Energetic Particles from Solar Explosions

M. I. Desai, SwRI & UTSA

LWS-IHY Heliophysics Summer School

Energetic ions and electrons from ~few eV -1 GeV observed in the interplanetary medium in association with explosive solar events such as flares and coronal mass ejections

Outline

1. **Overview of Heliospheric Particle Populations**
2. **Types of Solar Energetic Particles - SEPs**
3. **Interplanetary Transport - Theory & Observations**

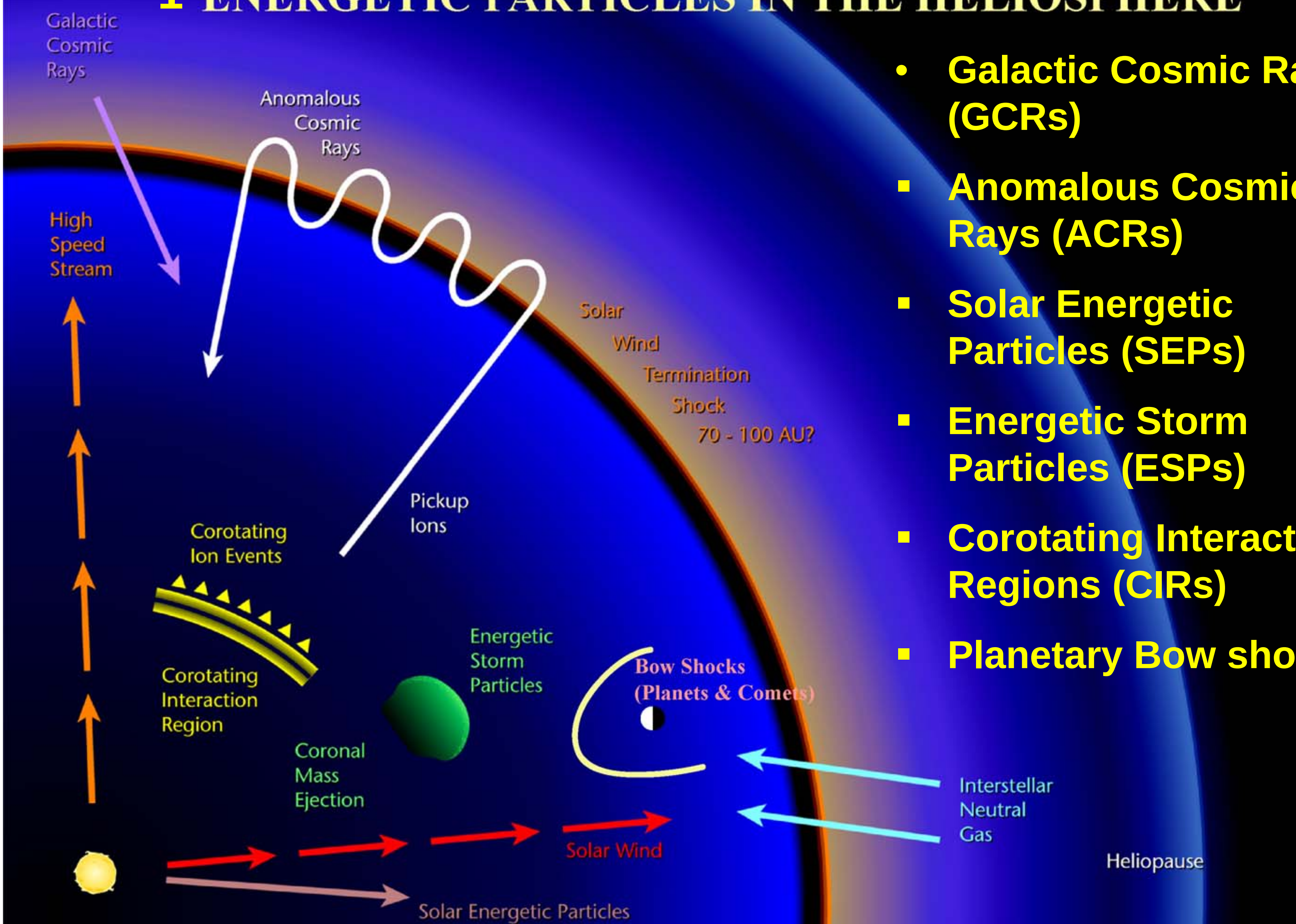
   Diffusion in space, pitch-angle, and momentum, wave-particle interactions, transport equations, Observations - Fits with transport equations

4. **Particle Acceleration - Theory**

   Direct Electric Fields, Shock drift acceleration, diffusive shock acceleration, self-generated turbulence, stochastic acceleration,

5. **SEP - Observations**
6. **Open Questions**

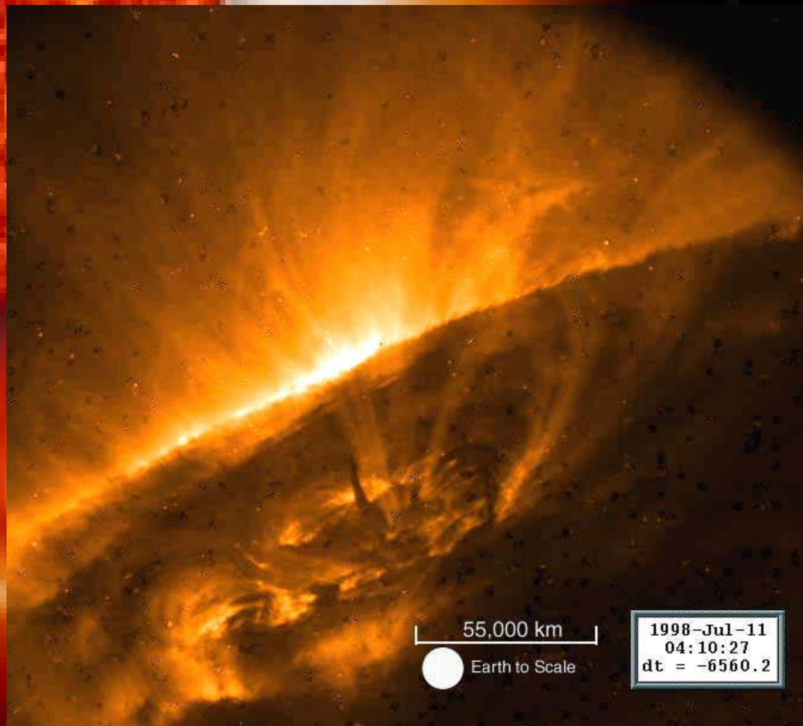
1 ENERGETIC PARTICLES IN THE HELIOSPHERE



- Galactic Cosmic Rays (GCRs)
- Anomalous Cosmic Rays (ACRs)
- Solar Energetic Particles (SEPs)
- Energetic Storm Particles (ESPs)
- Corotating Interaction Regions (CIRs)
- Planetary Bow shocks

Energies range from supra-thermal to 10^{20} eV

2 Solar Flares & CMEs



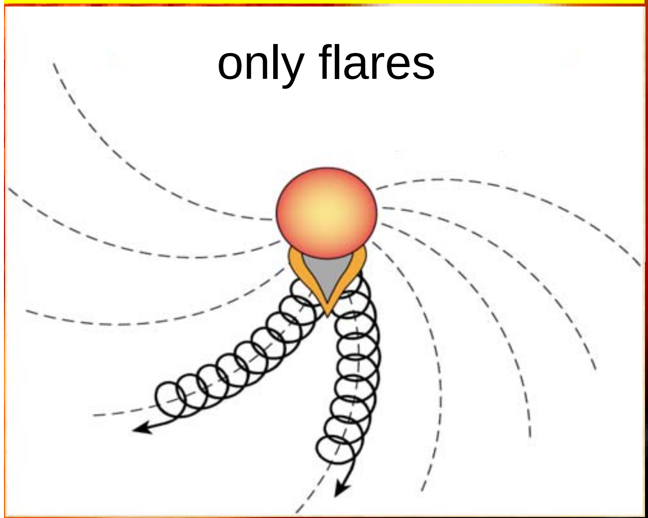
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- **Release ~10^{32} ergs in energy**
- **Plasma heated to ~10MK**
- **Accelerate particles**
  - **electrons to >100 MeV**
  - **ions to >1 GeV.**
- **Magnetic energy released in the solar corona - slow shocks**

- **CMEs drive fast shocks in the corona and interplanetary medium**
- **Shocks accelerate particles**
  - **electrons to >1 MeV (?)**
  - **ions to >1 GeV (?)**

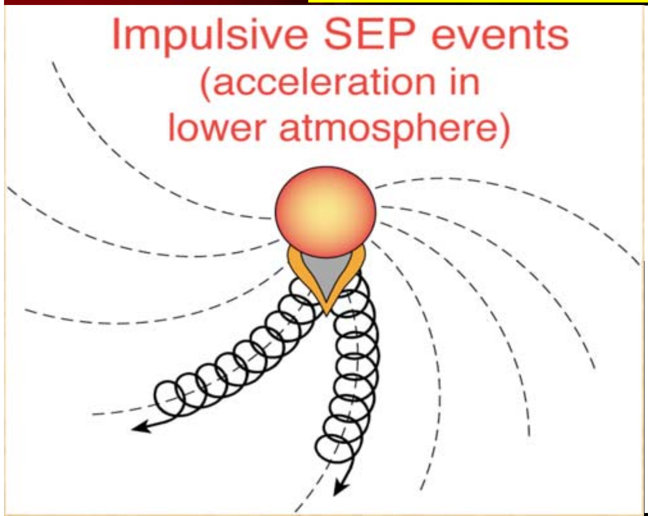
2 Solar Energetic Particles (SEPs)

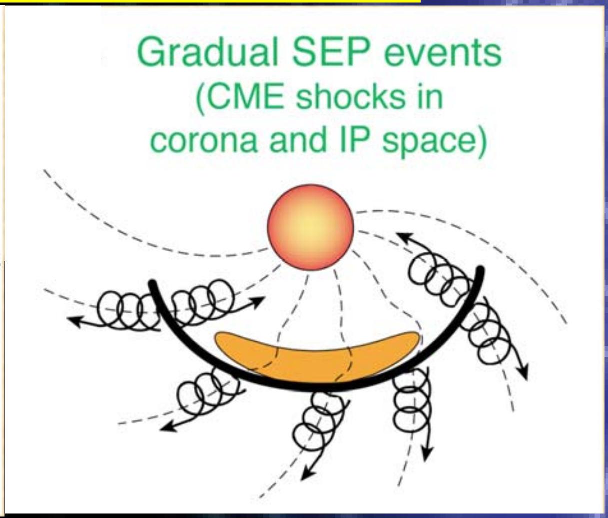
Old picture - up to 1990s'



- First discovered - Forbush 1946 from ground based ion counters
- Closely related to Hα flares - (Meyer 1956)

Current picture - two classes

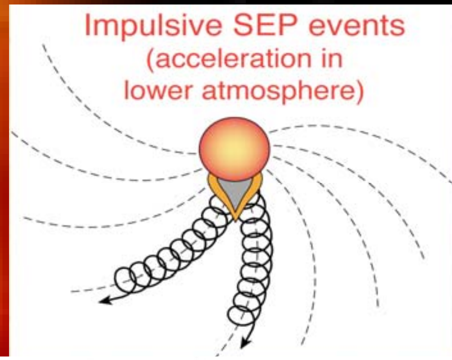




- Kahler et al. (late 1970s and early 1980s) found strong correlation with CMEs
- Cane et al. (1986) made association with 2 types of radio bursts

2 Two-Class Picture

Reames (1995)



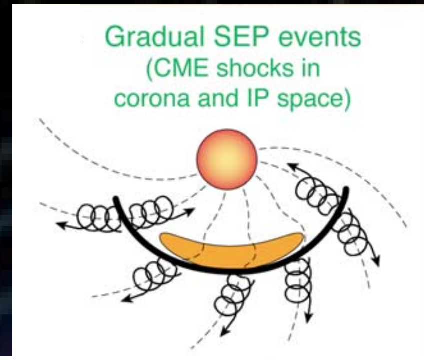
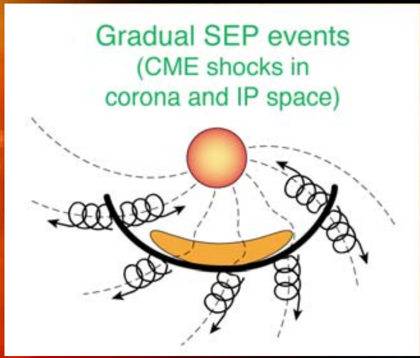


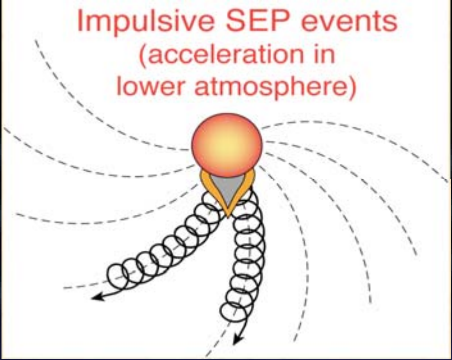
TABLE 1.PROPERTIES OF IMPULSIVE AND GRADUAL EVENTS (45)

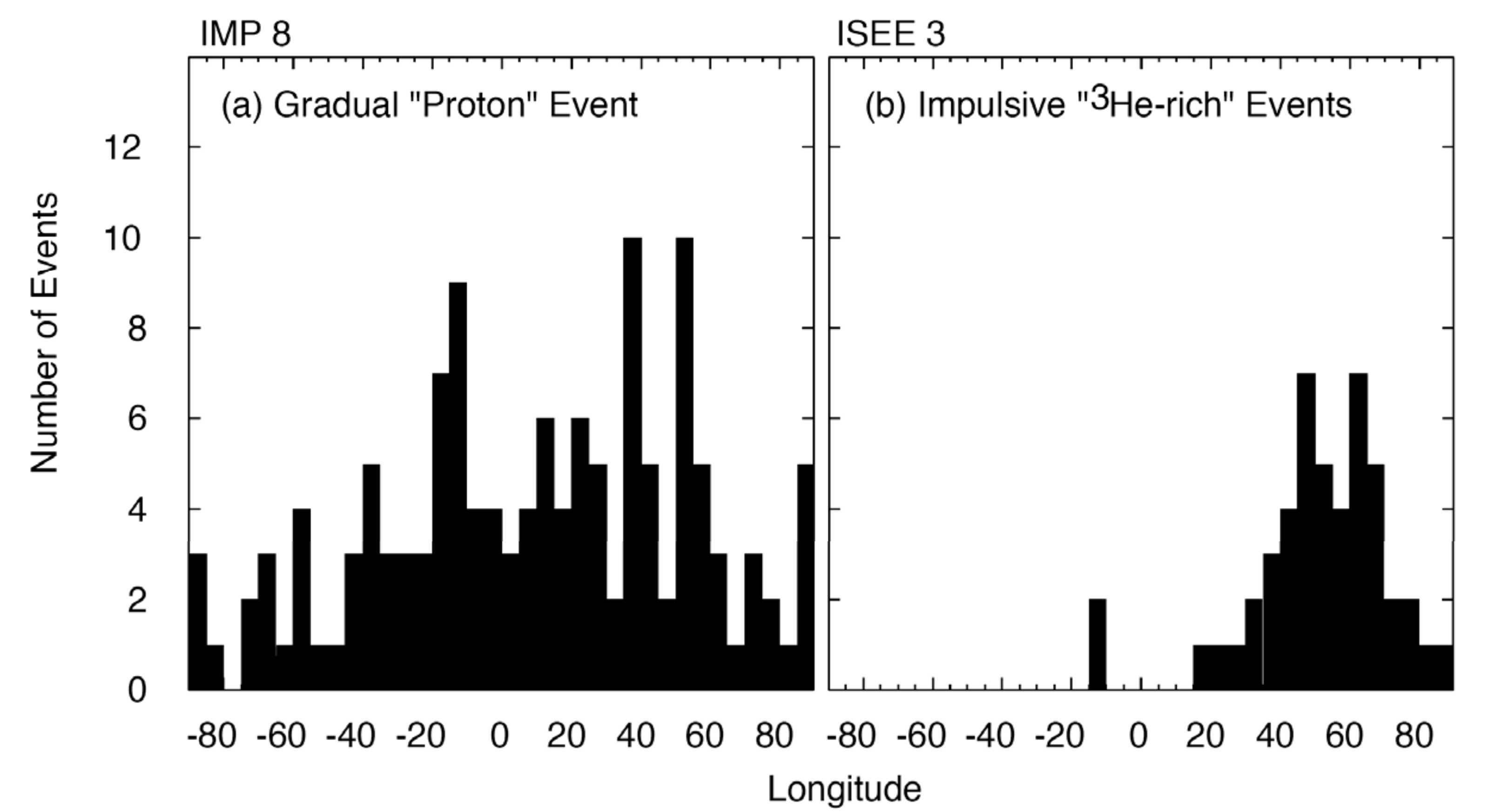
	IMPULSIVE	GRADUAL
PARTICLES:	ELECTRON-RICH	PROTON-RICH
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
DURATION	HOURS	DAYS
LONGITUDE CONE	<30°	~180°
RADIO TYPE	III, V(II)	II, IV
X-RAYS	IMPULSIVE	GRADUAL
CORONAGRAPH	---	CME
SOLAR WIND	---	IP SHOCK
EVENTS/YEAR	~1000	~10

