Solar Energetic Particles (SEP's)

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Lecture 1

High-Energy Charged Particles: Topics to be covered in 2 lectures

- Lecture 1:
  - Overview of energetic particles in the solar system
  - Basic theory of energetic particle distributions 1
    - Transport concepts, fluctuations, magnetic scattering
- Lecture 2:
  - Basic theory 2: Acceleration Mechanisms
    - Shock acceleration (CMEs and flares)
    - Stochastic acceleration (flares?)
  - Non-diffusive treatment

Cosmic rays or energetic charged particles are present in space wherever collisions are rare enough to permit them to exist.

Sun

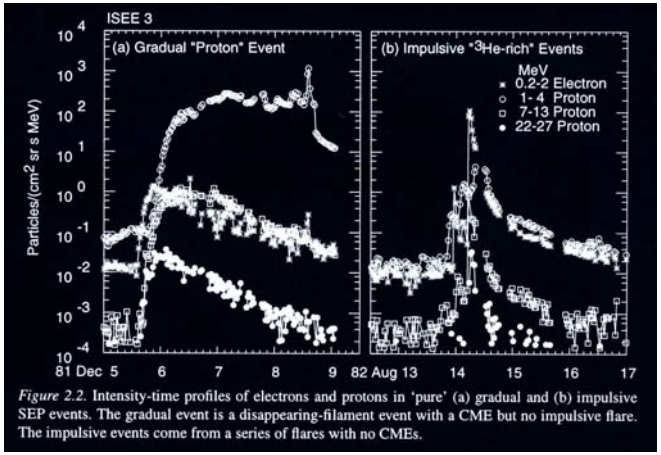
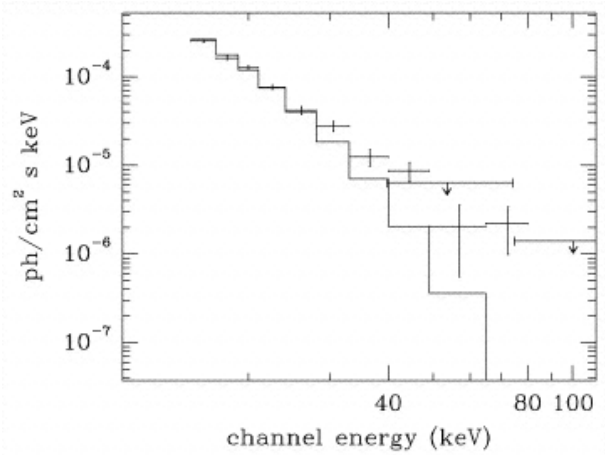


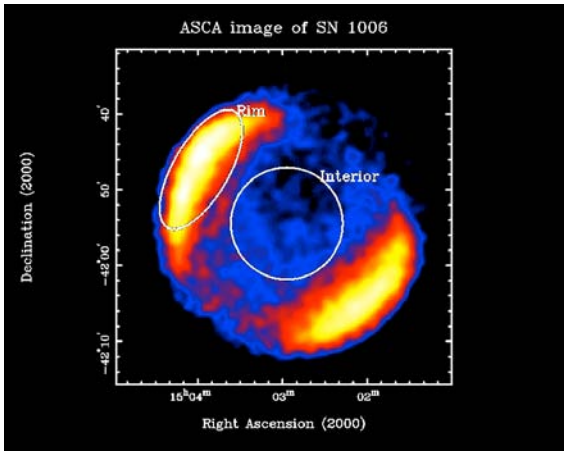
Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.

