observations/observational signatures of accelerated particles

Solar flare

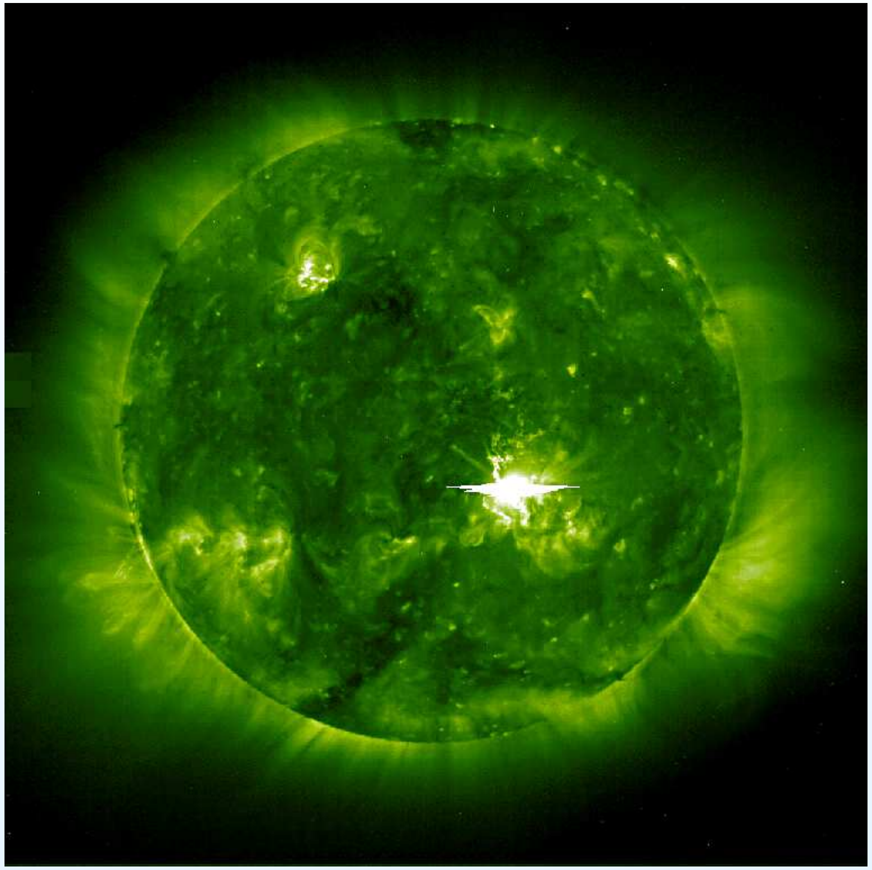


Figure 3: Image + limited spectral info. EIT/SOHO (movie)