2 Solar Longitude-dependence

Reames (1999)

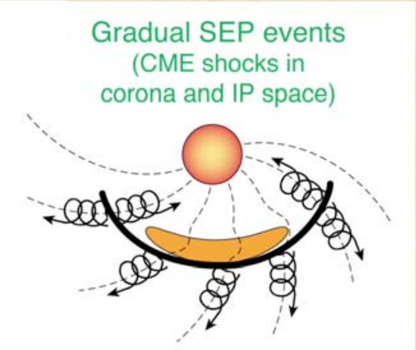


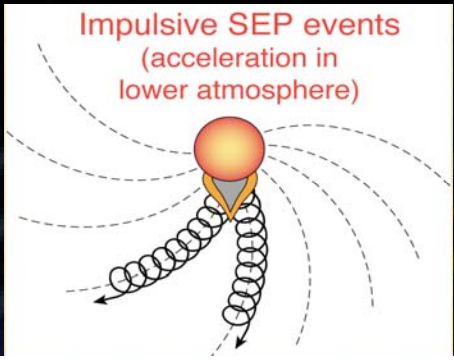


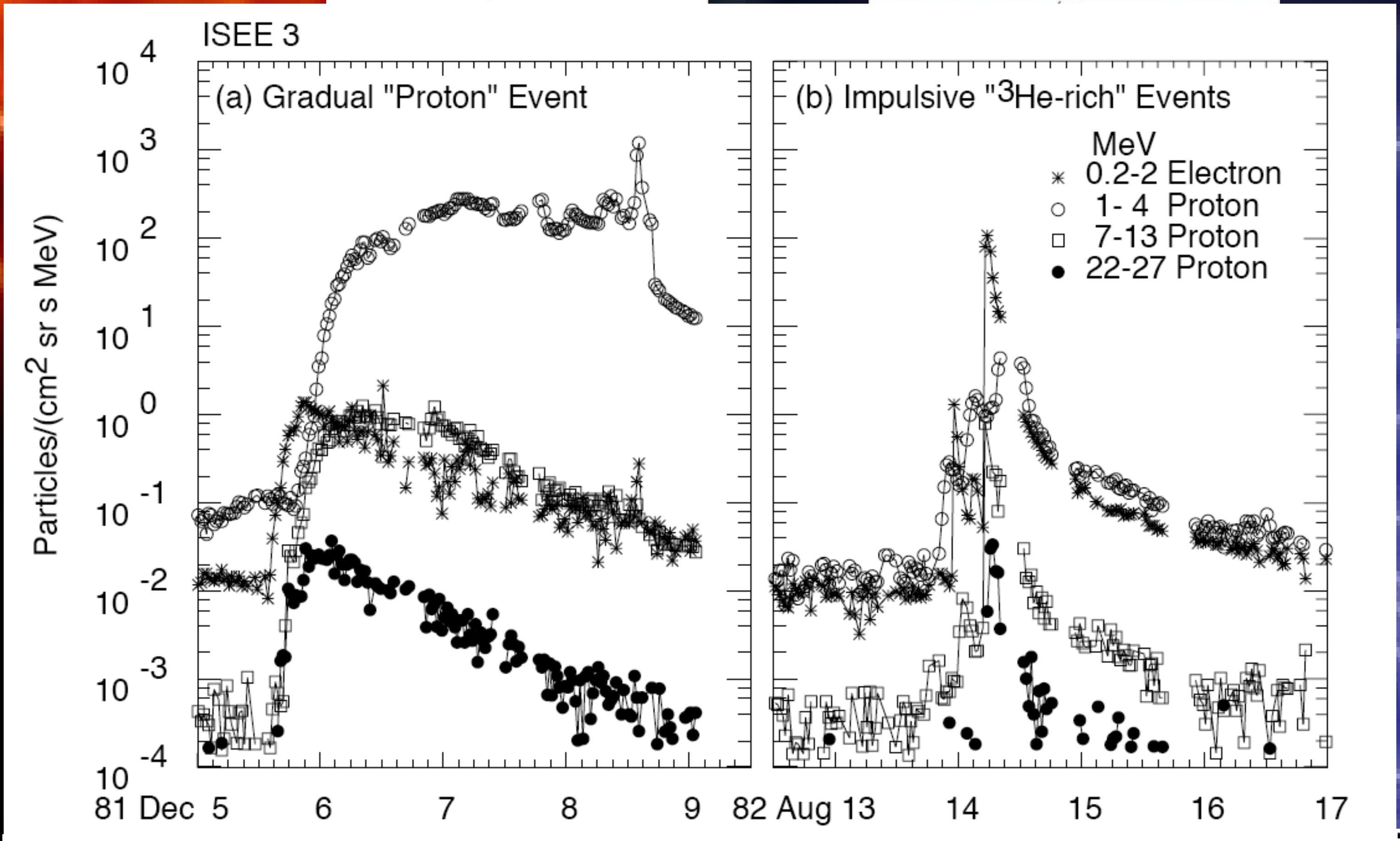


2 Intensity-profiles

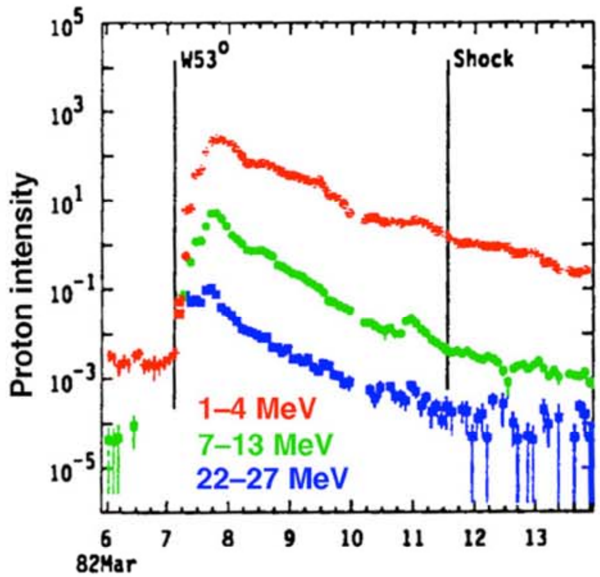
Reames (1999)

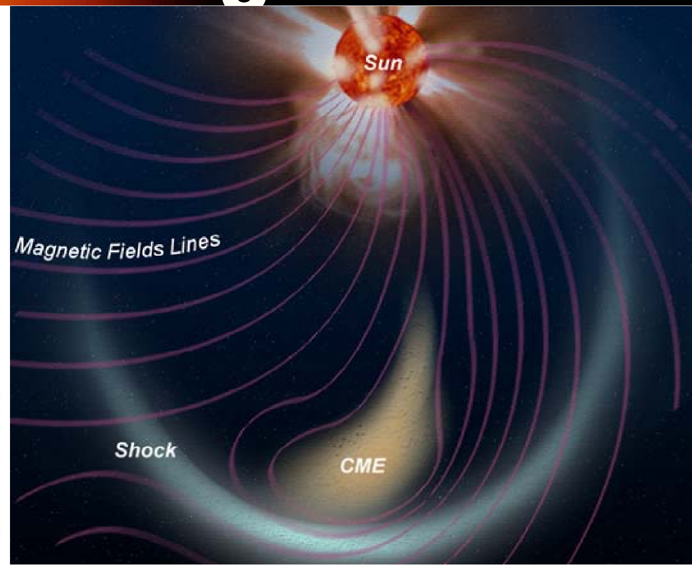


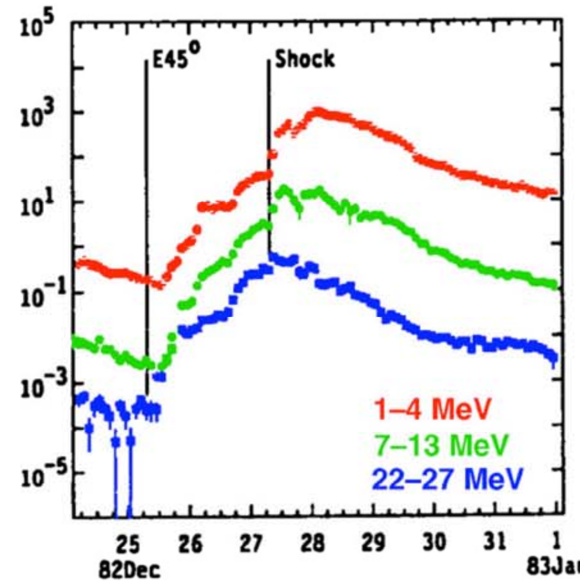


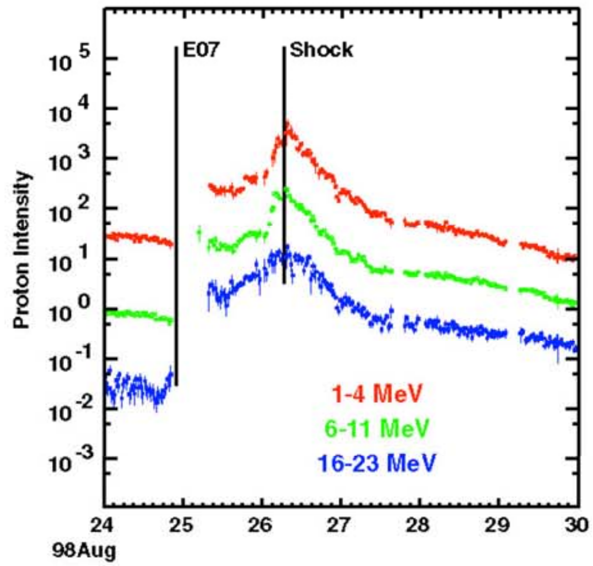


2 Longitudinal Distribution of large gradual SEPs









Only the fastest CMEs (top 1-2 %) drive shocks which make high-energy particles.

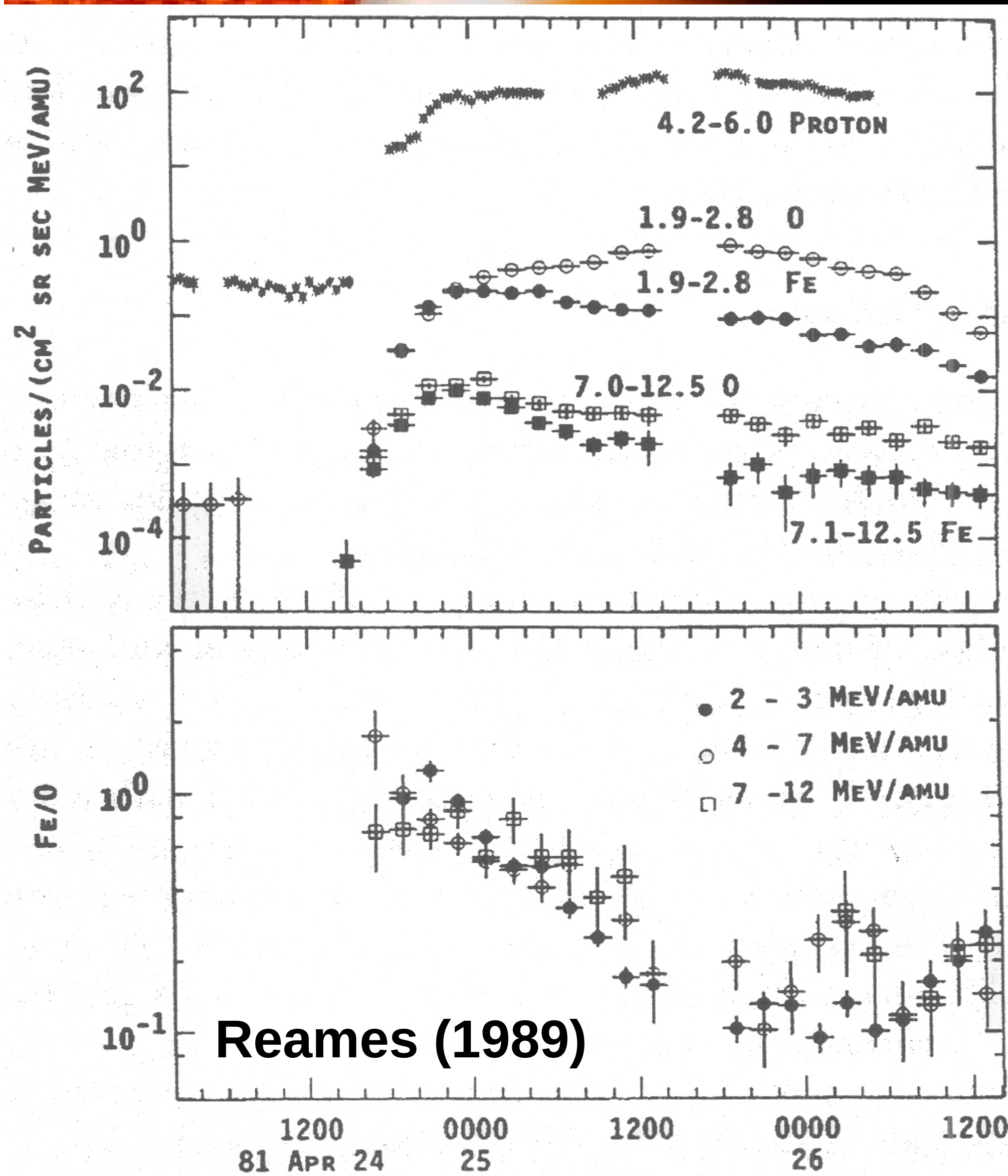
CMEs and the geometry of the Parker spiral explain the longitudinal dependence of SEP time profiles.

Cane et al (1986)

2. Summary of SEP events - 1990's

Property	Impulsive	Gradual
Acceleration site	Flare	CME-driven shock
Source Material	Hot (>5 MK) flare plasma	Coronal or solar wind plasma
How?	Reconnection-driven Stochastic, wave-particle interactions, parallel electric fields, betatron acceleration	Diffusive shock acceleration, stochastic processes
Transport	Scatter-free	Diffusive

3 Interplanetary Transport - Theory



- ✓ *Diffusion*
- ✓ *Convection*
- ✓ *Focusing*

3.1 Magnetic Irregularities

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Magnetic fluctuations in the solar wind exist at all spatial scales

Act as scattering centers and affect the propagation of energetic particles in the heliosphere

3.1 Particle Transport - Diffusion

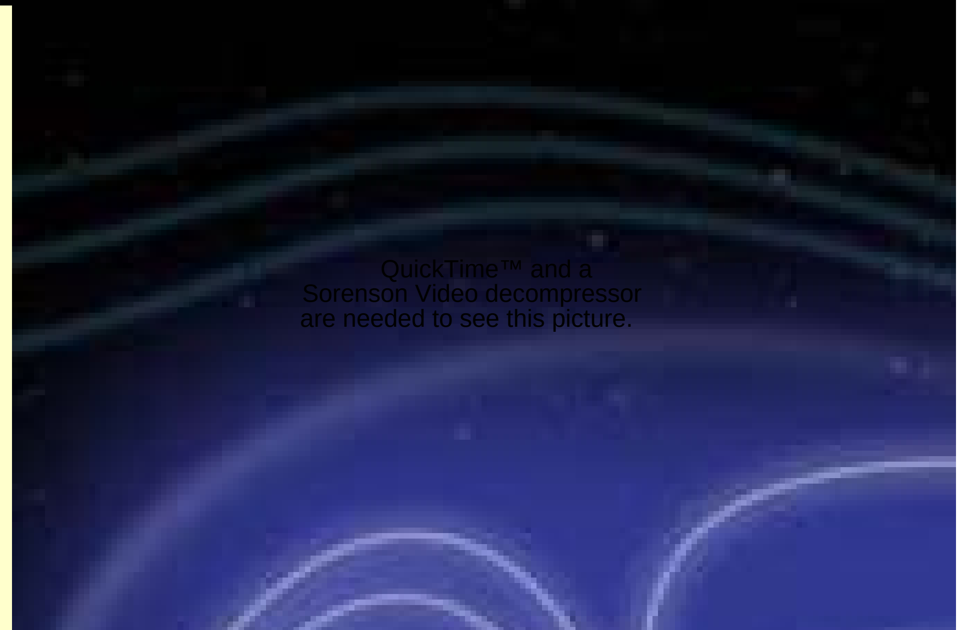
Particles are scattered by random, frequent collisions with magnetic irregularities