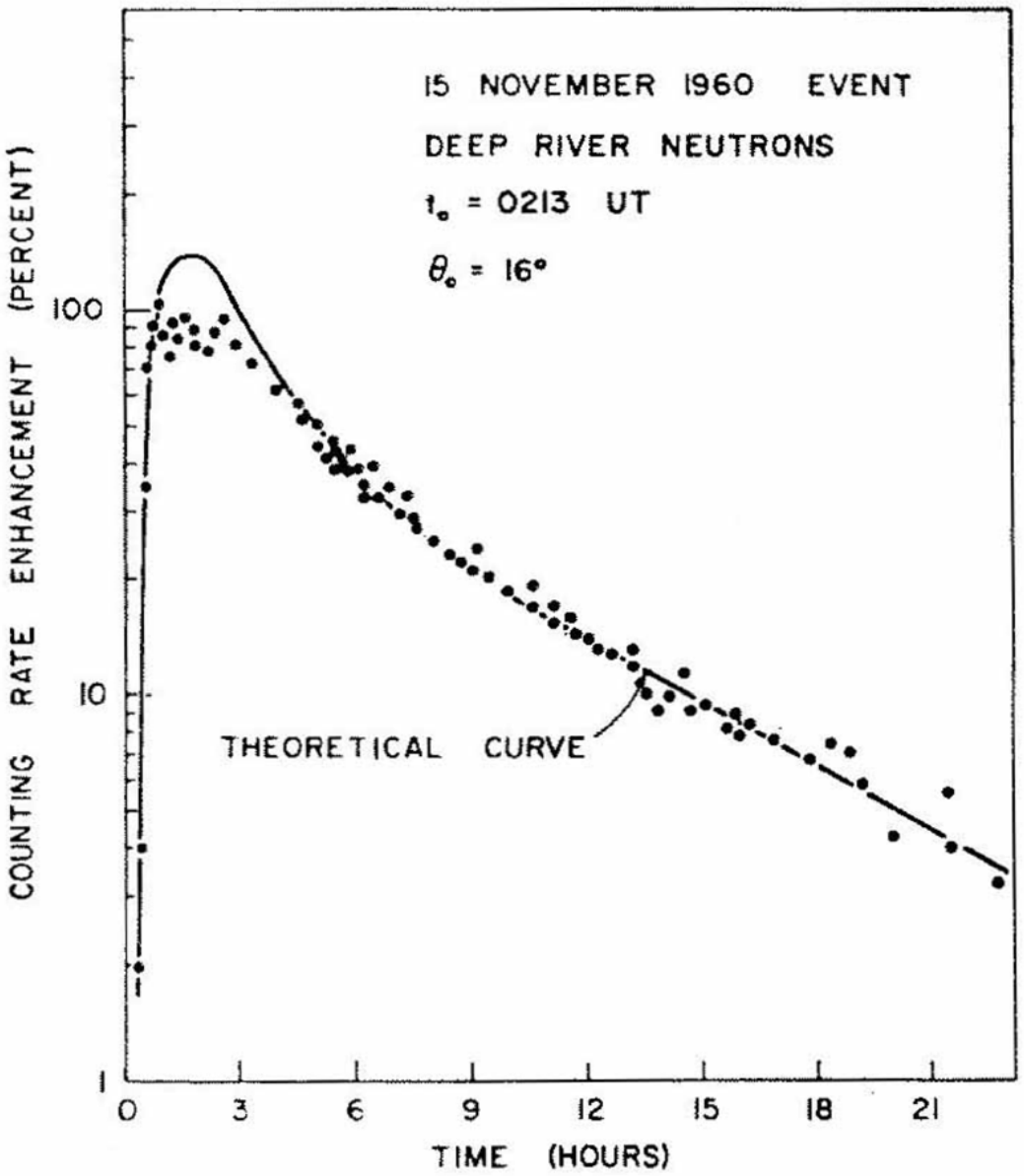
Heliosphere

Coma cluster of galaxeys

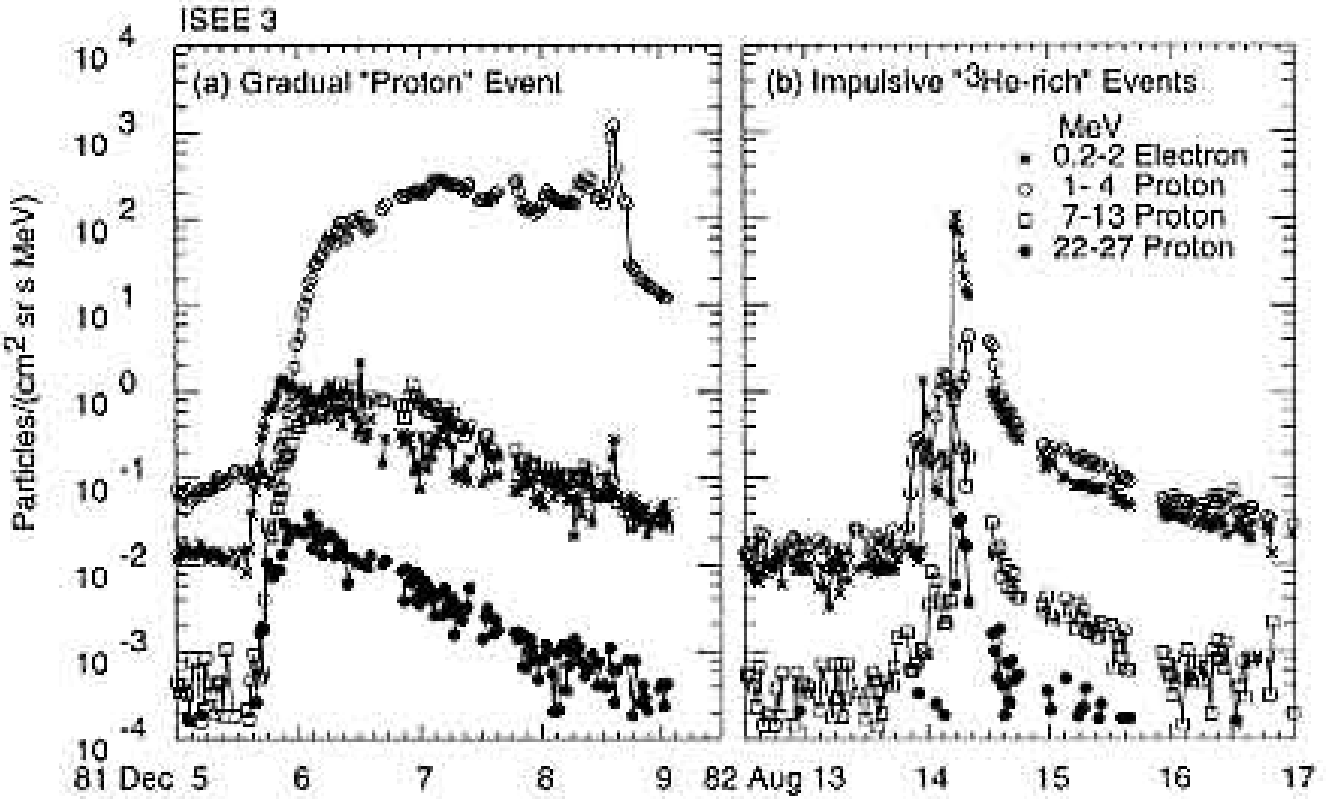


Galactic supernovae





Theoretical fit, using equation 122, to the Deep River neutron monitor data for the November 15, 1960, event. θ_0 is the angle between