Solar (radio) noise storm

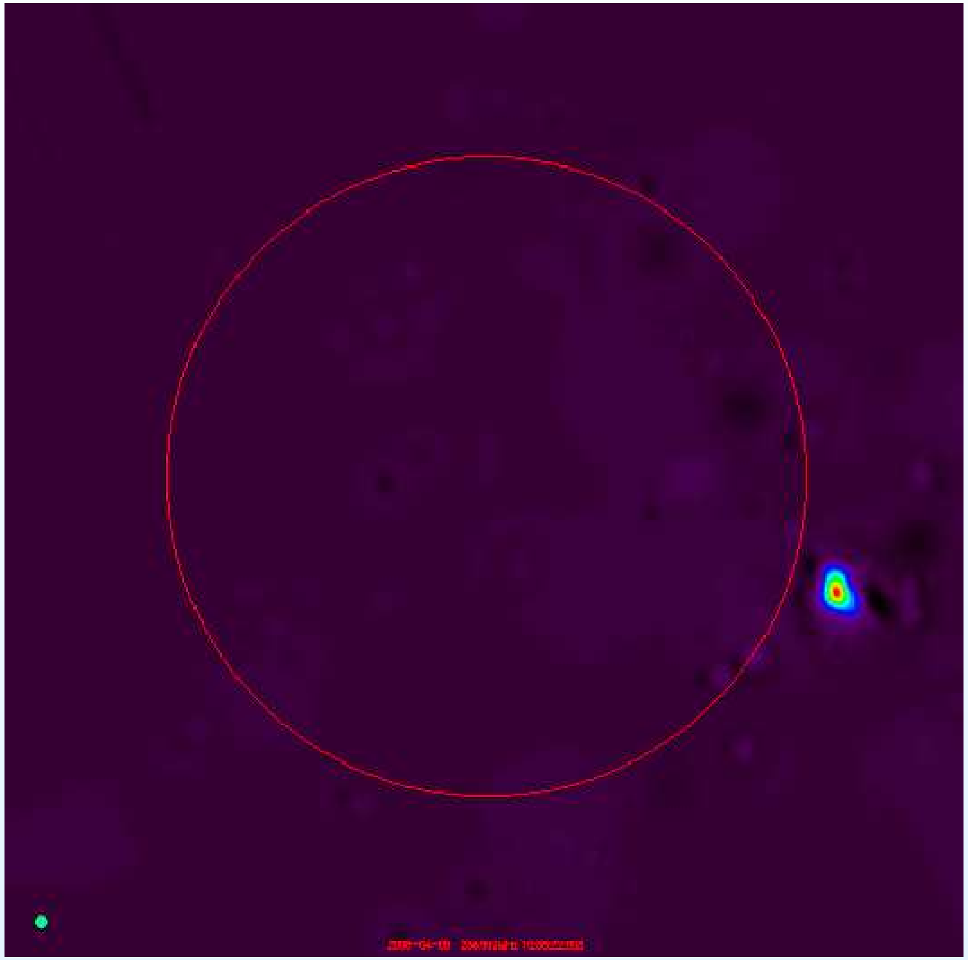


Figure 4: Only image, no spectral info. GMRT

Solar (radio) type II and type III emission

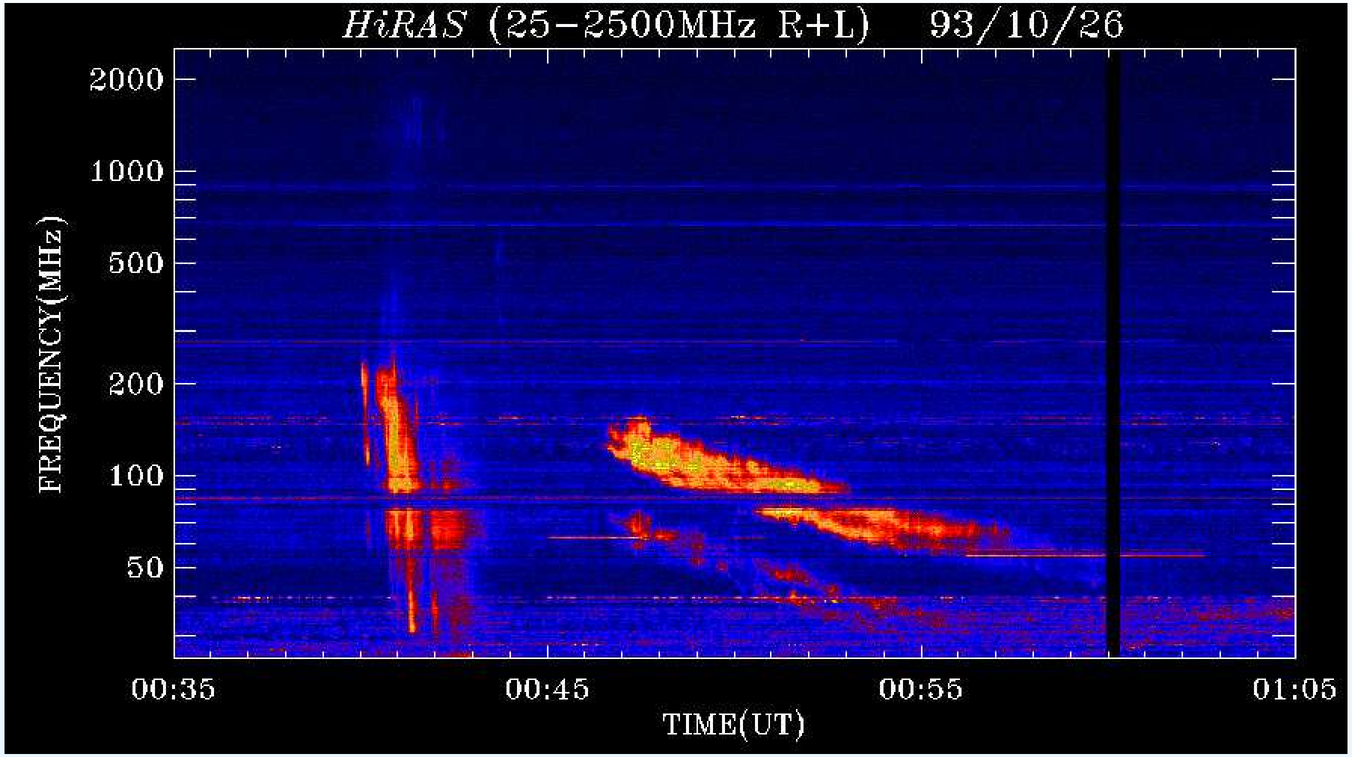