Diffusion - 3 types - all driven by gradients

1) Spatial diffusion

2) Pitch-angle diffusion

3) Momentum diffusion



NB. Momentum diffusion - particles gain or lose energy due to collisions

- just 2nd order Fermi

3.1 Diffusion Equation

- **Homogeneous gas in a fixed volume - no diffusion**
- **Density gradient => more particles in one part of volume; thus random walk takes more particles out of the higher density part, Driving force for diffusion**
- **Net transport - reduces the gradient, equalizes the distribution**
- **For anisotropic diffusion tensor *K*, and particle density *U, the streaming of particles S* is:**

$$\mathbf{S} = -\mathbf{K}\nabla U, \qquad (1)$$

=> Flow and gradient are largest for faster particles

Eqn. of Continuity N - number of particles; $\mathbf{S}$ - flux through a surface o volume V;

$$\frac{\partial N}{\partial t} + \oint_{O(V)} \mathbf{S} do = 0 \qquad (2)$$

For particle density U

$$\frac{\partial}{\partial t} \int_V U d^3 x + \oint_{O(V)} \mathbf{S} do = 0 \qquad (3)$$

3.1 Diffusion Equation

For particle density U

$$\frac{\partial}{\partial t}\int_V U d^3x + \oint_{O(V)} \mathbf{S}\, do = 0 \qquad (3)$$

Use Gauss' Theorem

$$\frac{\partial U}{\partial t} + \nabla \mathbf{S} = 0 \qquad (4)$$

Use Eq. (1) ==> $\frac{\partial U}{\partial t} = \nabla \cdot \left(\mathbf{K}\nabla U\right)$ (5)

For isotropic Diffusion: $\frac{\partial U}{\partial t} = \nabla \cdot \left(\kappa \nabla U\right)$ (6)

For isotropic Diffusion independent of space: $\frac{\partial U}{\partial t} = \kappa \nabla^2 U$ (7)

3.1 Solutions of Diffusion Equation

Depends on boundary conditions: Consider propagation from source Q at r_0

$$\frac{\partial U}{\partial t} - \kappa \nabla^2 U = Q(r_0, t) \cdot \tag{8}$$

Spherical geometry: $$\frac{\partial U}{\partial t} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa_r \frac{\partial U}{\partial r}\right) = Q(r_0, t) \tag{9}$$

κ_r - radial diffusion coefficient, between radial shells

Consider a pulse-like injection of N_0 SEP particles at position r_0 at time t_0

$$U(r,t) = \frac{N_0}{\sqrt{(4\pi\kappa_r t)^3}} \exp\left(-\frac{r^2}{4\kappa_r t}\right) \tag{10}$$

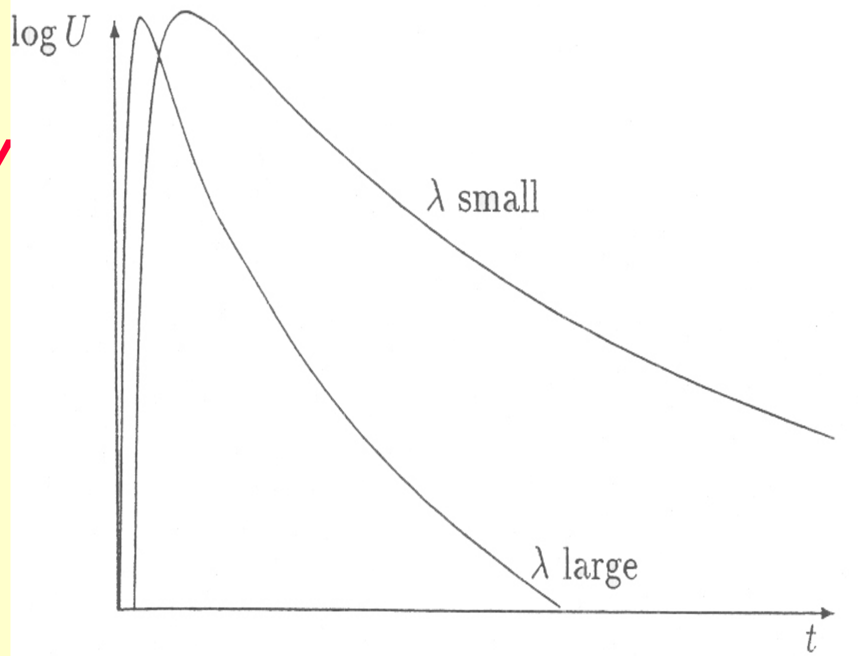
Intensity rises to a maximum and then decays slowly as $\sim t^{-3/2}$

(HW) Show that Time-of-Maximum: $$t_m(r) = \frac{r^2}{6\kappa_r} \tag{11}$$

Use $\kappa_r = \frac{1}{3} v\lambda$ in Eq. (11) and obtain $t_m(r) = \frac{r}{2\lambda}\frac{r}{v}$

3.1 Solutions of Diffusion Equation

- **Diffusive profiles**
- **TOM decreases with larger λ and v**
- **=> Diffusion in gases and liquids**



Since: $t_m(r) = \frac{r}{2\lambda}\frac{r}{v}$

$\frac{r}{2\lambda}$ => delay due to diffusion

Substituting Eq. (11) in Eq. (10) gives the density at TOM.

$$U(r,t_m) = \frac{N_0}{\sqrt{(4\pi r^2/6)^3}}\exp\left(-\frac{3}{2}\right) \sim \frac{N_0}{r^3}. \qquad (12)$$

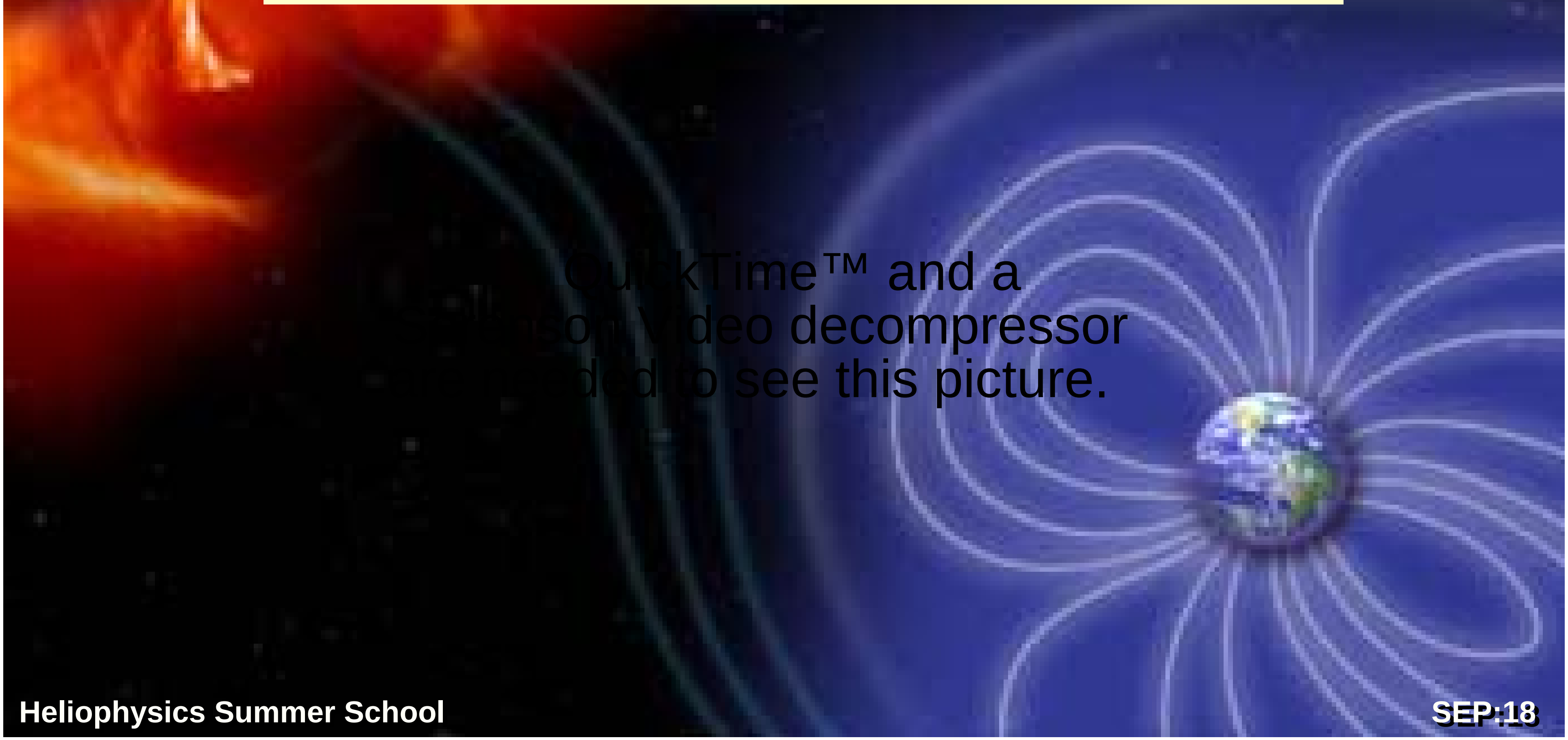
$$\lambda_r = \frac{r^2}{2\upsilon t_m} \qquad (13)$$

$$\lambda_r = \lambda_\parallel \cos^2\psi \quad or \quad \kappa_r = \kappa_\parallel \cos^2\psi \qquad (14)$$

ψ – angle between radial direction and IMF

3.2 Convection

Particles are scattered by magnetic irregularities that are frozen-in and move with the outflowing solar wind; thus carried out by solar wind



3.2 Diffusion-Convection equation

For scattering centers co-moving with bulk solar wind flow

e.g., oil drop in a river spreads out due to diffusion and is carried by the water.

The streaming in Eq. (1) must include convective streaming

$$\mathrm{S}_{\mathrm{conv}} = U\mathbf{V}_{sw}$$

$$\frac{\partial U}{\partial t} + \nabla\left(U\mathbf{V}_{sw}\right) = \nabla\left(\mathbf{K}\nabla U\right) \tag{15}$$

If $\mathbf{K}$ and $\mathbf{V}_{sw}$ are independent of space;

$$\frac{\partial U}{\partial t} + \mathbf{V}_{sw}\nabla U = \kappa \Delta U \tag{16}$$

For radial symmetry, and a δ-function injection:

$$U(r,t) = \frac{N_0}{\sqrt{\left(4\pi\kappa_r t\right)^3}} \exp\left\{-\frac{\left(r - V_{sw}t\right)^2}{4\kappa_r t}\right\} \tag{17}$$

3.3 Pitch-angle Diffusion

Waves scatter a particle by small angles => adds up to change direction by 90°

$\lambda_{//}$ is the scattering mean free path of the particle as its direction changes by 90°

Scattering depends on pitch-angle α and wave-particle interactions

Consider 1D only - guiding center motion is also 1D

Define: $\mu = \cos\alpha$; Scattering Term is: $\dfrac{\partial}{\partial\mu}\left(\kappa(\mu)\dfrac{\partial f}{\partial\mu}\right)$

$\kappa(\mu) =$ pitch – angle diffusion coefficient; $f =$ phase – space density;

Consider field-parallel motion $\mu\upsilon$ and streaming wrt scattering centers

$$\frac{\partial f}{\partial t} + \mu\upsilon\frac{\partial f}{\partial s} = \frac{\partial}{\partial\mu}\left(\kappa(\mu)\frac{\partial f}{\partial\mu}\right) \qquad (18)$$

$\dfrac{\partial f}{\partial s}$ is spatial gradient along B-field.

3.4 Momentum Diffusion

Collisions between particles as well as wave-particle interactions change particle momentum

If energy gain in each interaction is small compared with particle energy ==> diffusion in momentum

Streaming S_p in momentum

$$S_{\mathrm{p}} = -D_{\mathrm{pp}} \frac{\partial f}{\partial p} \qquad (19)$$

D_{pp} = Diffusion in momentum space

=>2nd order Fermi acceleration - stochastic acceleration

3.5 Focused Transport Equation

- **Diffusion** - **Spatial, Pitch-angle, Momentum**

- **Focusing**

  ✓ **IMF diverges, magnetic moment is conserved so pitch-angle decreases (90° at Sun --> 0.7° at Earth)**

$$\frac{\partial f}{\partial t} + \mu \upsilon \frac{\partial f}{\partial s} + \frac{1-\mu^2}{2\varsigma} \upsilon \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(\kappa(\mu) \frac{\partial f}{\partial \mu} \right) = Q(r, \upsilon, t) \qquad (20)$$

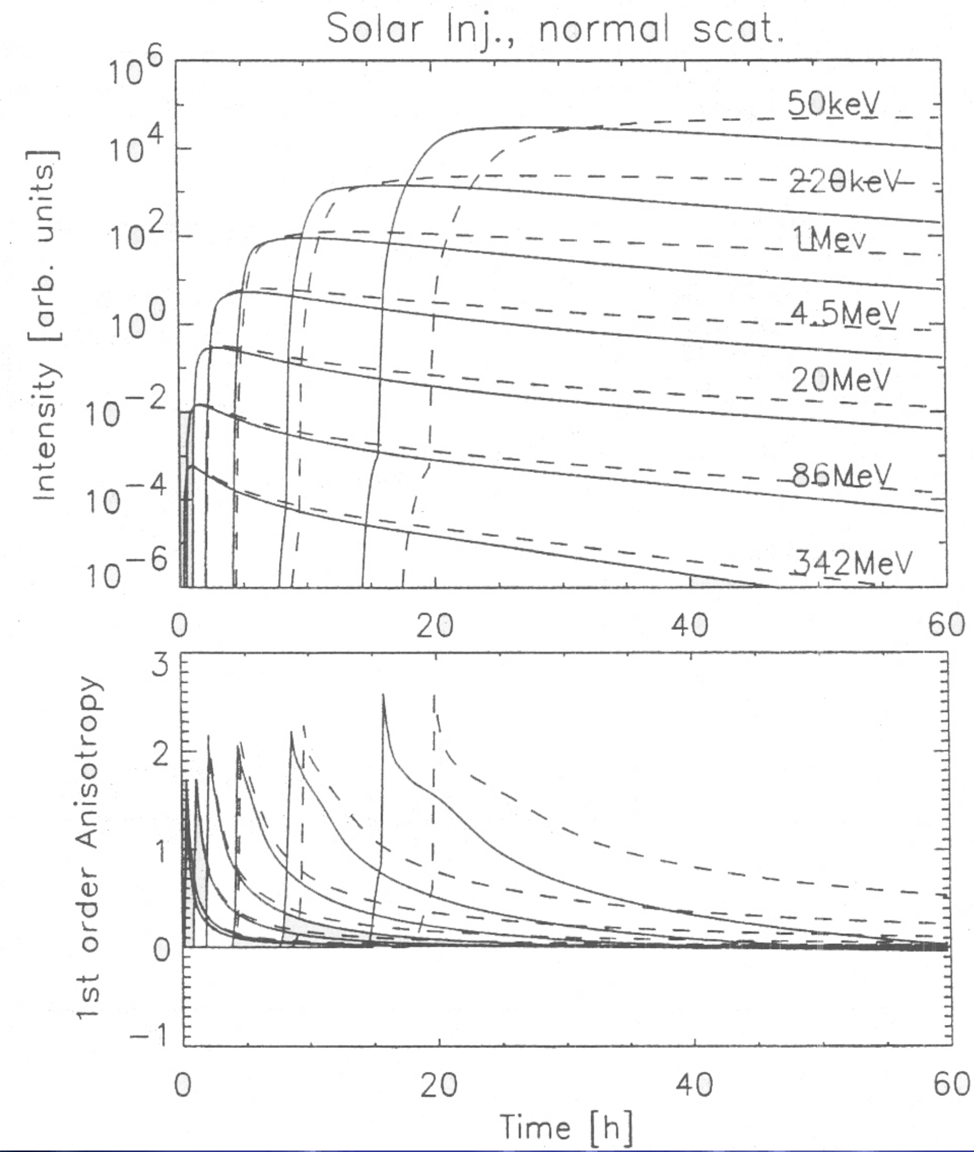
$s -$ length along B; focusing length $\varsigma = \dfrac{-B(s)}{\partial B / \partial s}$