the flare and the foot of the average magnetic field line passing through the point of observation [*Burlaga*, 1967].



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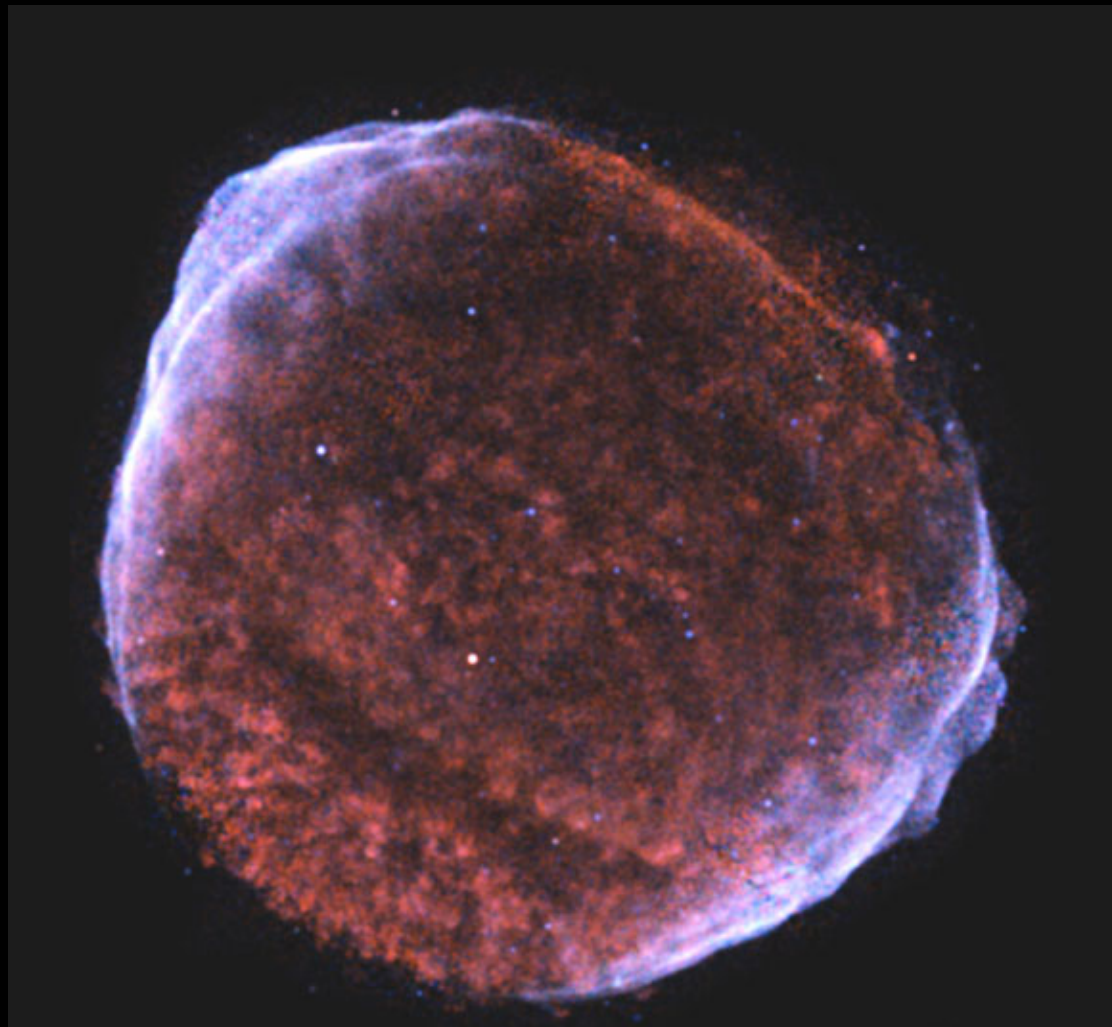
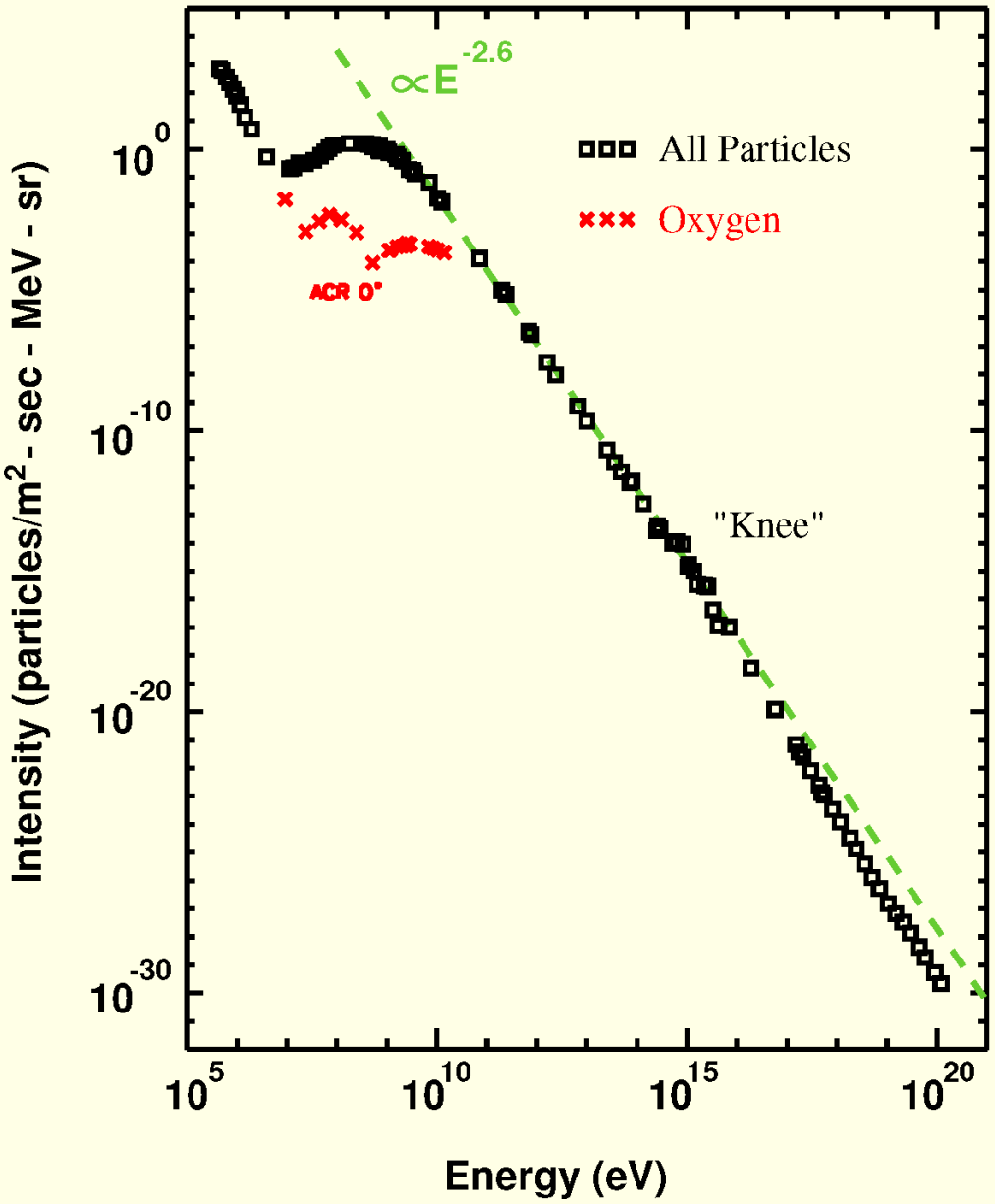
Galactic Cosmic Rays