Figure 5: No image, limited spectral info. Hiraiso

Solar Coronal Mass Ejection (CME) + flare

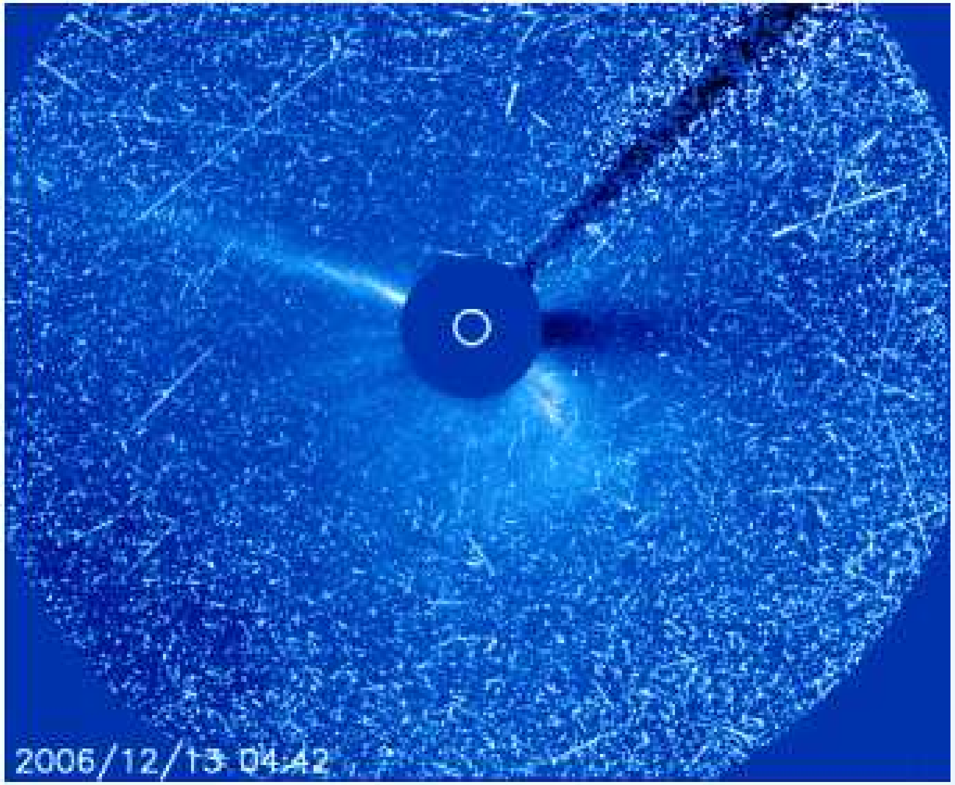


Figure 6: Accelerated particles. LASCO/SOHO (movie)

Flare-accelerated 10–100 GeV cosmic rays?