$f -$ phase space density as a function of time, position, and pitch - angle

3.6 Focused Transport with Convection

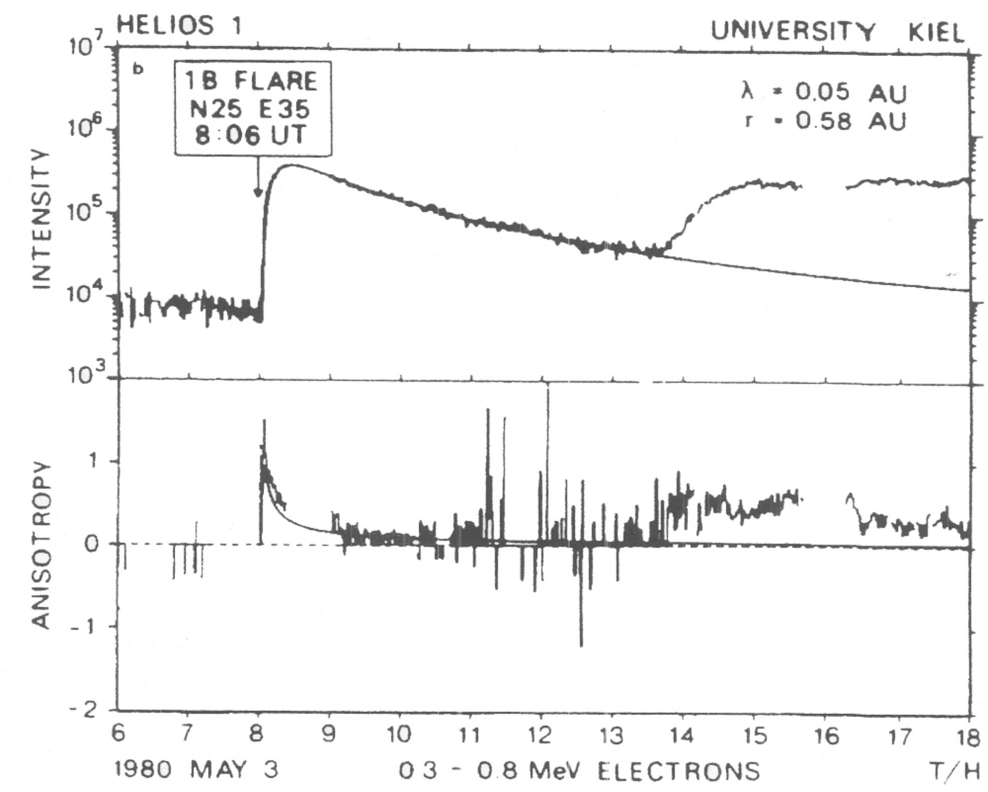
$$
\begin{aligned}
&\frac{\partial F}{\partial t} \\
&+\frac{\partial}{\partial s}\left(\left[\mu' \upsilon' + \left\{1-\frac{(\mu'\upsilon')^2}{c^2}\right\} V_{sw}\sec\psi\right]F\right) \\
&-\frac{\partial}{\partial p'}\left(p' V_{sw}\left[\frac{\sec\psi}{2\zeta}\left(1-\mu'^2\right)+\cos\psi\frac{d}{dr}\sec\psi'^2\right]F\right) \\
&+\frac{\partial}{\partial \mu'}\left(\upsilon'\frac{1-\mu'^2}{2\zeta}F-\kappa(s,\mu')\frac{\partial f}{\partial \mu'}\right) \\
&= Q(t,s,\mu',p') \quad (21)
\end{aligned}
$$

Solutions of the transport equation with (solid) and without (dashed) convection



3.7 Interplanetary Transport - Particle Observations

- Fits to particle intensity- and anisotropy-time profiles
- Particles travel along magnetic field
- Intensity profiles = particle injection + transport; use anisotropy to constrain
- λ~0.08-0.3 AU; diffusive to scatter-free



Diffusive profile of an electron event: Solid line = fits with transport model without convection

4 Particle Acceleration Mechanisms

- Electric Field (***F***=*q****E***)
  - Quasi-static large-scale electric fields (could be generated during reconnection)
  - e.g., solar flares, planetary magnetospheres
- Stochastic Acceleration (1949-1950's)
  - Particles gain or lose energy over short intervals, but gain energy over longer timescales
  - e.g., solar flares, interplanetary medium, near shocks
- Shock Acceleration (1970's)
  - Particles gains energy as scattering centers converge
  - First-order Fermi process
  - e.g., shocks, compression regions

4.1 Particle Acceleration in Flares

- Direct Electric Field (***F***=*q**E***) acceleration
  - ✓ Generated in current sheets
- Stochastic Acceleration
  - ✓ Gyroresonant wave-particle interactions in turbulent regions near the reconnection site and in outflowing jets
- First-order Fermi/DSA Acceleration
  - ✓ Slow shocks standing in flow
  - ✓ Fast shocks generated where outflowing jets meet the ambient B-field
- Distinction blurred - large homogenous DC E-field not realistic
- Fragmented current sheets & magnetic islands - impulsive or bursty reconnection, turbulent E-fields lead to a stochastic-type process

4.1 Direct Electric Fields

- Electric field strength
  - ✓ Weak sub-Dreicer
  - ✓ Strong super-Dreicer
- Time variability
  - ✓ Static
  - ✓ Dynamic
- Geometry
  - ✓ Current sheets
  - ✓ X-points
  - ✓ O-points
  - ✓ 2d, 3d

In the presence of a DC electric field $\mathbf{E}$, ions and e - s are accelerated in opposite directions and experience Lorentz Force

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad (22)$$

$$\text{along B}: \; m\frac{dv_{//}}{dt} = qE_{//} \qquad (23)$$

$$\perp \text{ to B}: \; m\frac{dv_{\perp}}{dt} = q(E_{//} + \mathbf{v}_{\perp} \times \mathbf{B}) \qquad (24)$$

Depending on electron - ion collisions:

Lorentz Force = Frictional Drag Force

For large rel. velocities

=> Frictional Force << Accelerating Force

e - s can be accelerated out of the thermal distribution

4.1 Direct Electric Fields

=> Runaway acceleration with Crititcal Runaway velocity v_r given when frictional force = Electric force

$$m_e \frac{v_r}{\tau} = eE \; ; \; \tau = \frac{v}{\langle \Delta v_{//} / \Delta t \rangle} \qquad (25)$$

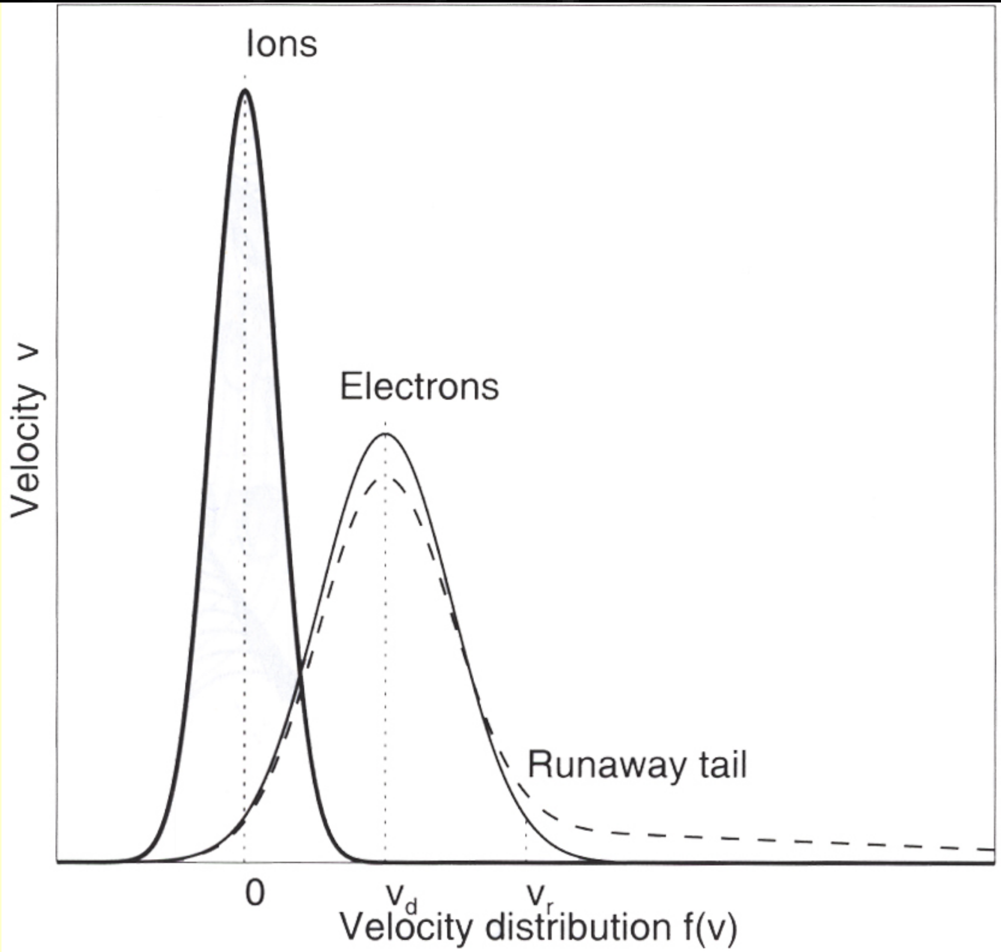
τ - slowingdown time due to interactions between ions and e - s.

Dreicer Electric Field $E_D = \dfrac{q \ln \Lambda}{\lambda_D^2}$ (26)

where $\ln \Lambda$ – Coulomb logarithm

plasma parameter $\Lambda = n_e \lambda_D^3$ (>> 1)

Debye length, $\lambda_D = \left(\dfrac{\varepsilon_0 k_B T_e}{n_e e^2} \right)^{1/2}$ (27)



$$\lambda_D = \frac{v_{Te}}{\omega_{pe}} = \frac{\text{Thermal speed}}{\text{Electron plasma frequency}}; \text{ where } v_{Te} = \left(\frac{k_B T_e}{m_e} \right)^{1/2} \text{ and } \omega_{pe} = \left(\frac{4 \pi n_e e^2}{m_e} \right)^{1/2}$$

4.1 Direct Electric Fields

Runaway speed $v_r = v_{Te}\left(\frac{E_D}{E}\right)$ (28)

Case 1) Sub-Dreicer ($E \geq E_D$) Weak fields require large-scale steady structures

=> acceleration occurs over large distances $\sim 10^9$ cm

Case 2) Super-Dreicer ($E >> E_D$) strong fields require smaller structures and

compact acceleration regions $\sim 10^4$ cm.

Other Types

Acceleration at X-points

- magnetic moment is not conserved

Acceleration at O-points

- Fast reconnection => strong convective electric fields

Acceleration in Time-varying electric field (betatron acceleration)

- Collisions => wave trubulence => increase in $\perp$ momentum

Field-aligned Electric Potential Drops

- Alfven waves set up parallel E potential drops close to chromosphere

4.1 Summary of Particle Acceleration in Flares

Acceleration Mechanisms	Electromagnetic fields
DC electric field acceleration:	
— Sub-Dreicer fields, runaway acceleration[1]	$E < E_D$
— Super-Dreicer fields[2]	$E > E_D$
— Current sheet (X-point) collapse[3]	$E = -u_{inflow} \times B$
— Magnetic island (O-point) coalescence[4]	$E_{conv} = -u_{coal} \times B$
— (Filamentary current sheet: X- and O-points)	
— Double layers[5]	$E = -\nabla V$
— Betatron acceleration (magnetic pumping)[6]	$\nabla \times E = -(1/c)(dB/dt$
Stochastic (or second-order Fermi) acceleration:	
Gyroresonant wave-particle interactions (weak turbulence) with:	
— whistler (R-) and L-waves[7]	$k \parallel B$
— O- and X-waves[8]	$k \perp B$
— Alfvén waves (transit time damping)[9]	$k \parallel B$
— Magneto-acoustic waves[10]	$k \perp B$
— Langmuir waves[11]	$k \parallel B$
— Lower hybrid waves[12]	$k \perp B$
Shock acceleration:	
Shock-drift (or first-order Fermi) acceleration[13]	
— Fast shocks in reconnection outflow[14]	
— Mirror-trap in reconnection outflow[15]	
Diffusive-shock acceleration[16]	

Priest (2004)

Ashwanden (2006)

4.2 Ingredients for Particle Acceleration at Shocks

- **3 Energy Changing Mechanisms**
  - **All involve Electric fields**
  - **Shock-drift (SDA)**
  - **Stochastic acceleration in turbulence**
  - **Diffusive Shock (DSA)**
- **Scattering centers**
  - **Energy changes can make the particle distributions anisotropic and impede energy gain**
- **Statistical Theory**
  - **To describe the net effect of these processes**

4.2 Mechanisms

- **Shock drift acceleration (SDA) in the induction electric field near the shock front**

  Perpendicular shocks, **where the induction electric field is maximum; but vanishes in parallel shocks.**

- **First-order Fermi due to repeated reflections in the plasmas converging at the shock front**

  Parallel shocks**, turbulence and fluctuations scatter particles across**

- **Stochastic (second-order Fermi) in the turbulence behind the shock front**

  Requires strong enhancements downstream

4.2.1 Shock-drift Acceleration

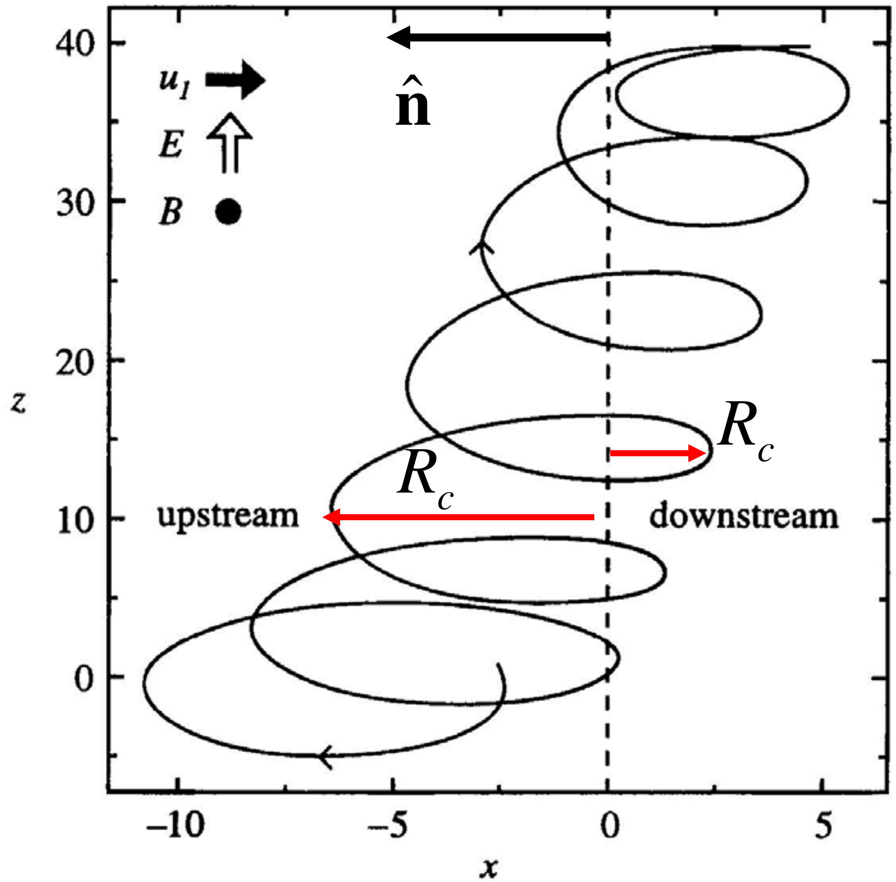
- **Strong gradient in B**
- **Particles drift along the shock front in the direction of the E field**
- **Quasi-perpendicular shocks**

$$\mathbf{E} = -\mathbf{u}_1 \times \mathbf{B}_1 = -\mathbf{u}_2 \times \mathbf{B}_2 \qquad (29)$$

Conservation of magnetic moment:

Particles reflected if their velocity

$$v > u_1 \tan\theta_{Bn} \sqrt{B_1 / B_2} \qquad (30)$$



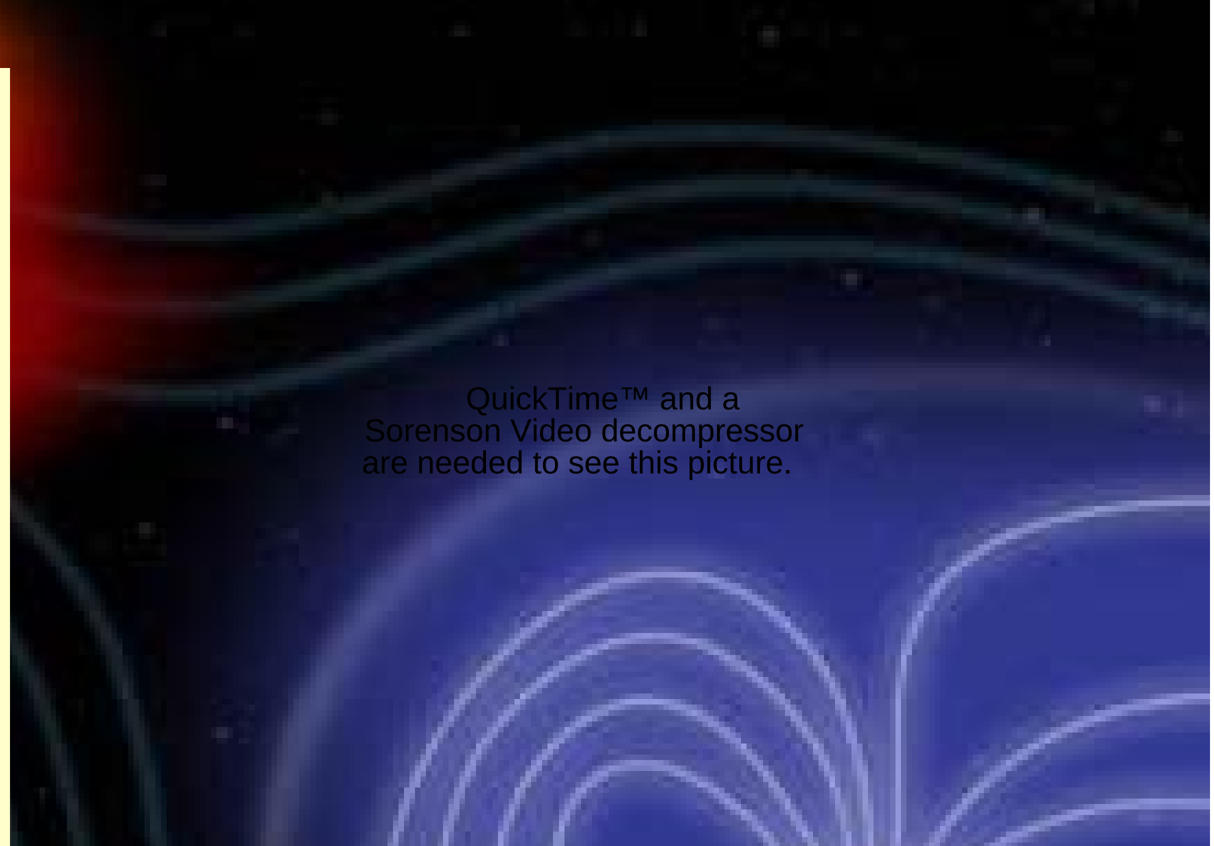
$$\text{Energy gain } \Delta \mathbf{E} \sim \frac{p u_1}{\theta_{Bn}} \qquad (31)$$

Average gain 1-5 x original energy

$\therefore$ require multiple encounters

4.2.2 Second-order Fermi (1949)

- **Motivation: Cosmic rays gain energy by colliding with magnetic clouds**
- **All scattering centers move at same speed**
- **Gains energy in a head-on collision, loses energy in an overtaking collision**
- **1st order term in energy change cancels**
- **Over long periods, net energy gain because more head-on collisions**
- **Flares, downstream of shocks, interplanetary medium**



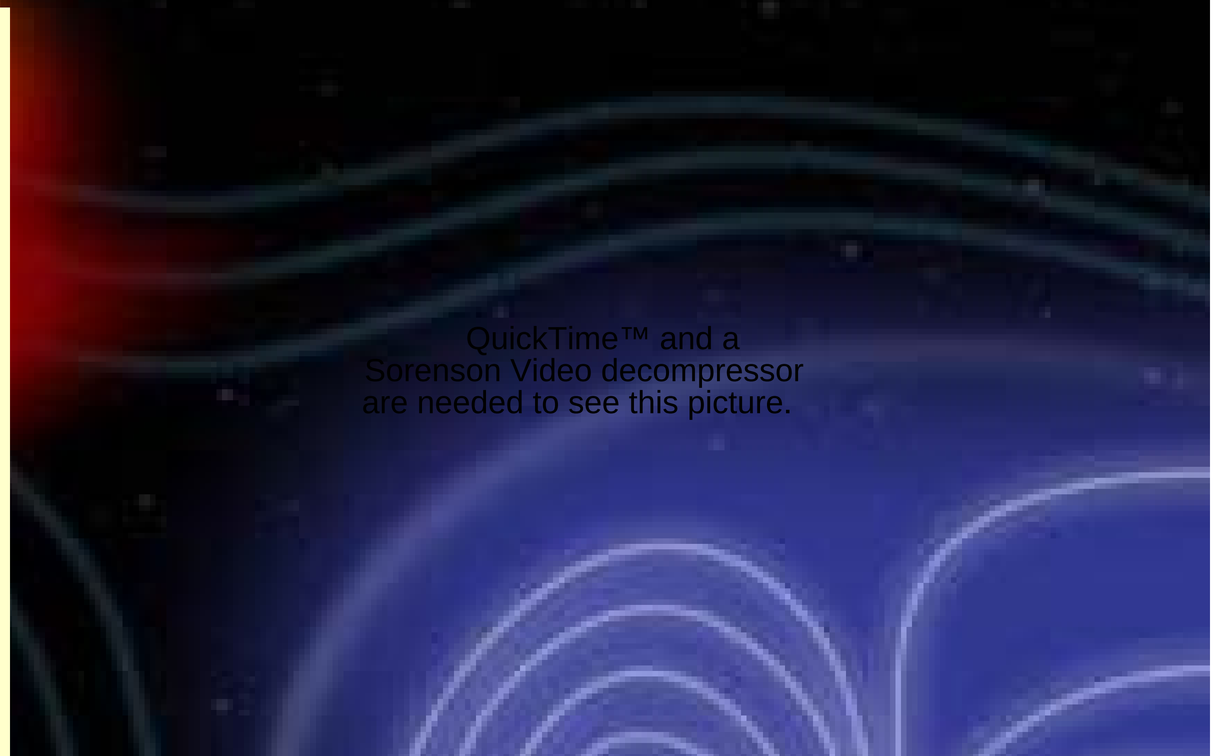
$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \left(\frac{V_A}{v} \right)^2 \qquad (32)$$

where ΔE is the energy gain for a particle

with initial energy $E = \frac{1}{2} m v^2$

4.2.3 First-order Fermi (1954)

- **More efficient acceleration for "head-on" collisions**
- **Repeated scattering both sides of the shock**
- **Upstream: gains energy due to a head-on collision**
- **Downstream: Loses energy because scattering center moves away**
- **However, the flow speed (i.e., the speed of the scattering center) is larger upstream - net gain per cycle.**
- **Quasi-parallel shocks, compression regions**



u_1 u_2

$$\left\langle \frac{\Delta E}{E} \right\rangle \propto (u_1 - u_2) \propto \Delta V \qquad (33)$$

ΔV is the difference in the velocities of the upstream and downstream scattering centers (i.e., flow speeds)

4.2.4 Diffusive Shock Acceleration

$$\frac{\partial f}{\partial t} + V_{sw}\nabla f - \nabla\cdot(\mathrm{K}\nabla f) - \frac{\nabla V_{sw}}{3} p \frac{\partial f}{\partial p} + \frac{f}{T} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left(\frac{dp}{dt}\right)f\right) \qquad (34)$$

Parker developed the cosmic ray transport equation that incorporated various physical effects that can affect particle distributions (f = phase-space density):

$$\frac{\partial f}{\partial t} + V_{sw}\nabla f - \nabla\cdot(\mathrm{K}\nabla f) - \frac{\nabla\cdot V_{sw}}{3} p \frac{\partial f}{\partial p} = Q(p,r,t) \qquad (35)$$

Convection diffusion energy change Source

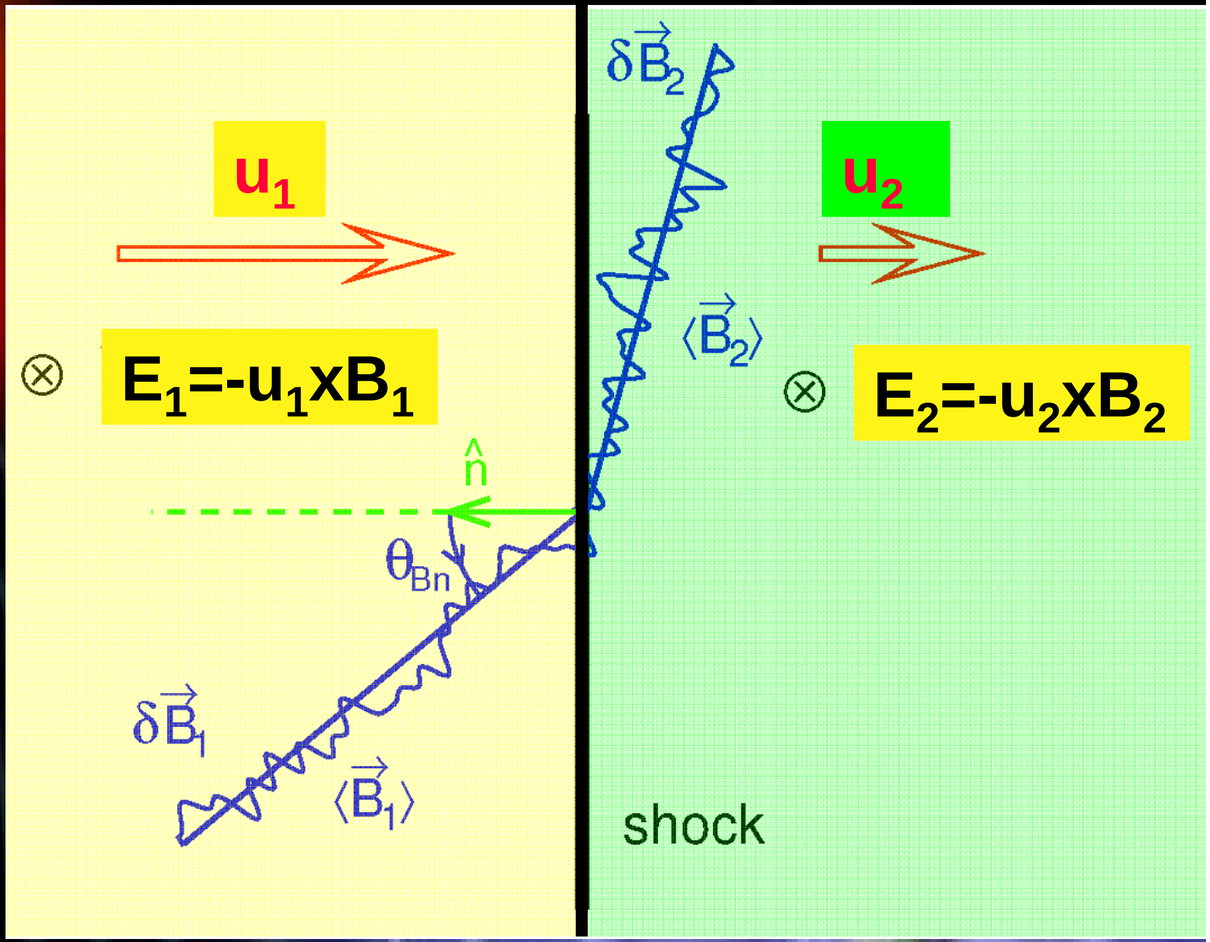
Steady-state conditions can be used to determine acceleration time τ_a, energy spectrum, and intensity increase upstream of shock.

4.2.4 Diffusive Shock Acceleration

Diffusive shock acceleration is obtained by putting a shock i.e., a step-like function for flow speed

***u* and κ change discontinuously**

Solve Parkers' Eq. assuming 1D (planar) shock, and that *f* changes in 1 direction only.



4.2.4 Energy Spectrum

Differential intensity $j = p^2 f \propto E^{-\frac{(H_s+2)}{2(H_s-1)}}$

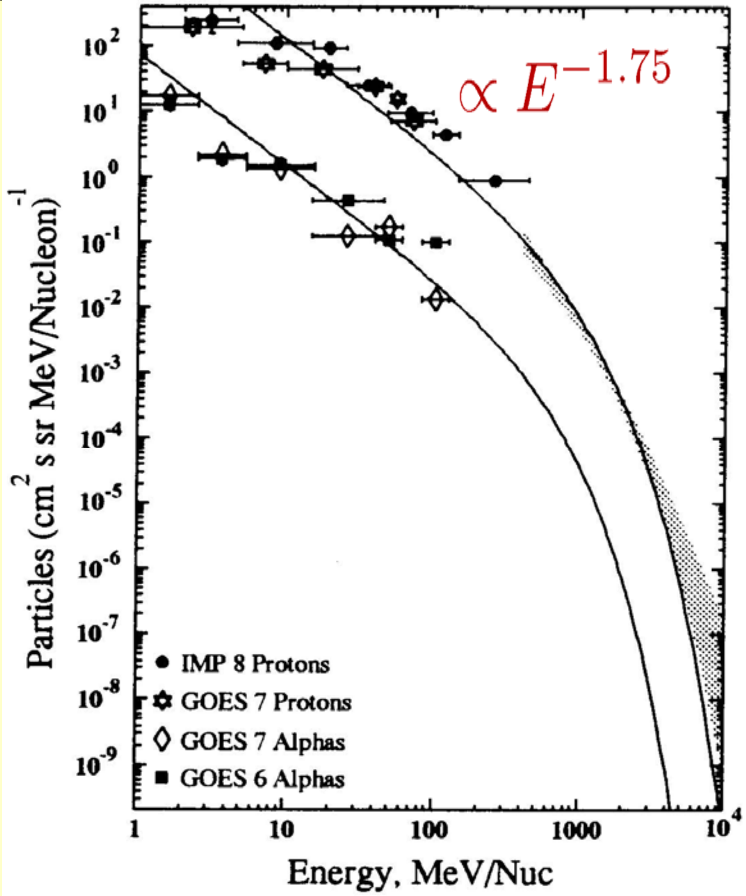
In the limit of a strong shock, $H_s \to 4$,

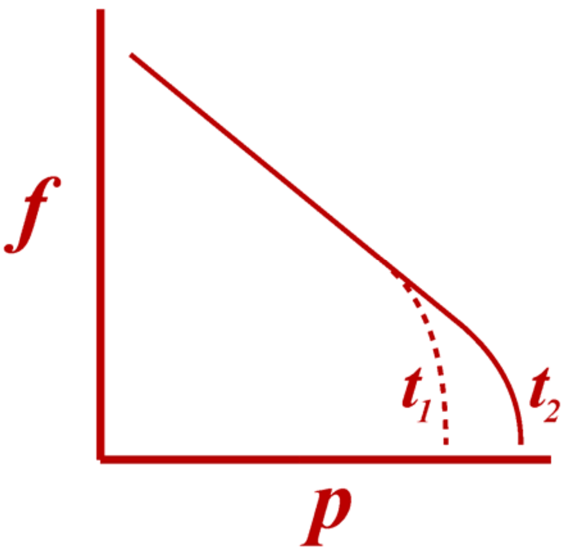
: $f \propto p^{-4}$, which corresponds to $j \propto p^{-2} \propto E^{-1}$

Close to observations at lower energies.

Why does the spectrum

roll-over at higher energies?





Assumptions: 1D steady-state, infinite shock.

But shock has curvature and is 3D structure.