- Galactic Cosmic Rays up to about 10^{15}eV kinetic energy are believed to originate from supernovae remnants, where they are accelerated by the expanding shock wave

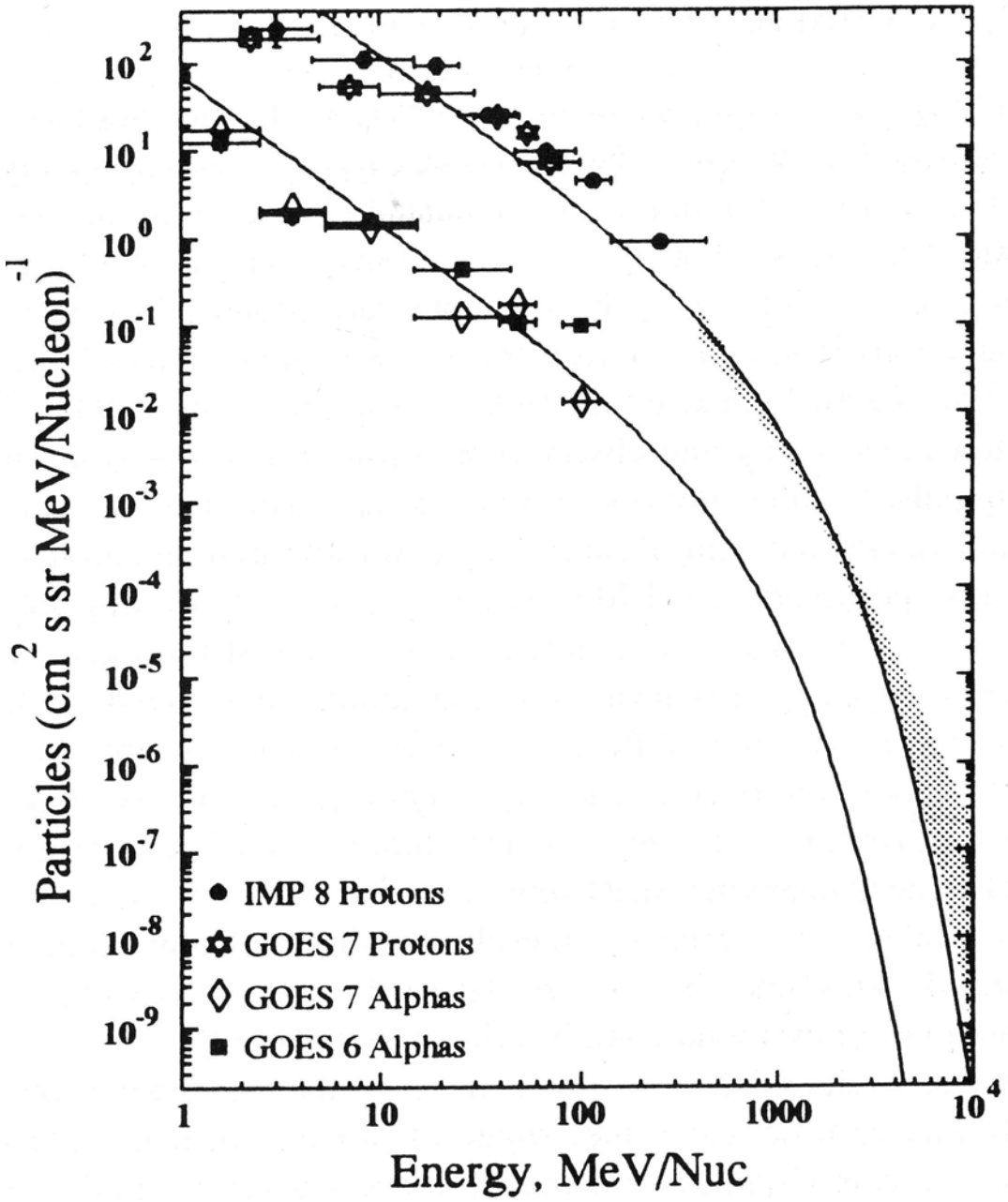


Supernova Remnant 1006 – Chandra image

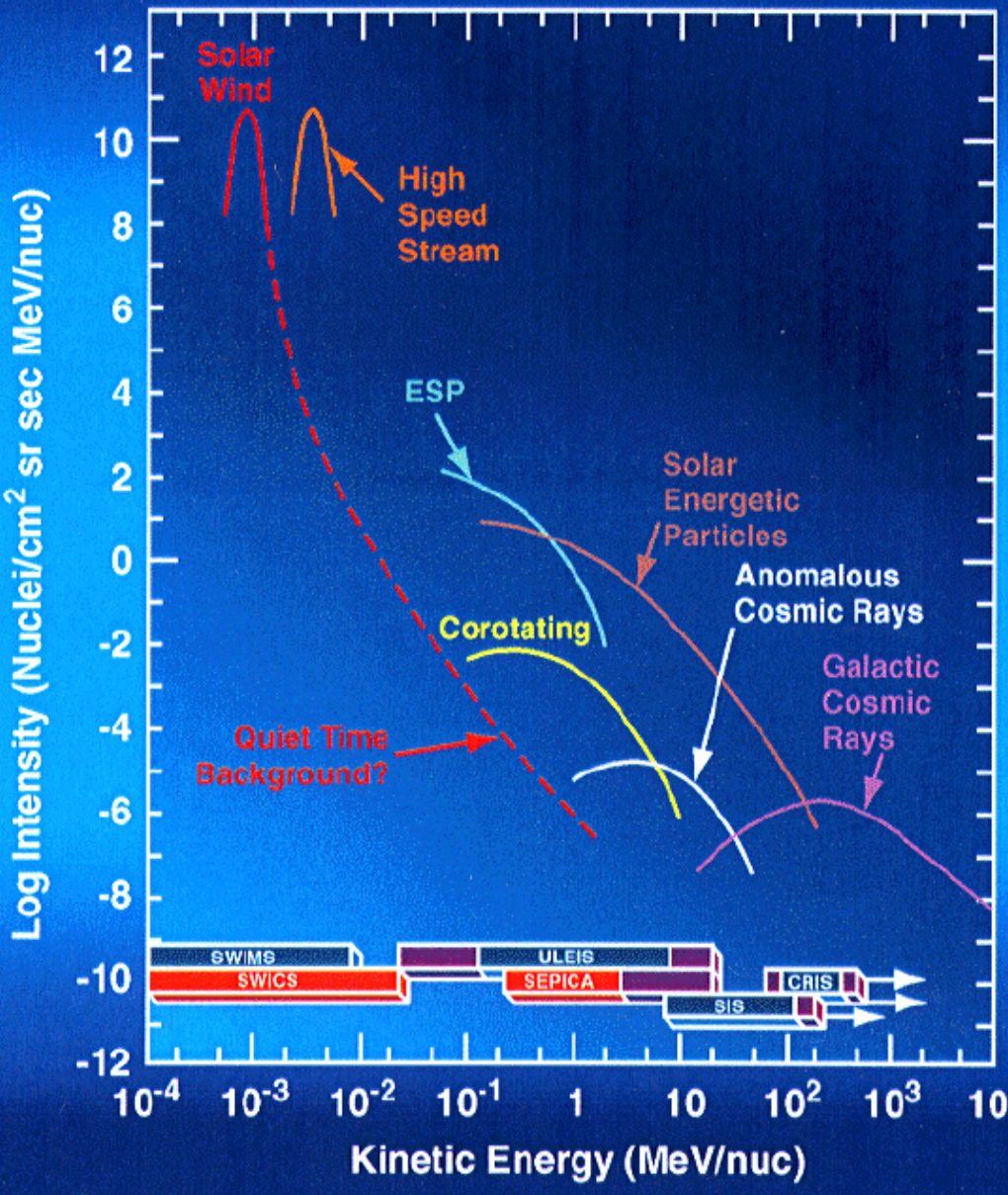
Cosmic-Ray Spectrum



Spectrum of SEP's

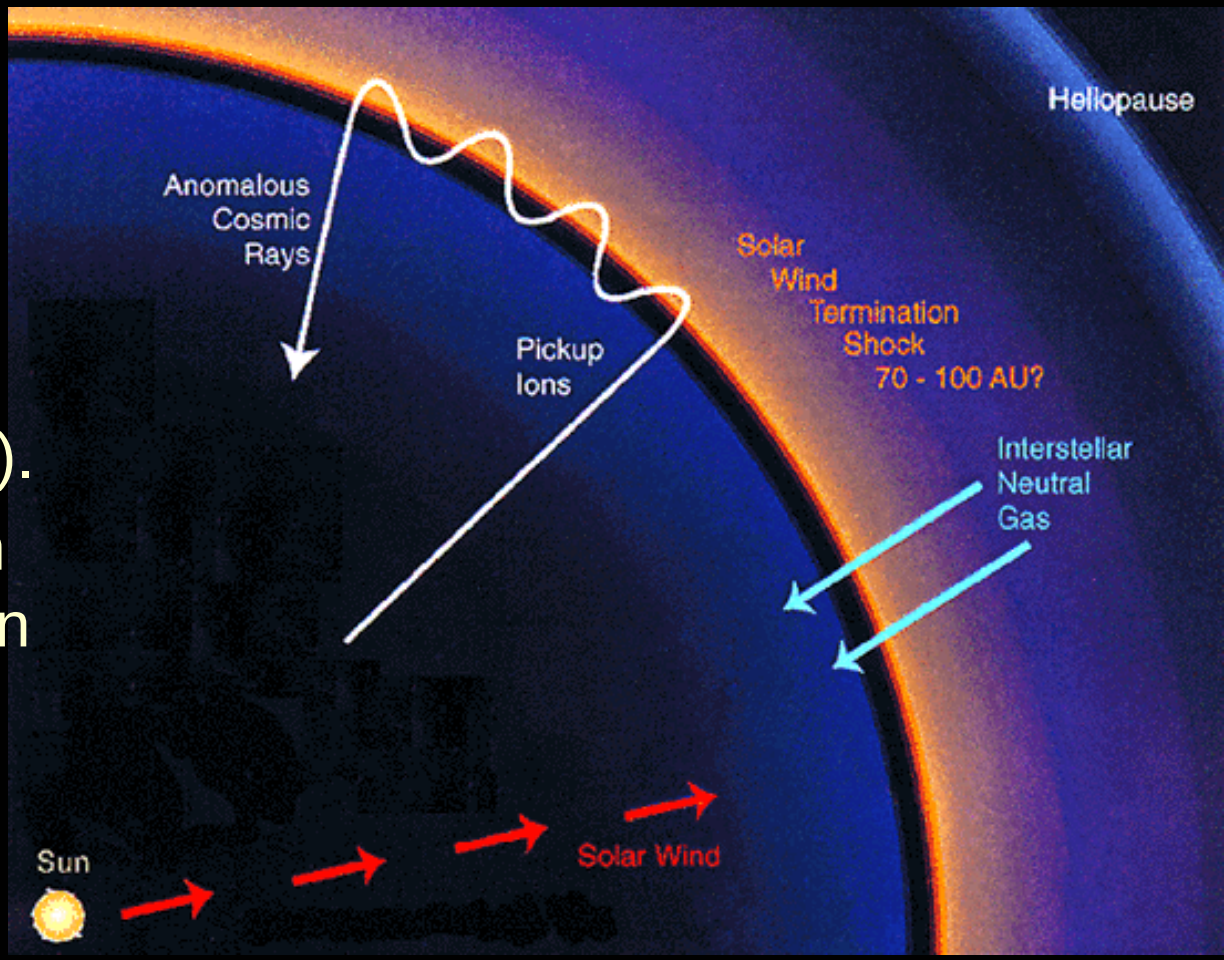


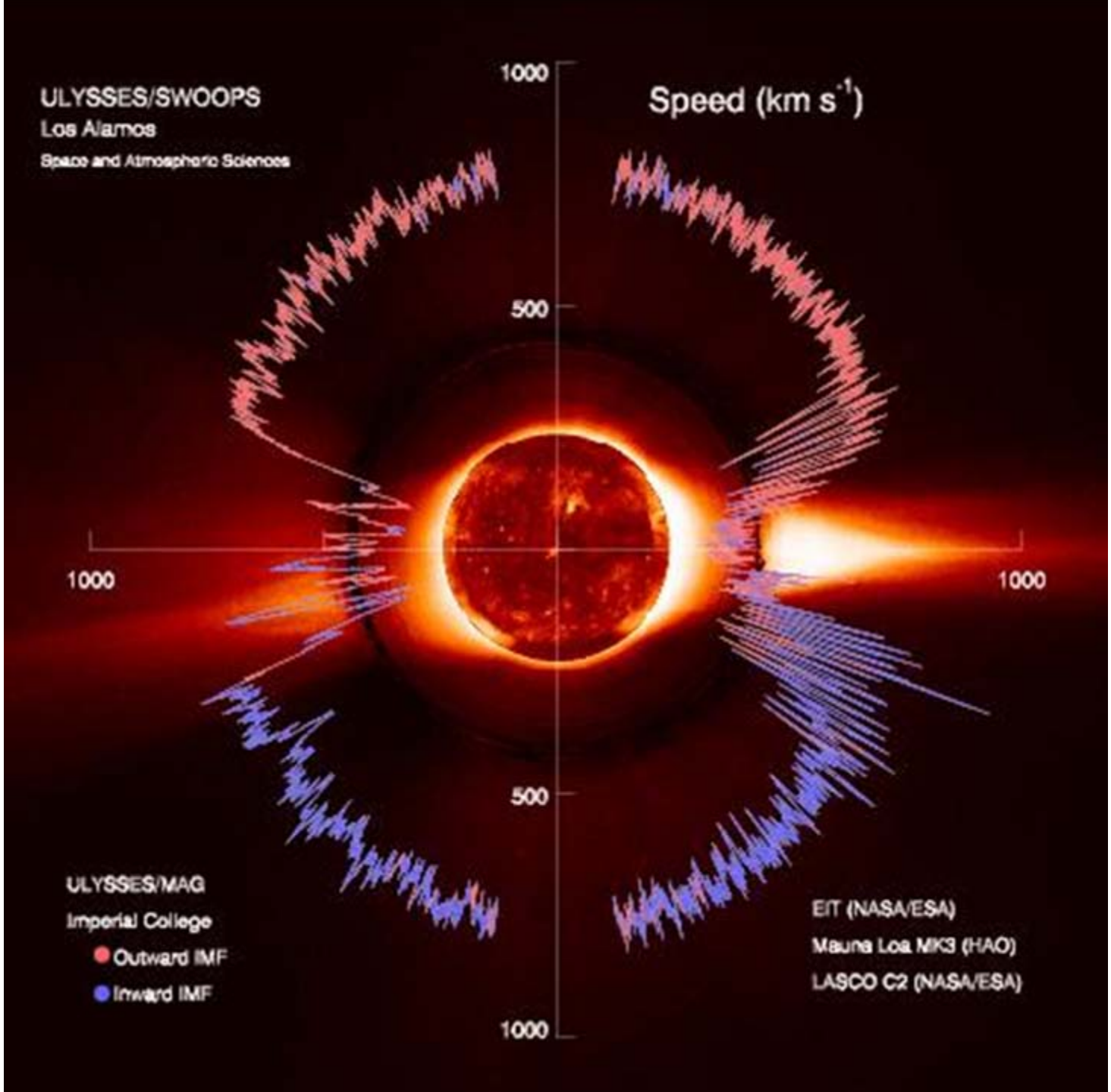
Spectra of Energetic Oxygen Nuclei



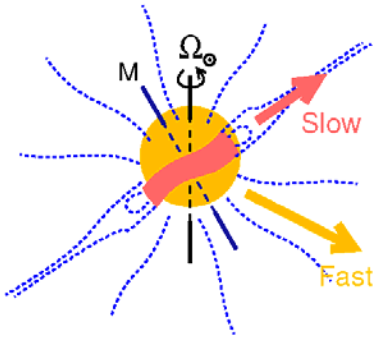
Anomalous Cosmic Rays