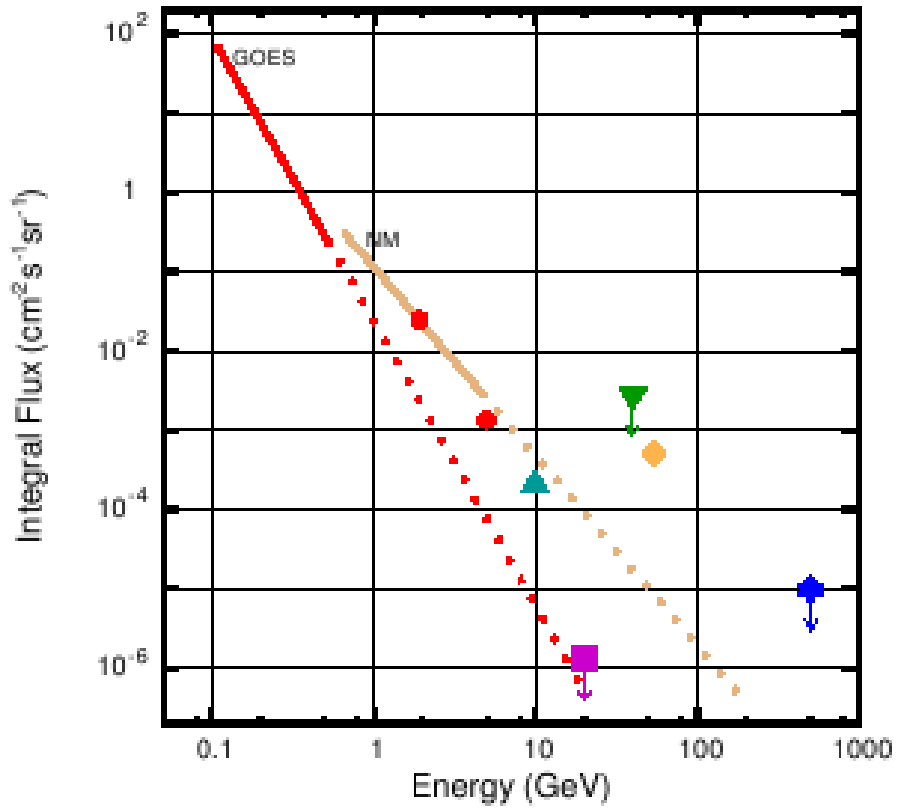