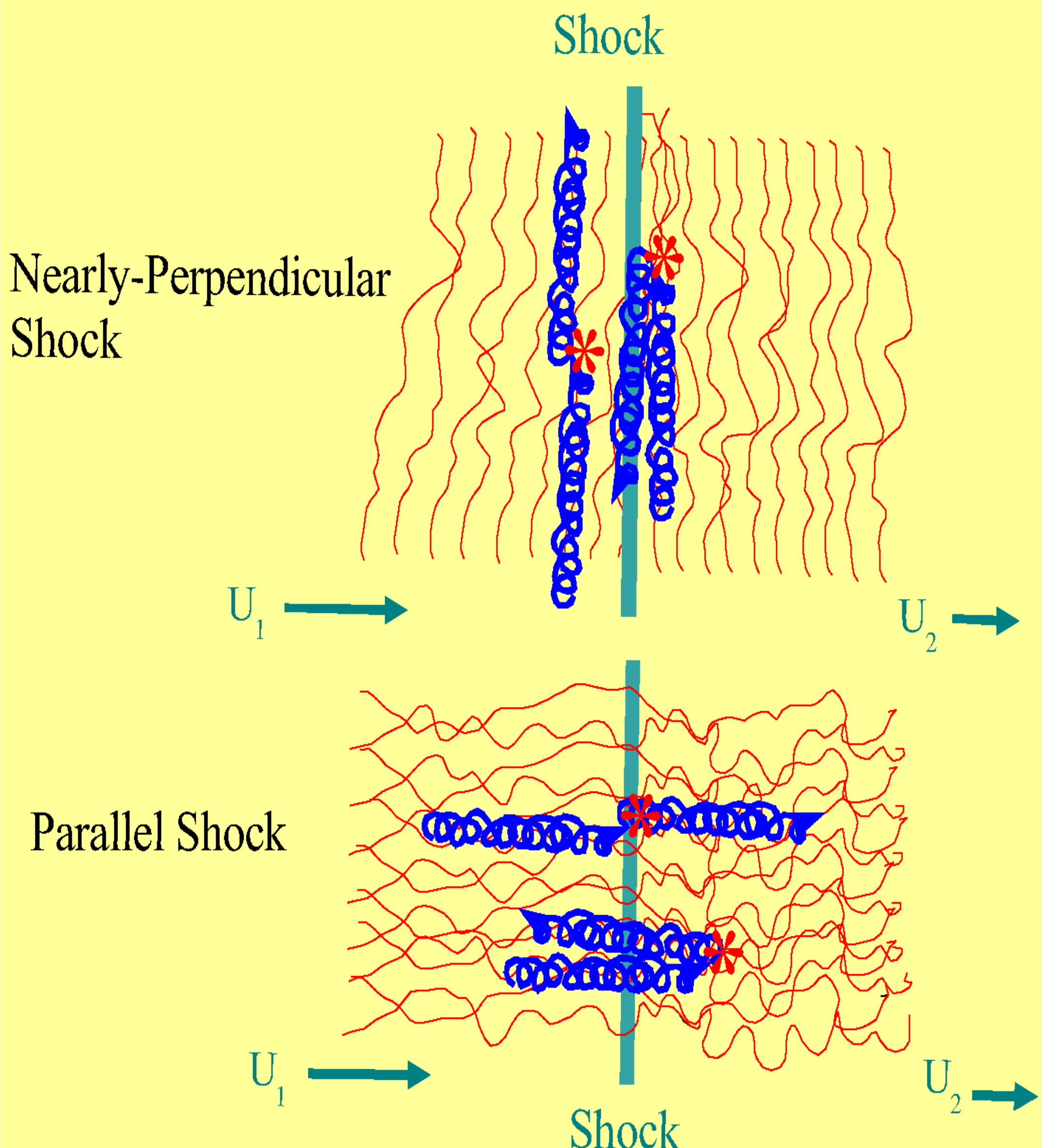
Time-dependence, geometry effects

4.2.4 Self-generated Turbulence

- Accelerated particles stream away from the shock
- Amplify low-frequency MHD waves in resonance with them
- Particles accelerated later are scattered by these waves back into the shock and gain additional energy
- More energetic particles escape from the shock and amplify waves in resonance with higher energies
- Net effect = equilibrium between particles and waves in which time shifts to higher energies and larger wavelengths
- Non-linear system with complex interactions between plasmas, waves, and energetic particles

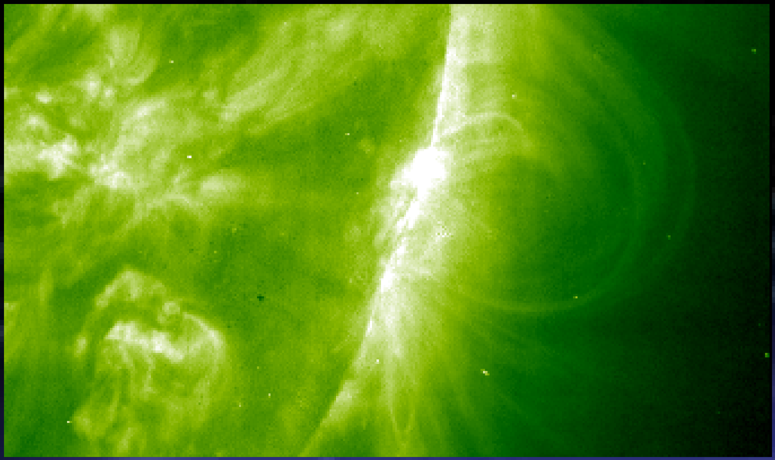
4.5 Summary

- Perpendicular
  - ✓ SDA
- Parallel
  - ✓ DSA
- Oblique
  - ✓ Both processes
- Stochastic processes operate in the presence of downstream turbulence

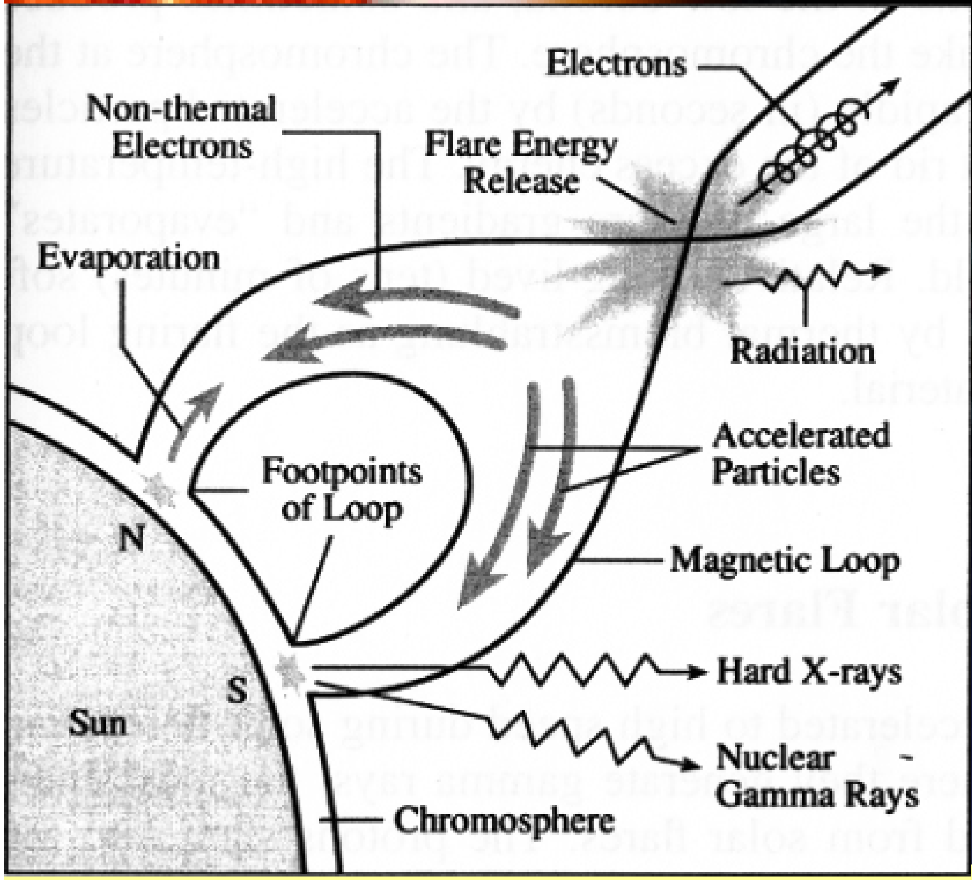


5.1 Main issues in SEP events

- **Where?**
  - **At shocks or in flares**
- **What material?**
  - **Ambient corona, solar wind, or other**
- **How accelerated?**
  - **Reconnection-driven or CME-shock acceleration**
- **Transport to Earth?**
  - **Turbulence, fluctuations, particle scattering**

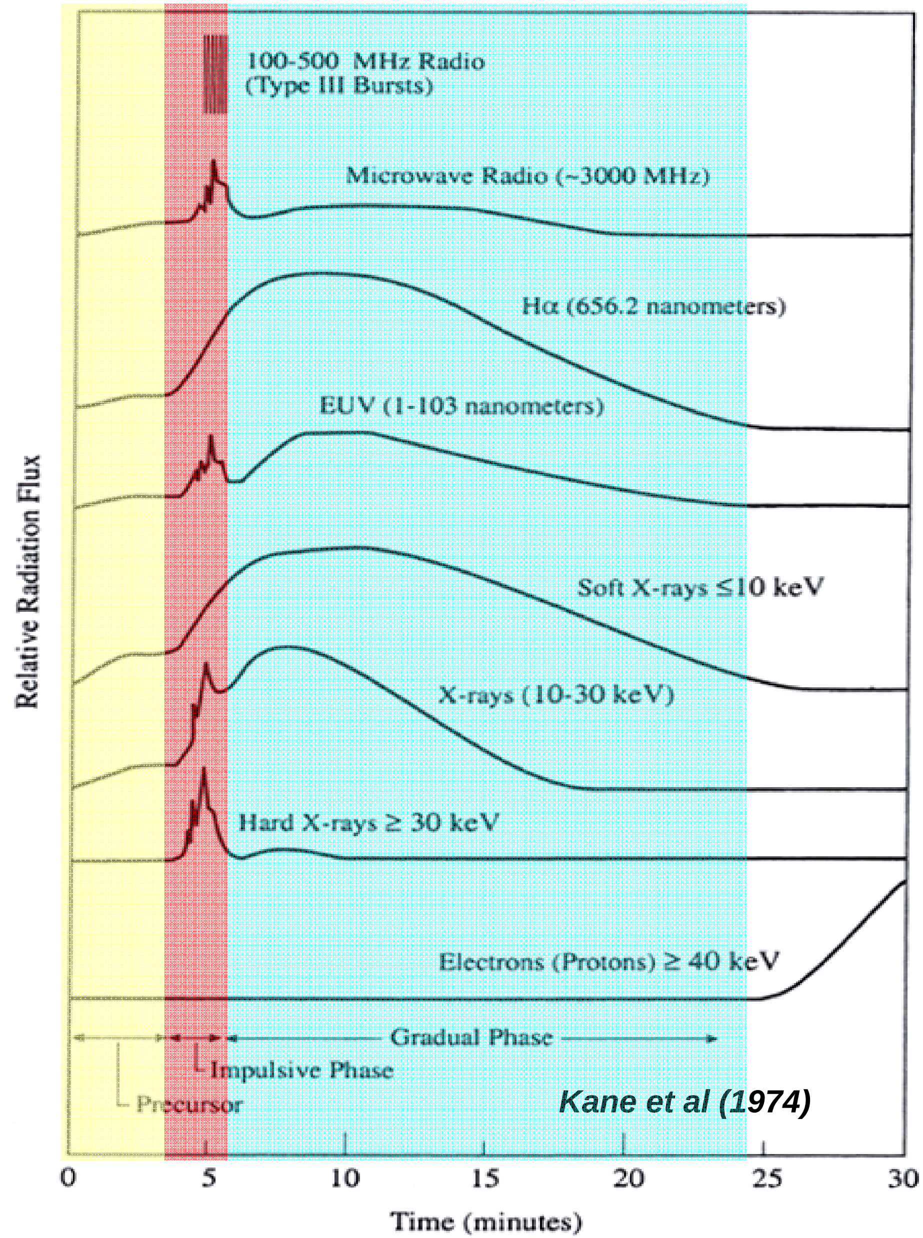


5.2 Acceleration in Flares



Energy released via large-scale magnetic reconnection

3He and heavy ions like C-Fe and ultra-heavies > 100 AMU

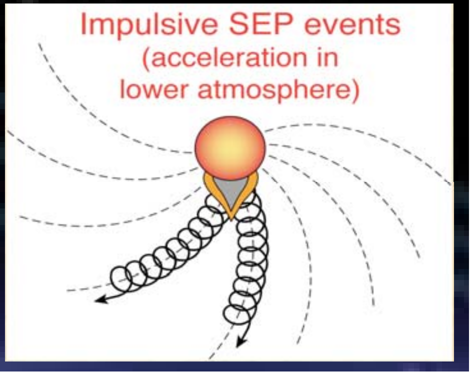


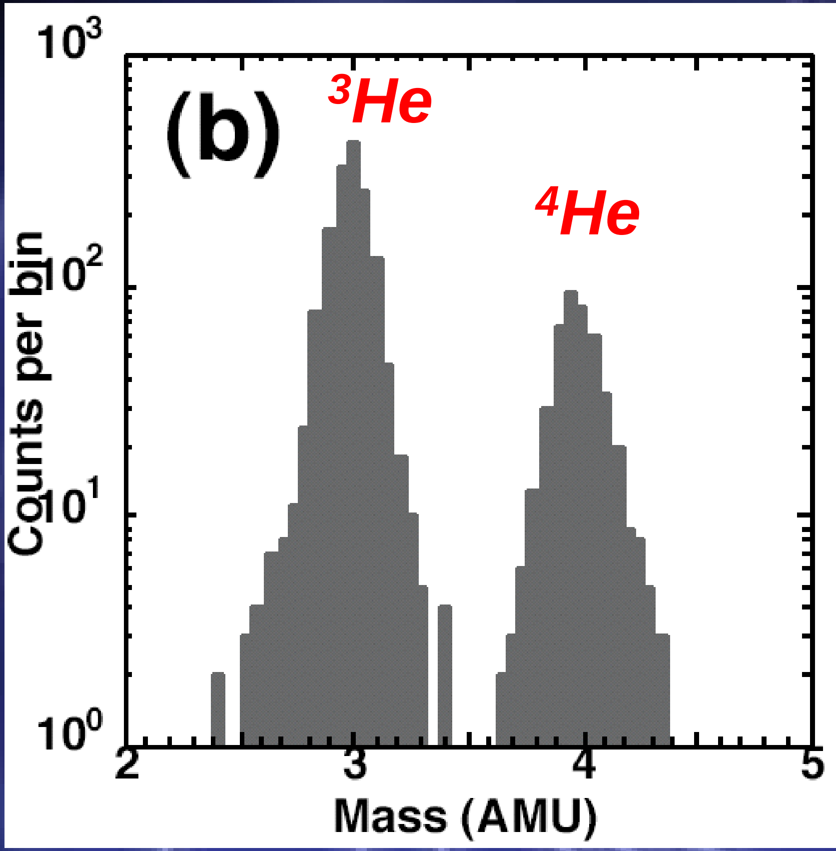
Kane et al (1974)

5.2 3He-rich SEP events - *ACE*

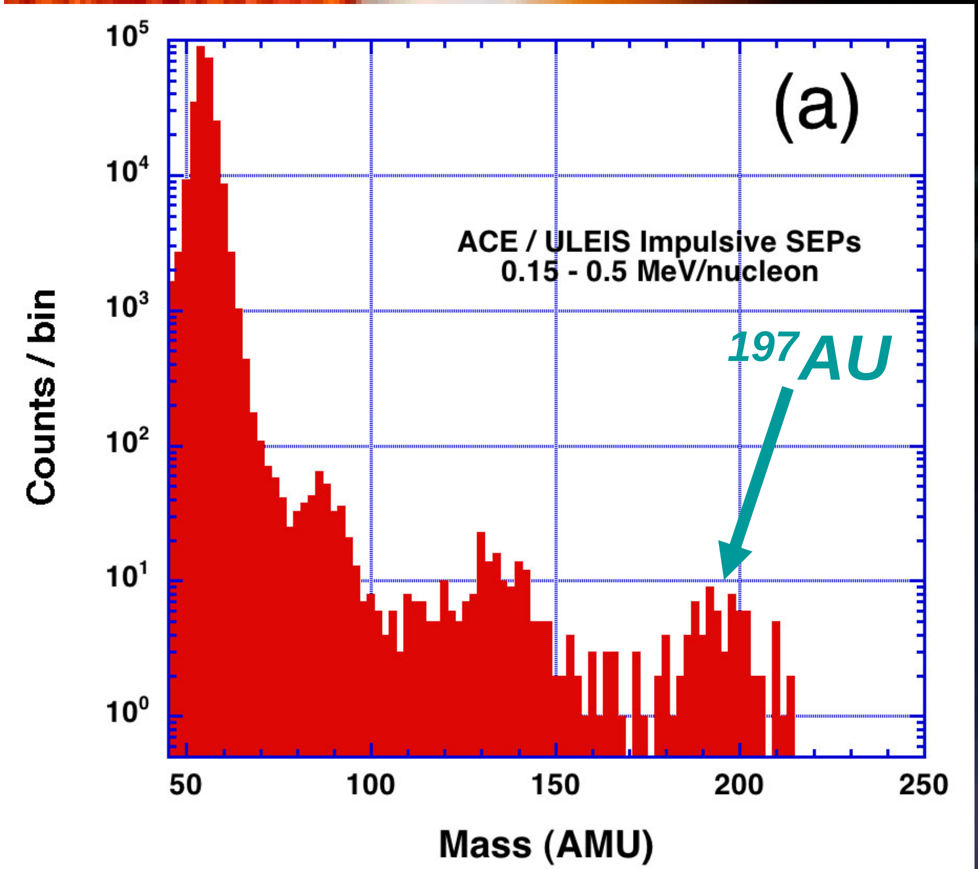
- Discovered in late 1960s
- $^3He/^4He$ ratio >> solar wind value of $\sim 5 \times 10^{-4}$
- Heavy ions up to iron by factor of 5-10
- Impulsive electron events
- Scatter-free propagation
- Often lack of any flare association on Sun
- Sometimes ions fully stripped of electrons