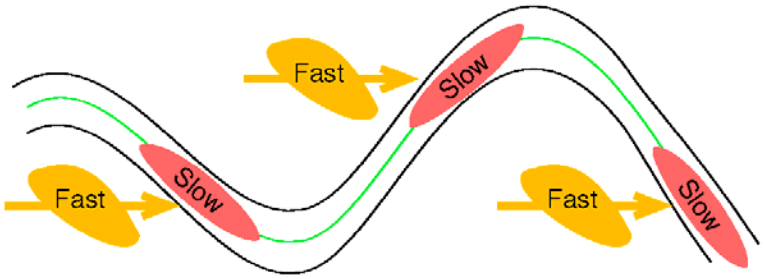
- Accelerated interstellar pickup ions
- Low charge states (+1) imply that they are accelerated rapidly (about 1 year).
- The best explanation for this is acceleration by a termination shock that is *nearly perpendicular* over most of its surface

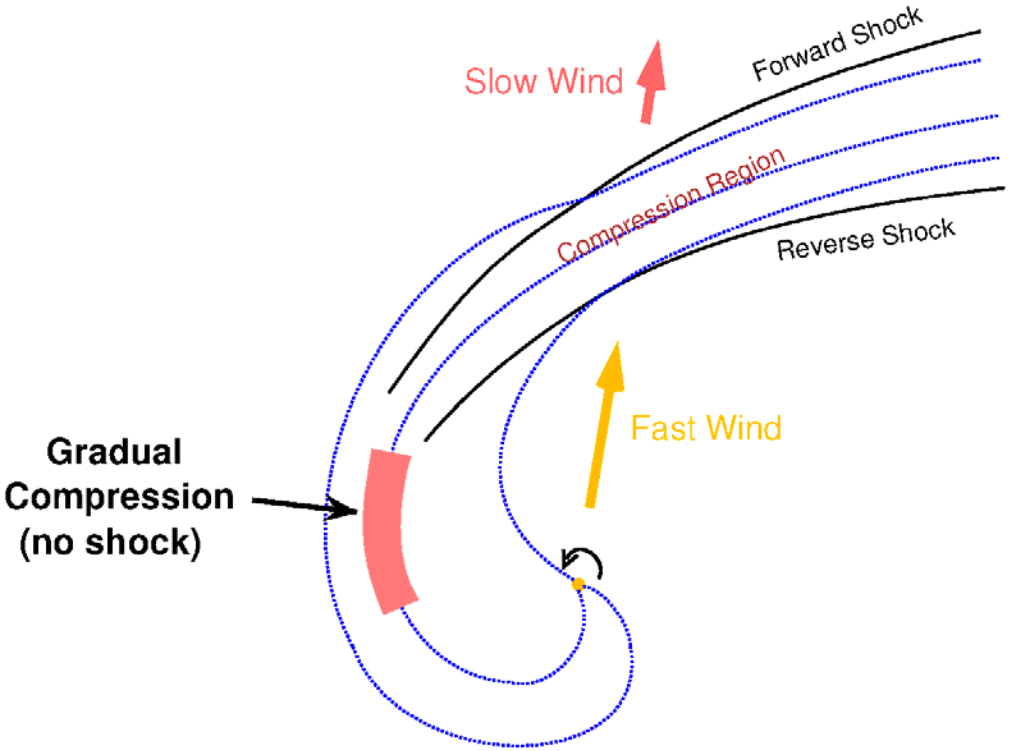



ULYSSES/SWOOPS
Los Alamos
Space and Atmospheric Sciences
Speed (km s-1)
1000
500
1000
1000
500
1000
ULYSSES/MAG
Imperial College
Outward IMF
Inward IMF
EIT (NASA/ESA)
Mauna Loa MK3 (HAO)
LASCO C2 (NASA/ESA)