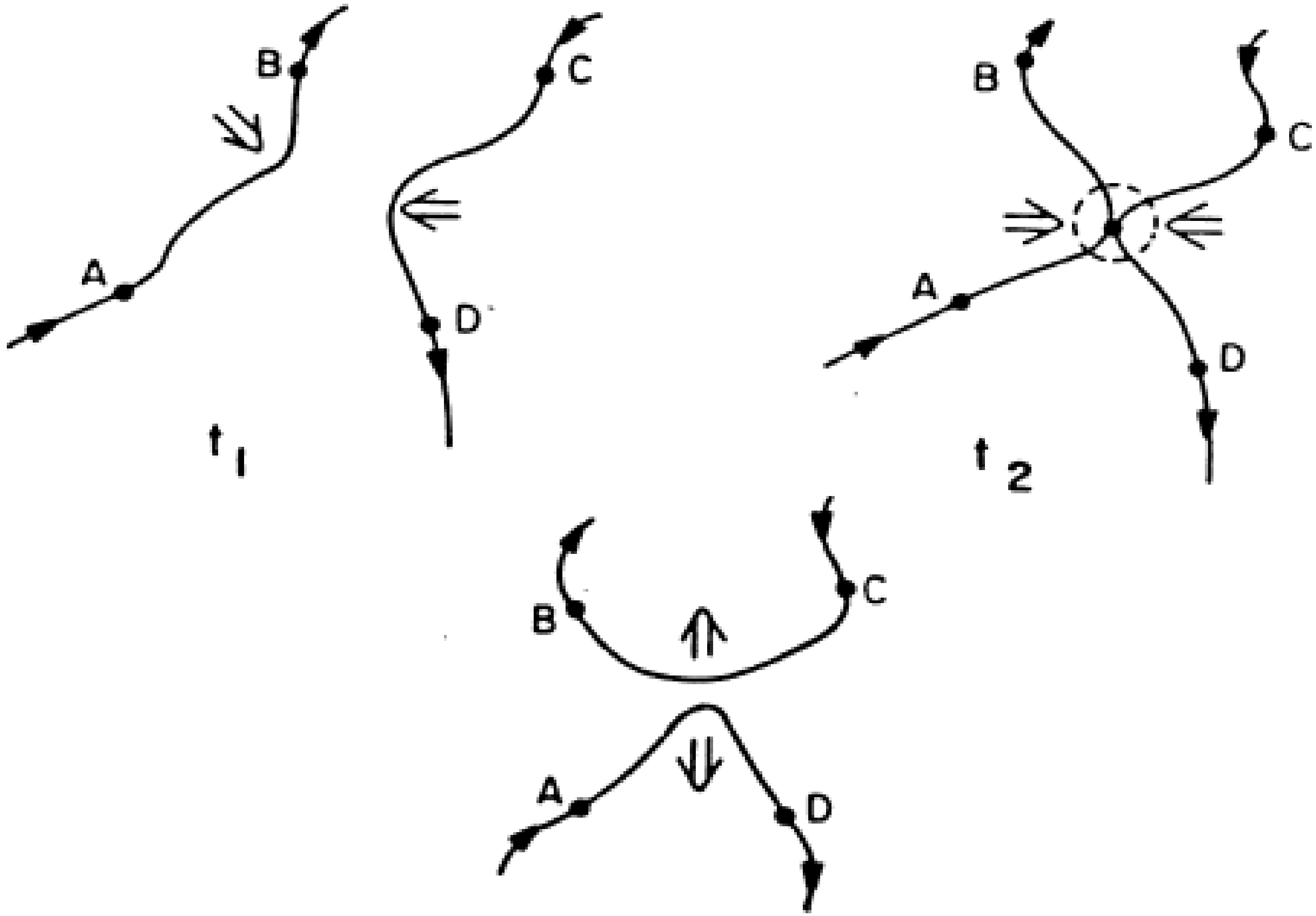