Mason et al. (2002)

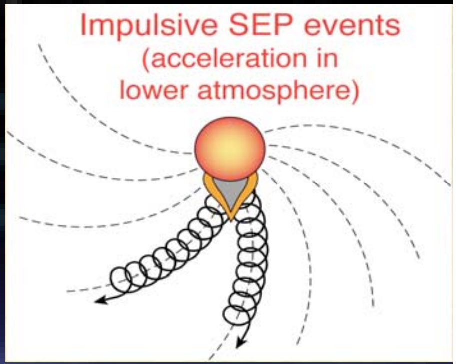


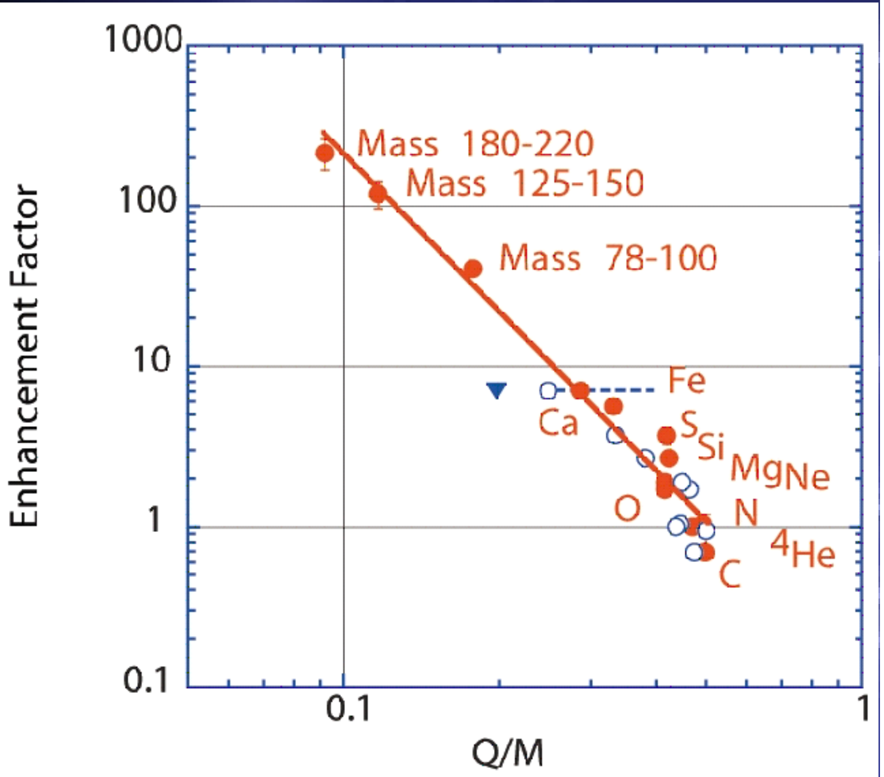


5.2 Heavy and UH heavy ions



Mason et al. (2004)



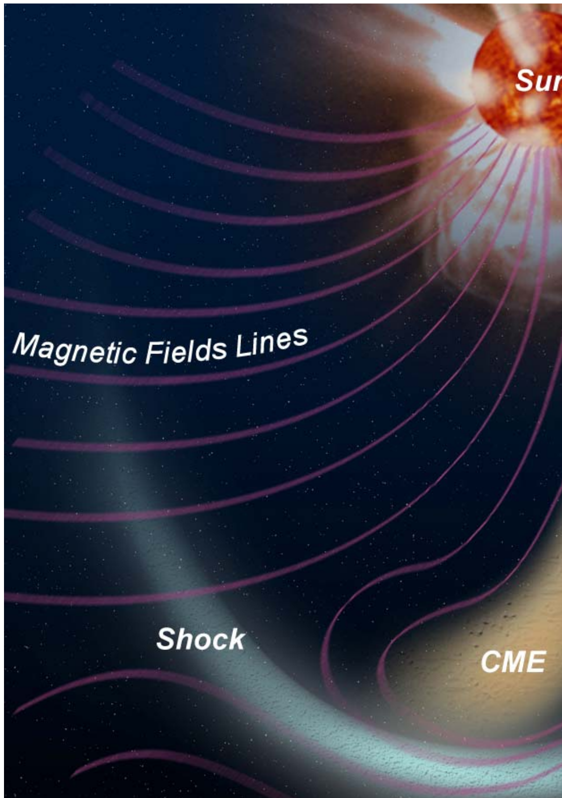


- **Ultra-heavy ions ~200 times SW value**
- **Acceleration depends on M/Q ratio**
- **No satisfactory theory**

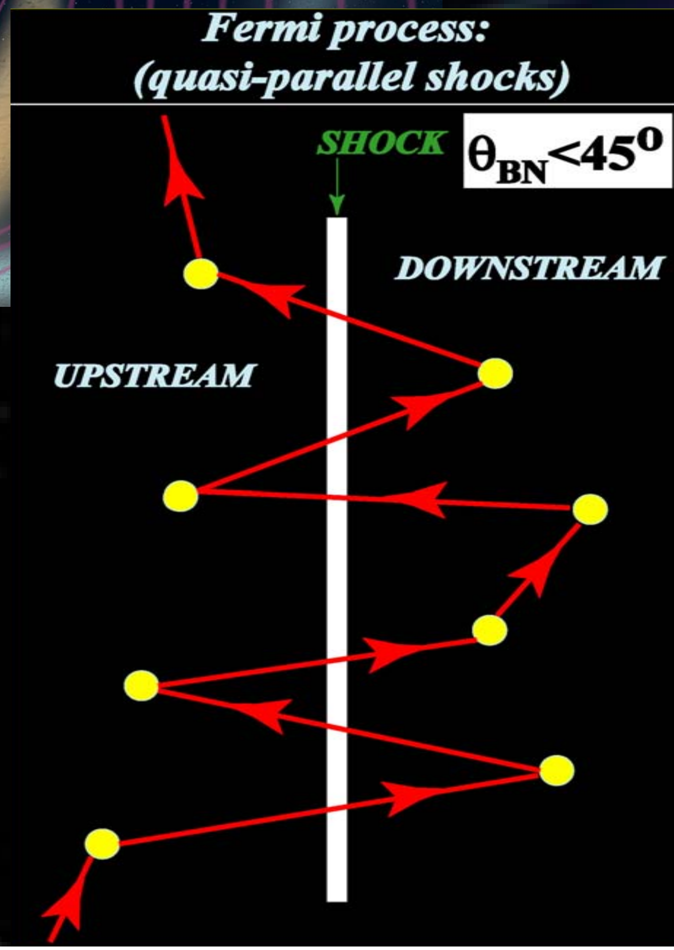
5.2 Problems with Flare Models

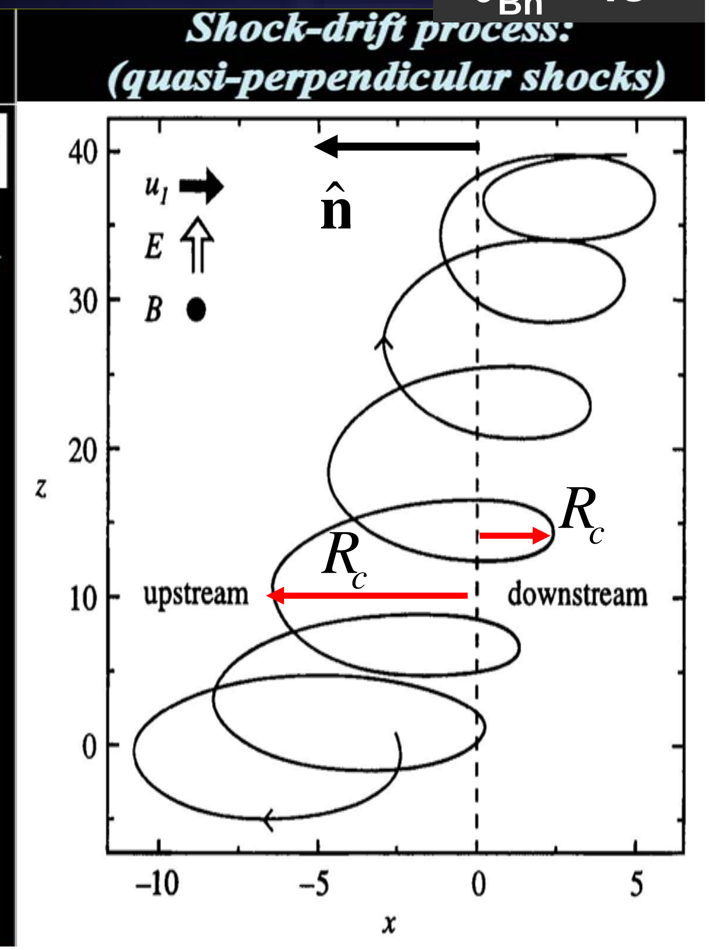
- Electric Field (***F***=*q****E***)
  - Can account for fast electron acceleration upto ~ 10 MeV
  - Cannot explain 3He or heavy ion enhancements
- Stochastic Acceleration (1949-1950's)
  - Can explain e-, 3He and heavy ion enhancements
  - Cannot explain ultra-heavy ion (not enough wave power)
- Shock Acceleration (1970's)
  - Cannot explain e-s upto ~few MeV (?)
  - Cannot explain 3He (?)
  - Under some circumstances could account for the heavy and UH enhancements

5.3 Acceleration at CME Shocks



θ_{Bn} >45°

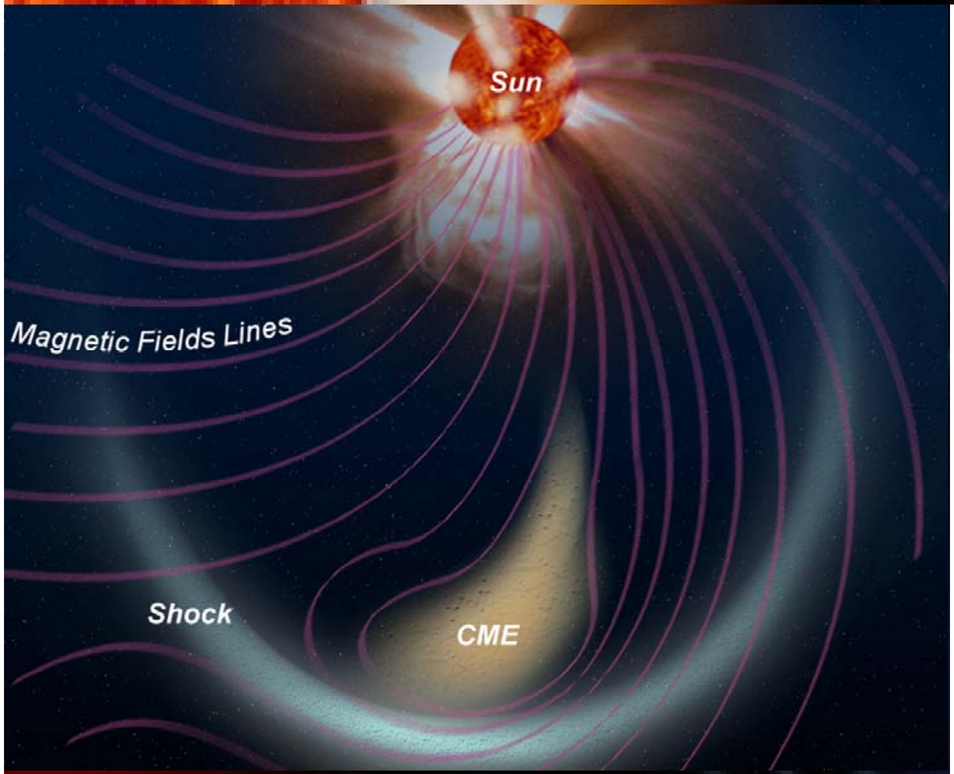


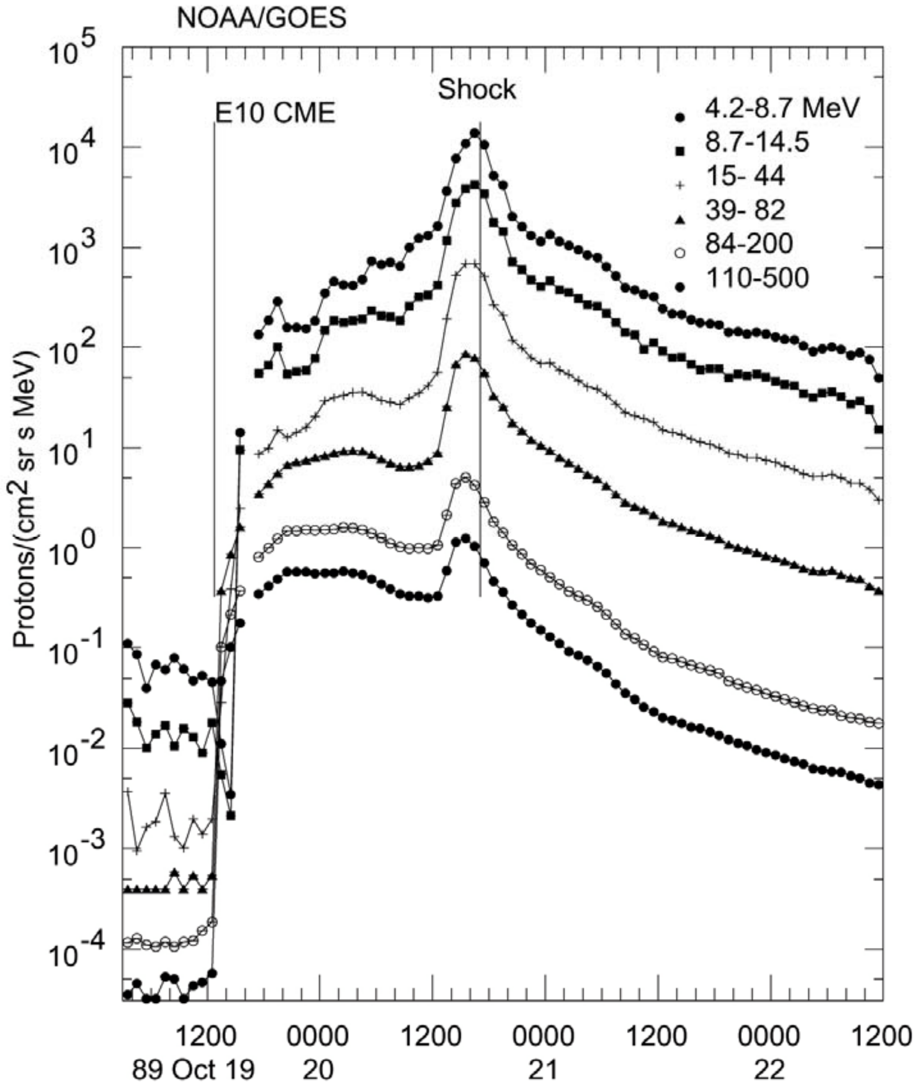


Fast CMEs drive shocks

Diffusive shock acceleration of solar wind ions?

5.3 ESP + SEP





- **CMEs drive shocks in the corona and the interplanetary medium**
- **Shocks accelerate particles**
  - **electrons to >1 MeV (?)**
  - **ions to >1 GeV (?)**

Reames.SSR, 1999

5.3 Heavy Ion Acceleration

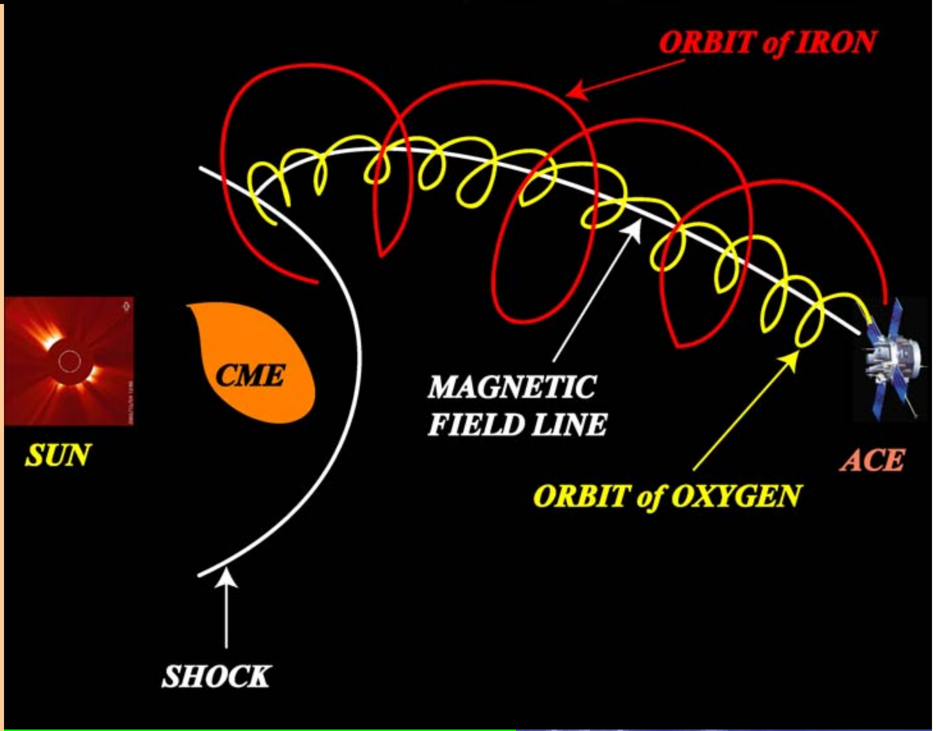
Quasi - linear scattering theory

$$\kappa_{\|} = \frac{1}{3} v \lambda_{\|} = \frac{1}{3} v \eta R_c \qquad (36a)$$

1) $\lambda_{\|}$ is the scattering mean free path along the magnetic field direction.
This is the distance a particle travels along the magnetic field before being scattered.