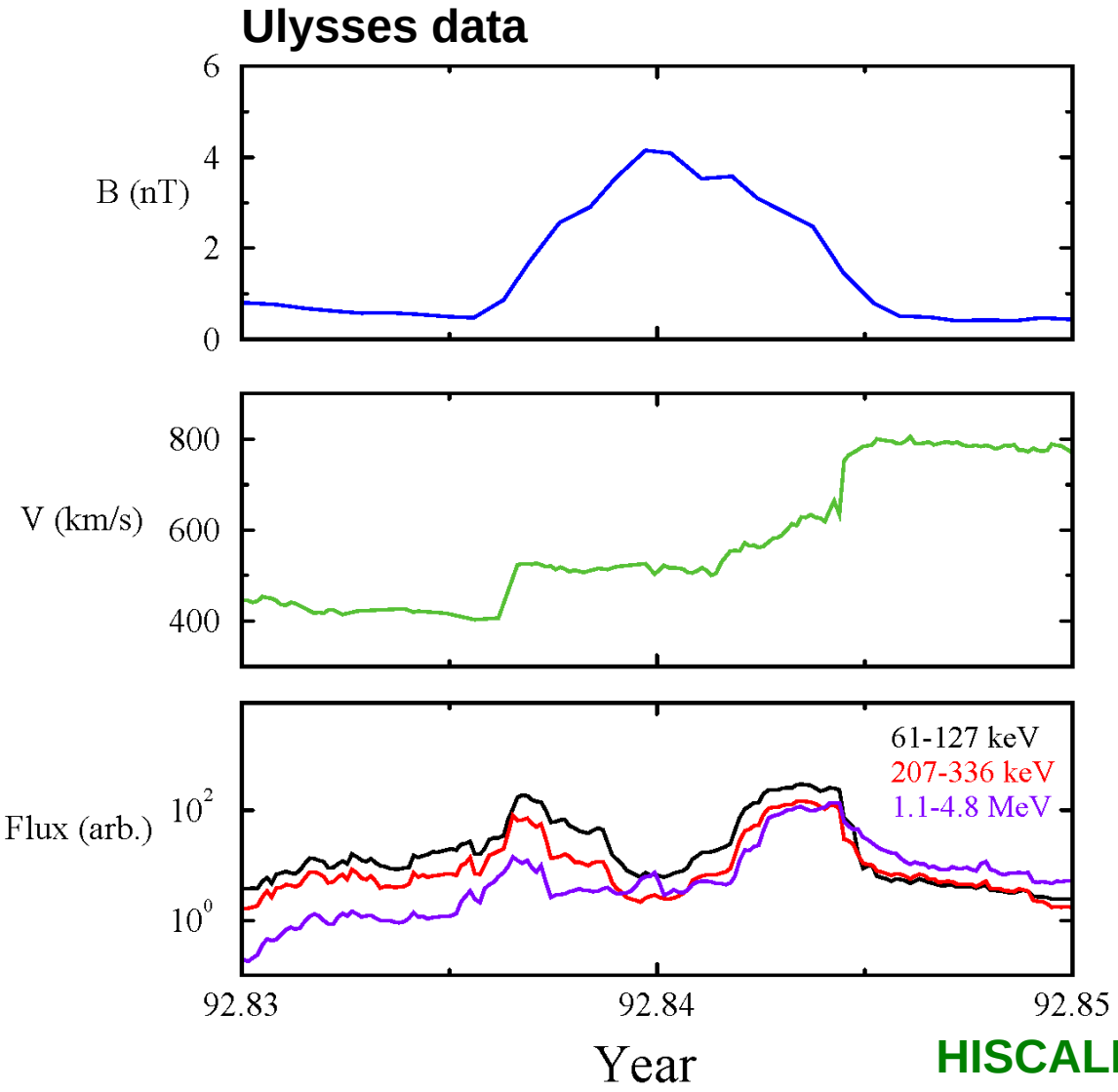
Co-rotating Interaction Regions







Corotating Interaction Regions



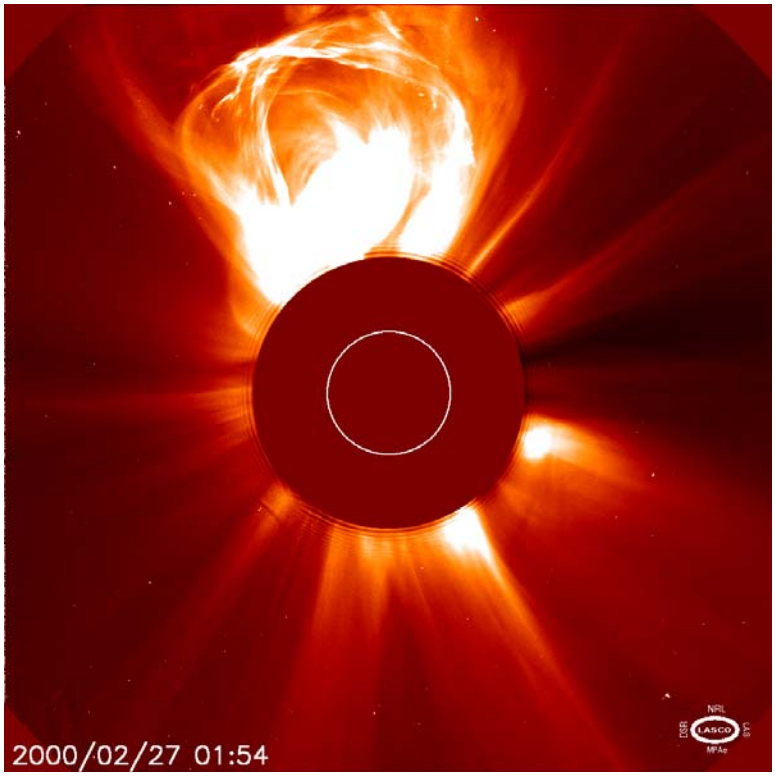
Compression of the magnetic field within CIR.

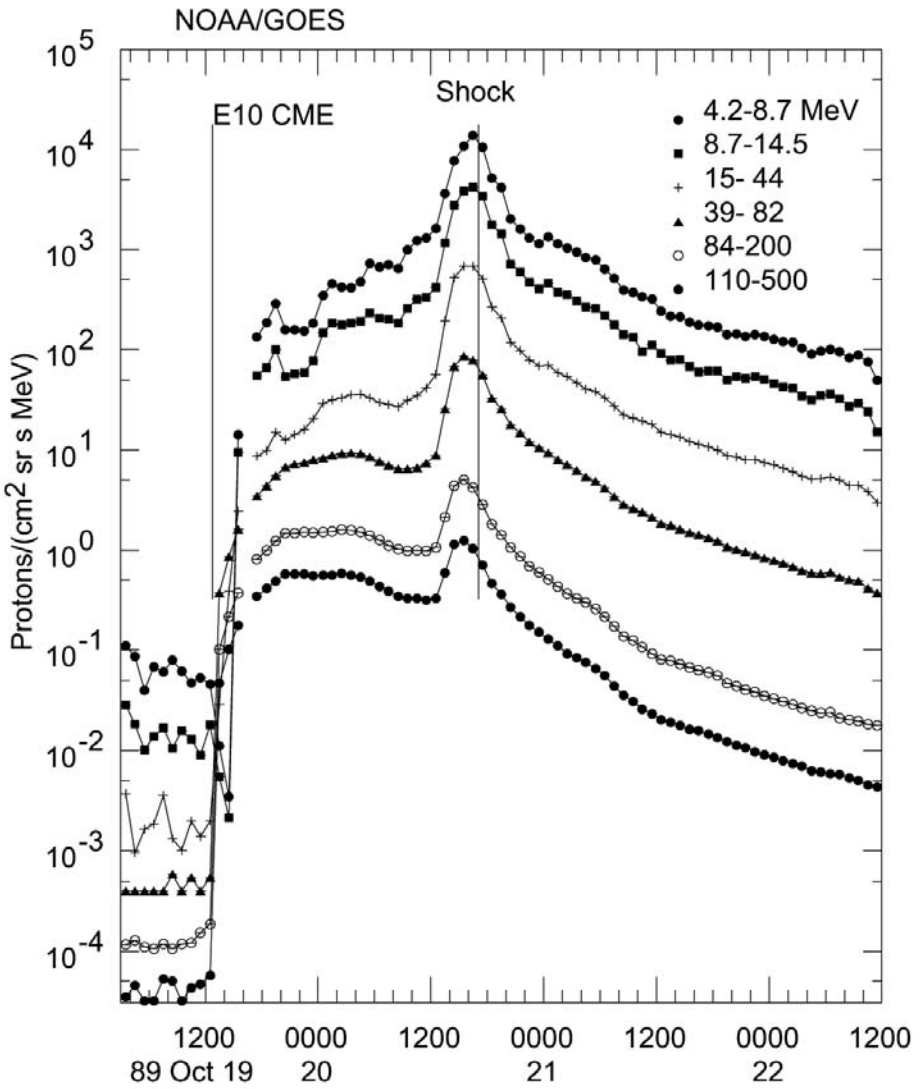
Slow, intermediate, and fast wind and both a Forward (F) and Reverse (R) shock.