FIG. 11: Integral flux of protons with energy on 28 October 2003; a) Based on 100-600 MeV GOES-10/11 and sub-GeV balloon data, b) World-wide NM data, c) ■ $\gtrsim$20 GeV GRAPES-3 upper limit, d) ▲ >10 GeV AGASA flux on 4 June 1991, e) ▼ >40 GeV L3 upper limit on 14 July 2000, f) ★ >500 GeV Baksan upper limit on 29 September 1989, g) ● NM data on 15 April 2001, h) ⧫ NM data on 23 February 1956.

Microphysical processes: reconnection

- Rearrangement of magnetic field topology
- Stressed field tries to return to potential (i.e., minimum energy) configuration via reconnection
- $\longrightarrow$ release of excess energy
- $\longrightarrow$ direct $\vec{E}$ field acceleration
- Also turbulent outflows $\longrightarrow$ stochastic acceleration

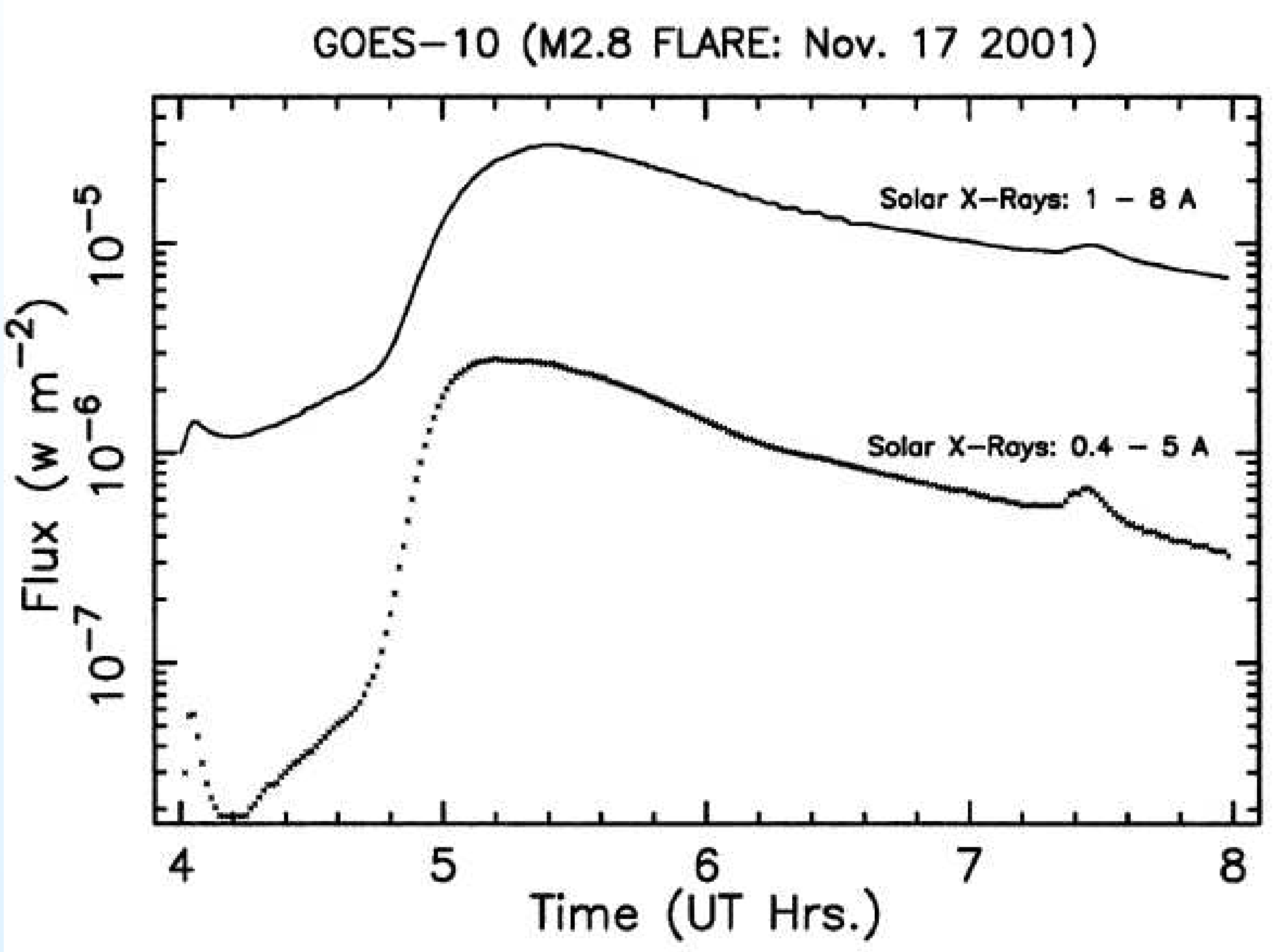
Reconnection



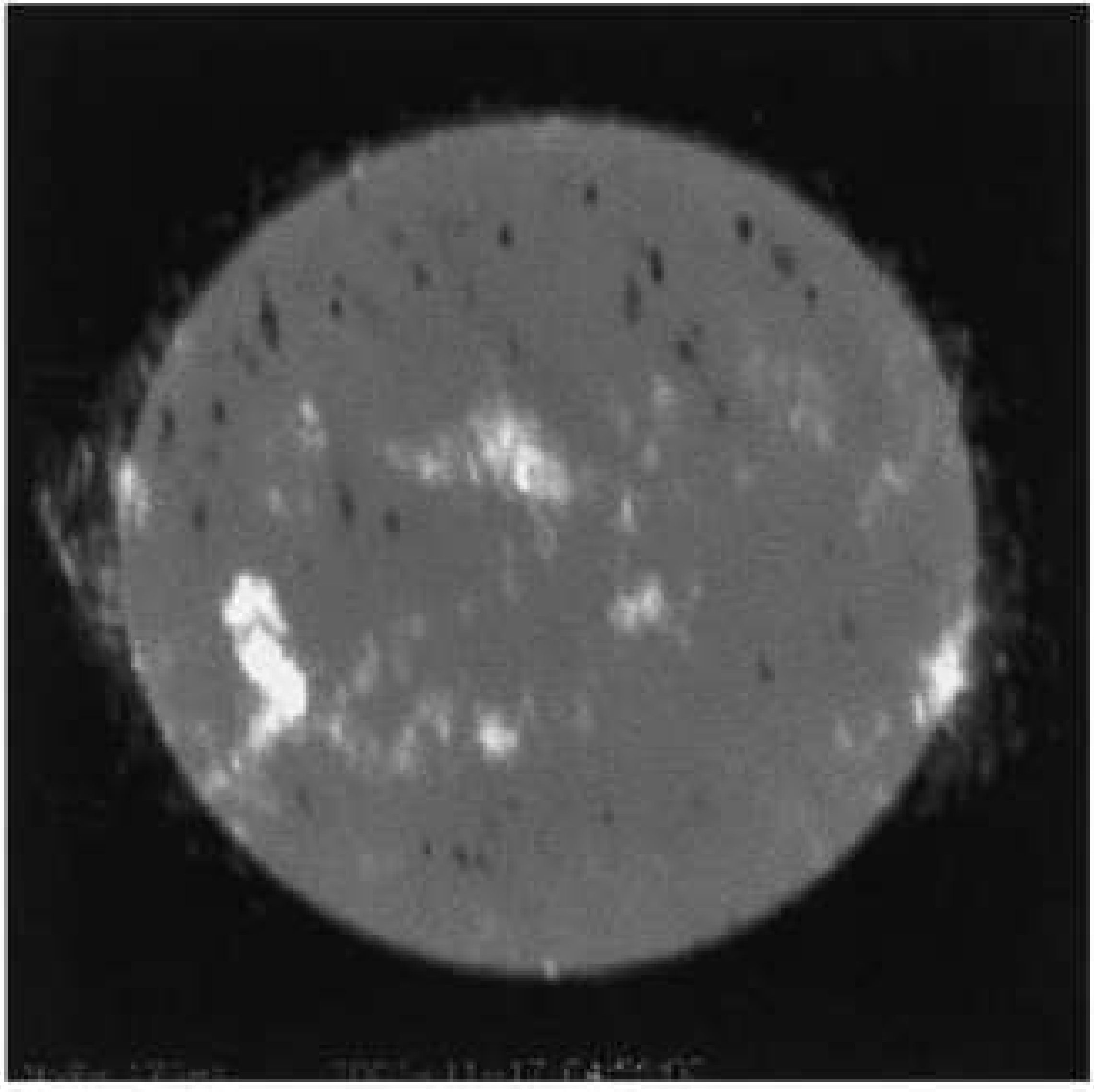
An electron acceleration example

- Subramanian et al (2003, Solar Physics, 218, 247; 2007, Astronomy & Astrophysics, 468, 1099)
- Decimetric continuum at 1060 MHz (≈ 20 cm) observed with GMRT; associated with strong (M class) flare and partial halo CME.