Energetic Particles peaking at The F/R shocks, with a larger intensity at the reverse shock.

HISCALE data courtesy Tom Armstrong

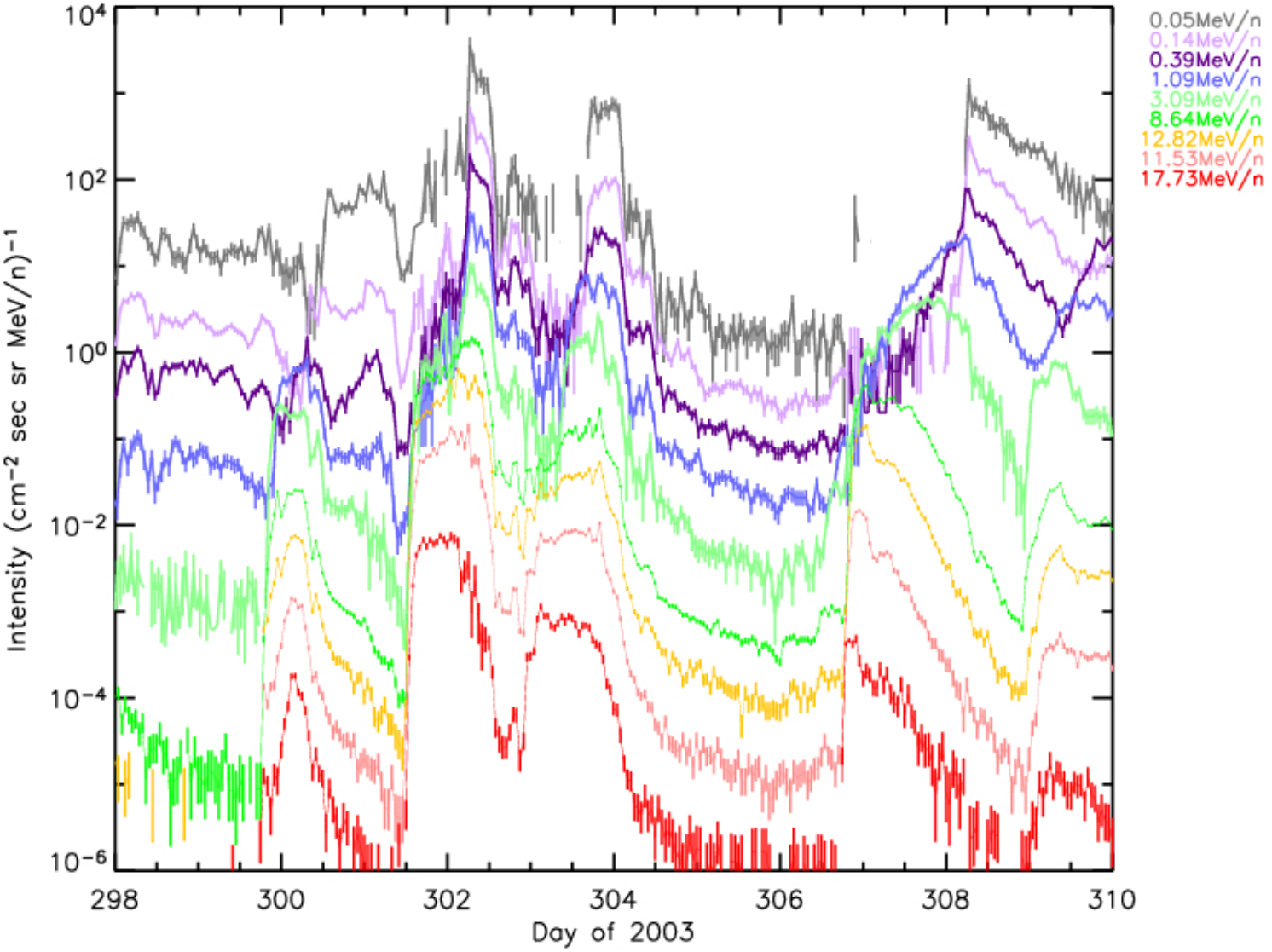
Large CME-related SEP events





Reames.SSR, 1999

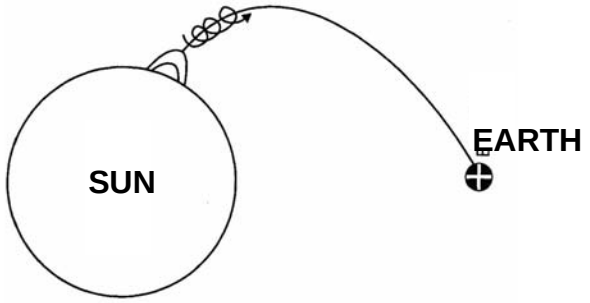
ACE Observations (1AU)



Solar-Energetic Particle (SEP) Paradigms

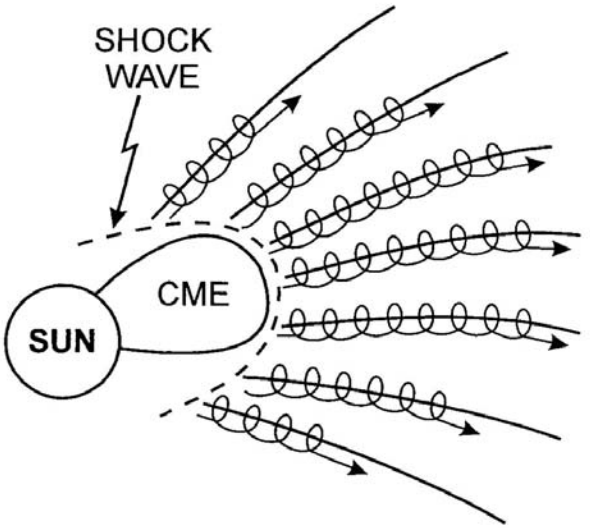
The initial view was that *ALL* SEPs originated from flares

Impulsive Events



In the early-mid 1990's, the two-class paradigm was suggested

Gradual Events

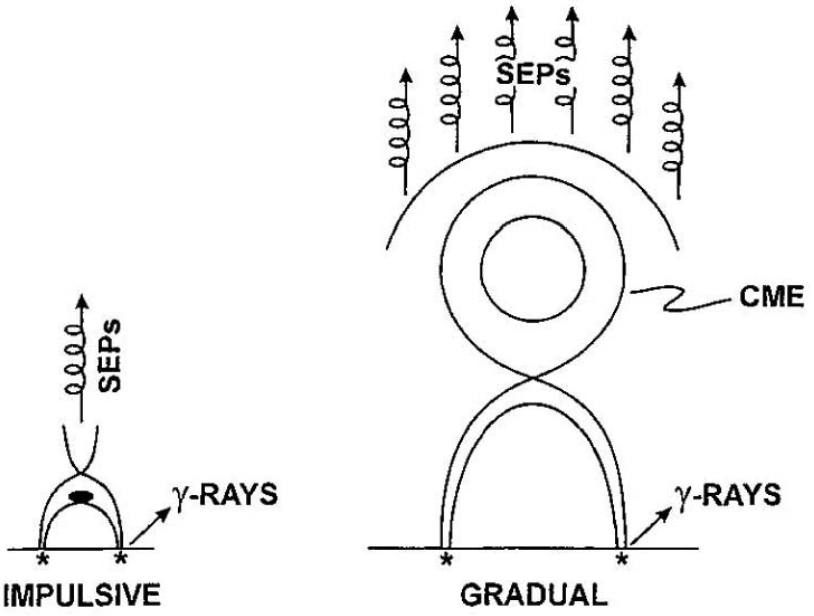


- In the two-class paradigm, SEP events are associated with impulsive solar flares, or gradual solar flares

- More-sensitive instrumentation (ACE, WIND, SOHO, TRACE, etc.) has clearly demonstrated that the distinction is NOT CLEAR

TABLE 1. PROPERTIES OF IMPULSIVE AND GRADUAL EVENTS (45)

	IMPULSIVE	GRADUAL
PARTICLES:	ELECTRON-RICH	PROTON-RICH
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
DURATION	HOURS	DAYS
LONGITUDE CONE	<30°	~180°
RADIO TYPE	III, V(II)	II, IV
X-RAYS	IMPULSIVE	GRADUAL
CORONAGRAPH	---	CME
SOLAR WIND	---	IP SHOCK
EVENTS/YEAR	~1000	~10



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  - Basic theory of energetic particles 1
    - Particle distributions, diffusion, convection
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Lecture # 1

Acceleration

$$\Delta T = \int_t^{t+\Delta t} q \underset{\sim}{w} \cdot \underset{\sim}{E}\, dt$$ along particle trajectory

$\underset{\sim}{E}$ = electric Field

$\underset{\sim}{w}$ = particle velocity

hydro dynamic

$$\Rightarrow \underset{\sim}{E} = -\frac{\underset{\sim}{u} \times \underset{\sim}{B}}{c}$$

deal with ensembles of particles

$f(\underset{\sim}{p}, \underset{\sim}{r}, t)$ = phase space distribution

$f(\underset{\sim}{p}, \underset{\sim}{r}, t) d^3r d^3p$ = # particles at position $\underset{\sim}{r}$, momentum $\underset{\sim}{p}$ in volume element $d^3p d^3r$

... 6 Dimensions

observers $\Rightarrow \frac{dj}{d\Pi} = p^2 f$

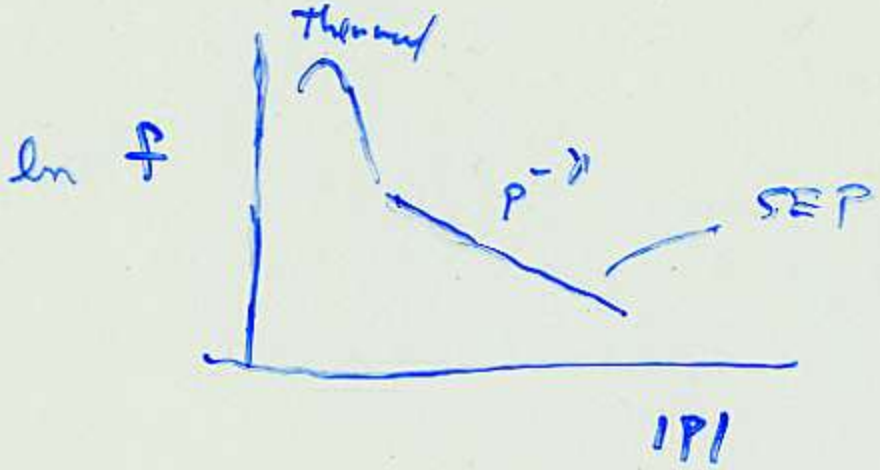
per unit energy per unit solid angle.

in most cases

f is isotropic

if $f \propto p^{-5}$

$$\frac{dj}{d\Pi} \propto p^{-3}$$



$n_{ep} << n_{thermal}$

$n_e(T_{ep}) << n k T$

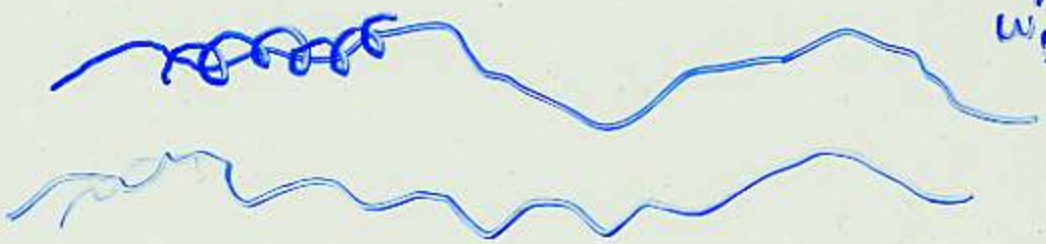
$<< n m_p u^2$

Therefore: treat SEP's as "test" particles

$$m \frac{dw}{dt} = q \underset{\sim}{E} + \frac{q}{c} \underset{\sim}{w} \times \underset{\sim}{B}$$

α pitch angle

$w_g = \frac{mc^2}{qE}$

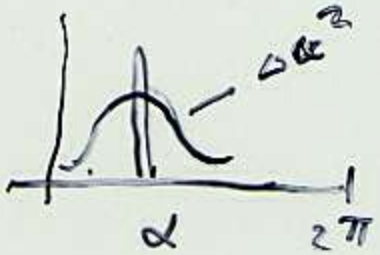


α changes random way

$\Rightarrow$ isotropy $\Rightarrow$ scattering.

quasilinear approx.

$$\Rightarrow \frac{\langle \Delta\alpha^2 \rangle}{\Delta t} \propto P\left(k \sim \frac{1}{r_c \cos\alpha}\right)$$

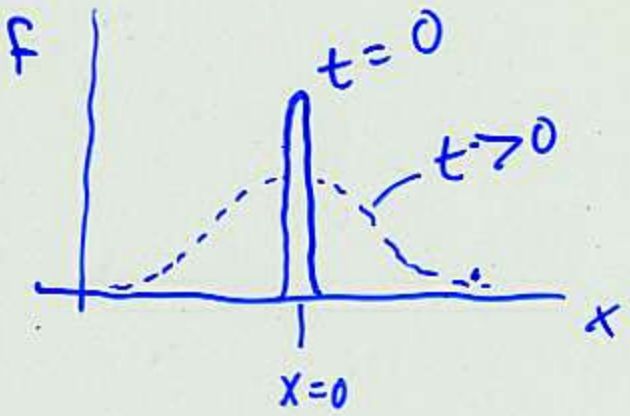


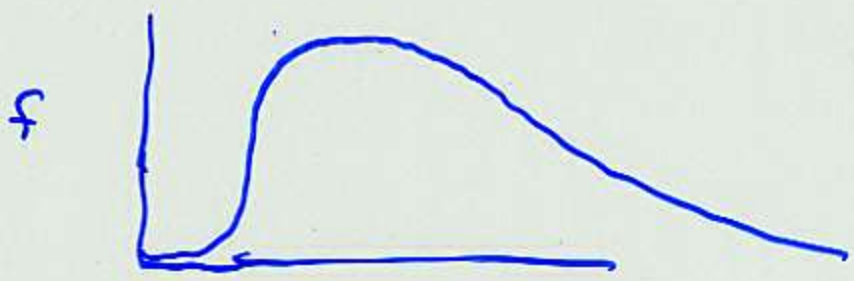
$\Rightarrow \lambda_{sc}. \Rightarrow \kappa \sim \frac{1}{3} w \lambda_{sc}$

$\Rightarrow$ diffusion equation

$$\frac{\partial f}{\partial t} = K \frac{\partial^2 f}{\partial x^2} + Q$$

$$= \frac{\partial}{\partial x}\left(K \frac{\partial f}{\partial x}\right) + Q$$





at a given $x > 0$

$$f = C\, e^{-(x-x_0)^2/2Kt}$$

add

$$\underset{\sim}{U} = V_w \hat{e}_r$$

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial R}\left(k \frac{\partial f}{\partial R}\right) - V_w \frac{\partial f}{\partial r} + \frac{1}{3} \nabla \cdot \underset{\sim}{U} \frac{\partial f}{\partial \ln R} = Q$$