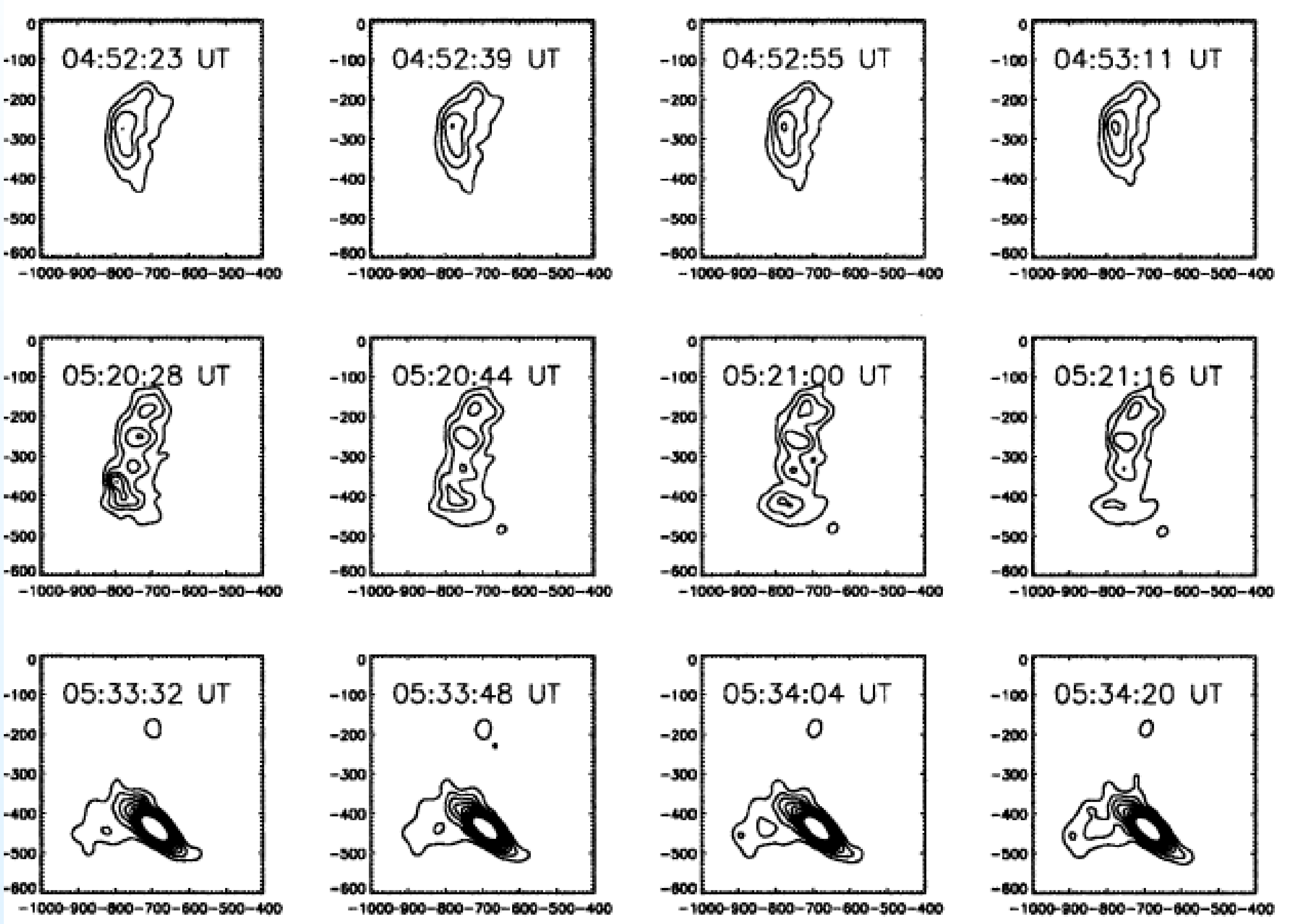
X-ray flare


GOES−10 (M2.8 FLARE: Nov. 17 2001)
Solar X−Rays: 1 − 8 A
Solar X−Rays: 0.4 − 5 A
Flux (w m^{-2})
10^{-5}
10^{-6}
10^{-7}
4
5
6
7
8
Time (UT Hrs.)

Radio source



GMRT (1060 MHz) source



What can one discern about the source

- Brightness temperature of post-flare decimetric continuum $T_b \approx 10^9$ K, so emission is clearly nonthermal
- This kind of emission is known to be due to an emission process known as *plasma emission*, which is initiated by an accelerated electron population
- Assume a 2nd order Fermi acceleration mechanism for the electrons, assume $\mathcal{D} \propto p^2$
- Calculate complete (power-law) spectrum of accelerated electrons, estimate power input $L_{\rm in}$ to the electron acceleration process
- We have a fair idea of the power $L_{\rm out}$ contained in the observed radiation
- The efficiency of the plasma emission process turns out to be $2 \times 10^{-8} > \eta \equiv L_{\rm out}/L_{\rm in} > 2 \times 10^{-9}$