2) η is a constant that depends on the type and level of magnetic fluctuations.

3) $R_c = \dfrac{m v_{\perp}}{qB}$, is the particle gyroradius.



Fe: M/Q ~ 4.5

O: M/Q ~ 2.3

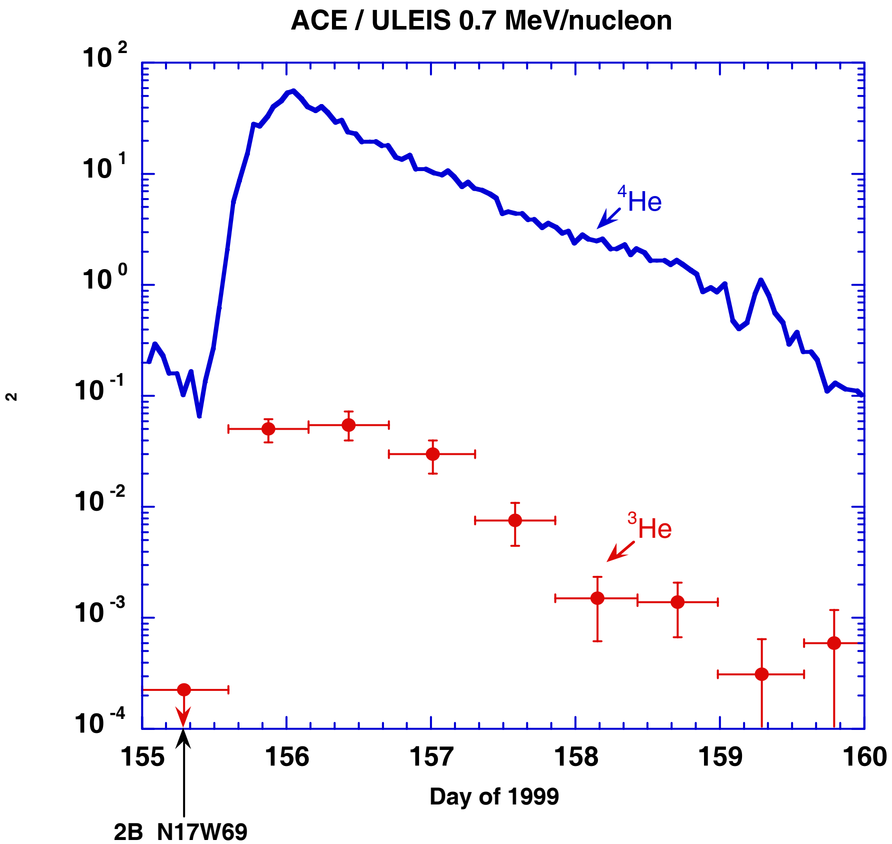
Iron is accelerated less efficiently than oxygen

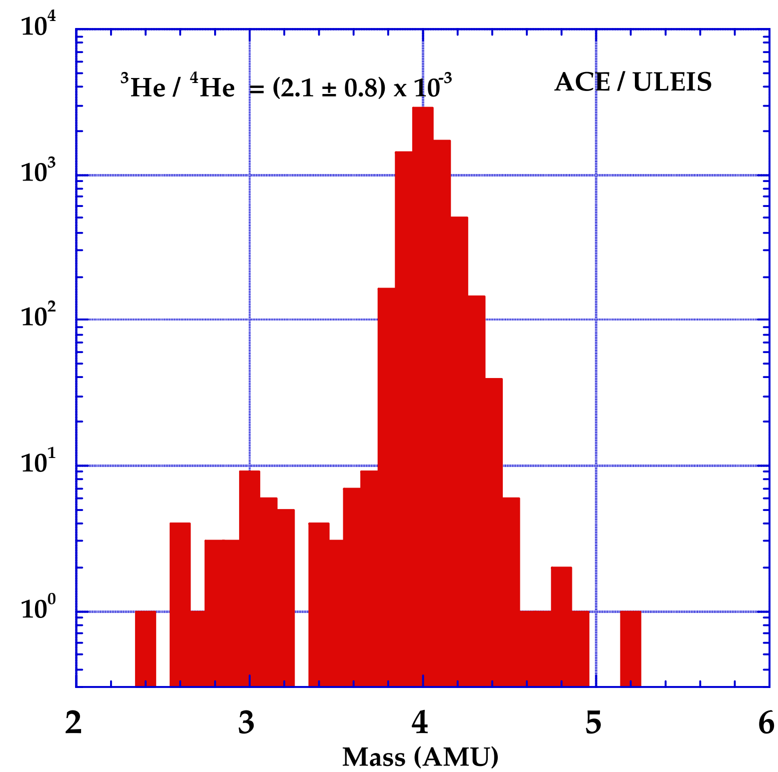
5.3 Expectations from CME-Shock acceleration of solar wind material

- $^3He/^4He \sim 4\times10^{-4}$
- C-Fe abundances should show systematic M/Q-dependent fractionation wrt SW composition
- $Fe/O < 0.1$
- Fe, Q-state ~ 10-14
- Fe/O decrease with increasing energy

5.3 3He in Gradual Events - *ACE*

^{3}He observed in <u>some</u> CME-shock related events with abundance >> solar wind value (~0.04%)

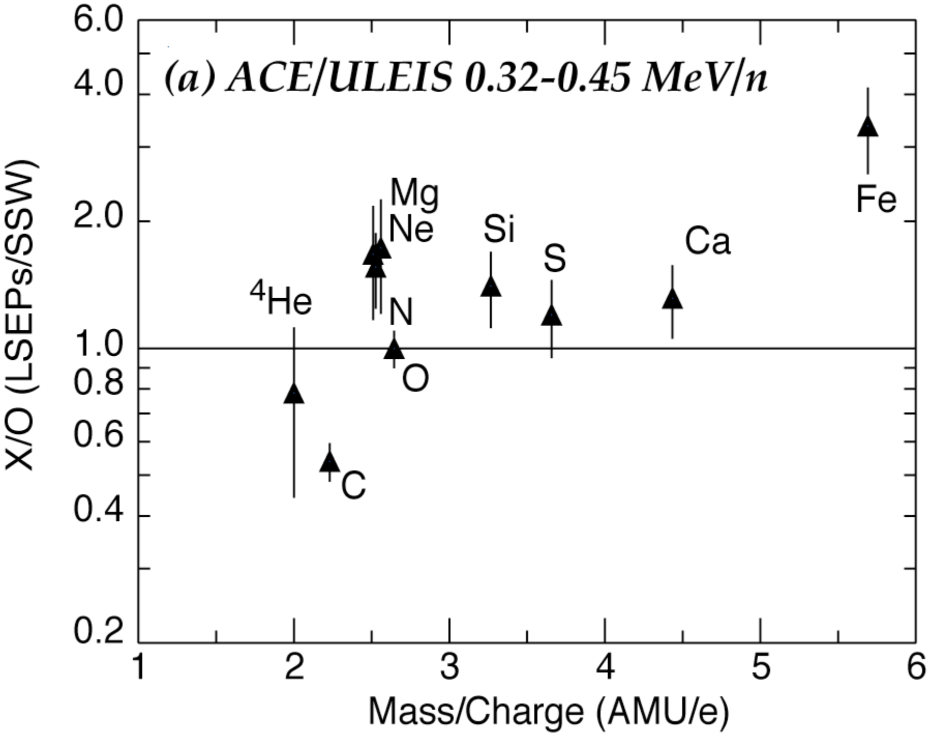




(Mason et al. 1999 ApJ, 525, L133).

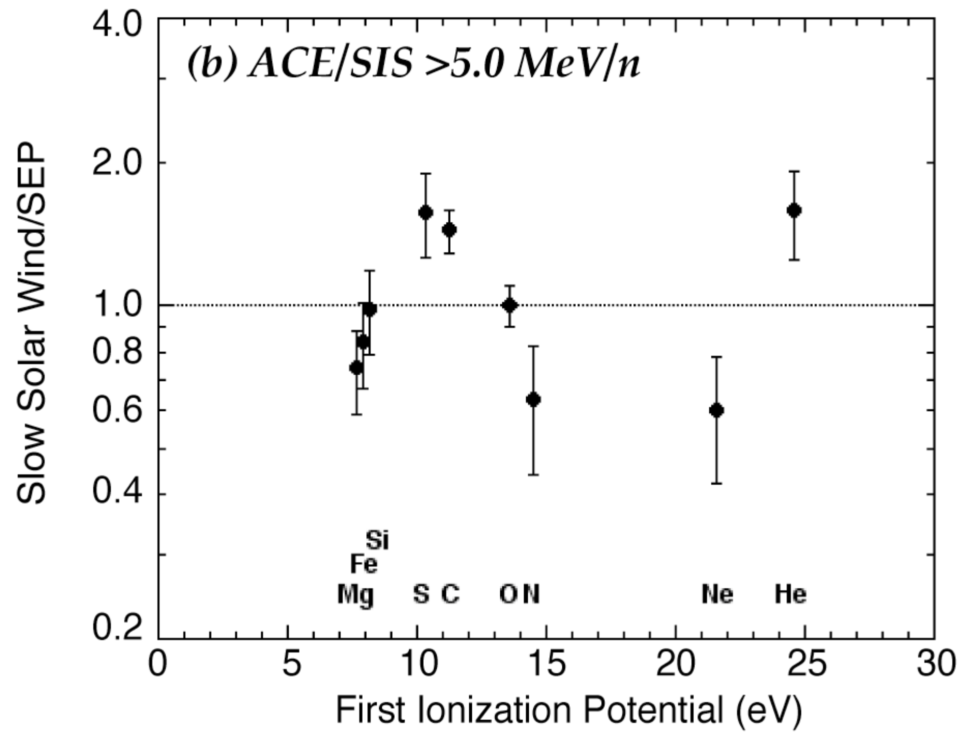
5.3 Heavy ion abundances

0.32-45 MeV/n vs. M/Q



Desai et al., ApJ., vol. 649, 470, 2006

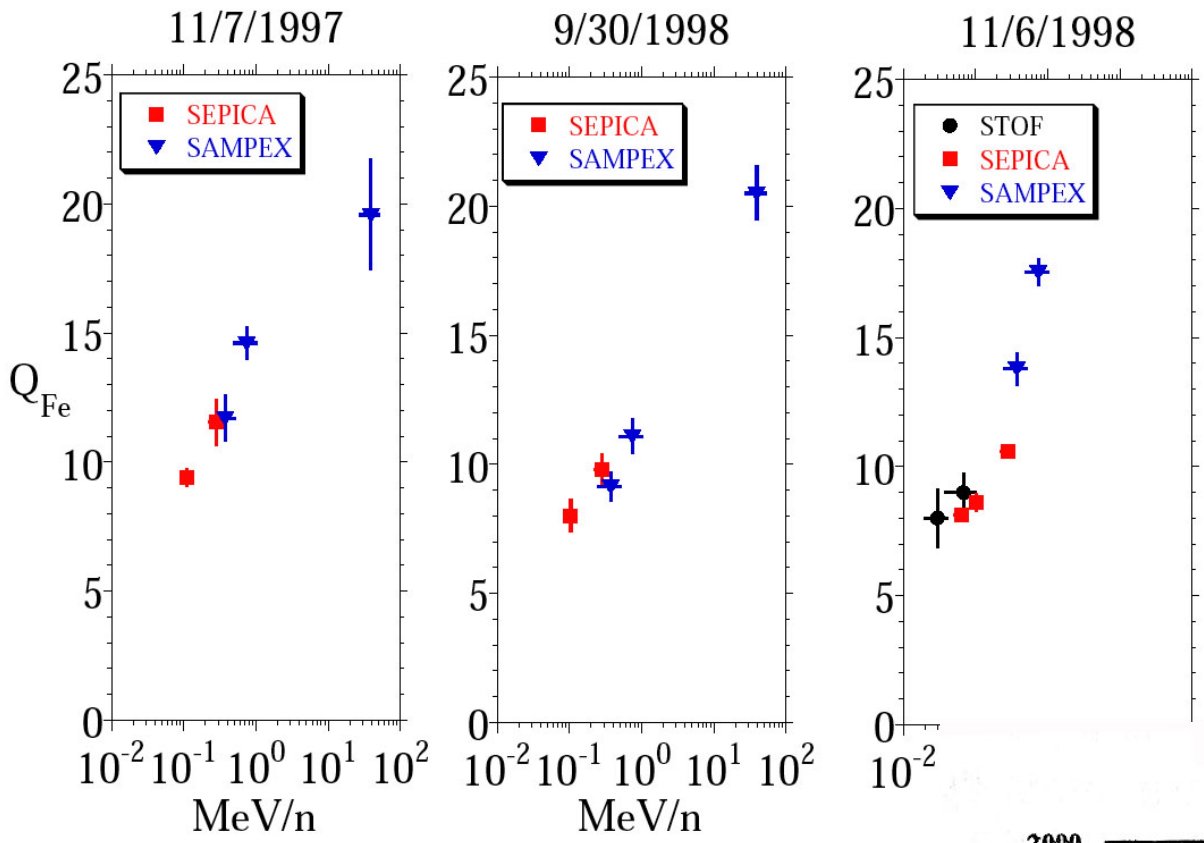
>5 MeV/n vs. FIP



(Mewaldt et al., 2002)

Not well organized by any simple physical quantity (e.g., M/Q ratio, FIP, etc.)

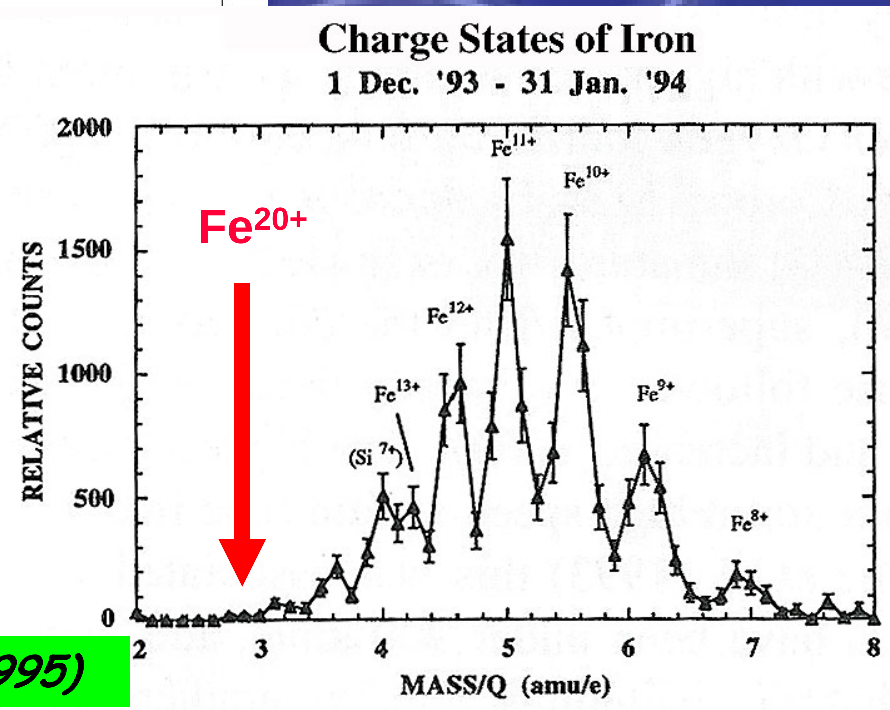
5.3 Ionic Charge States



Mean Q-states of Fe increase with Energy

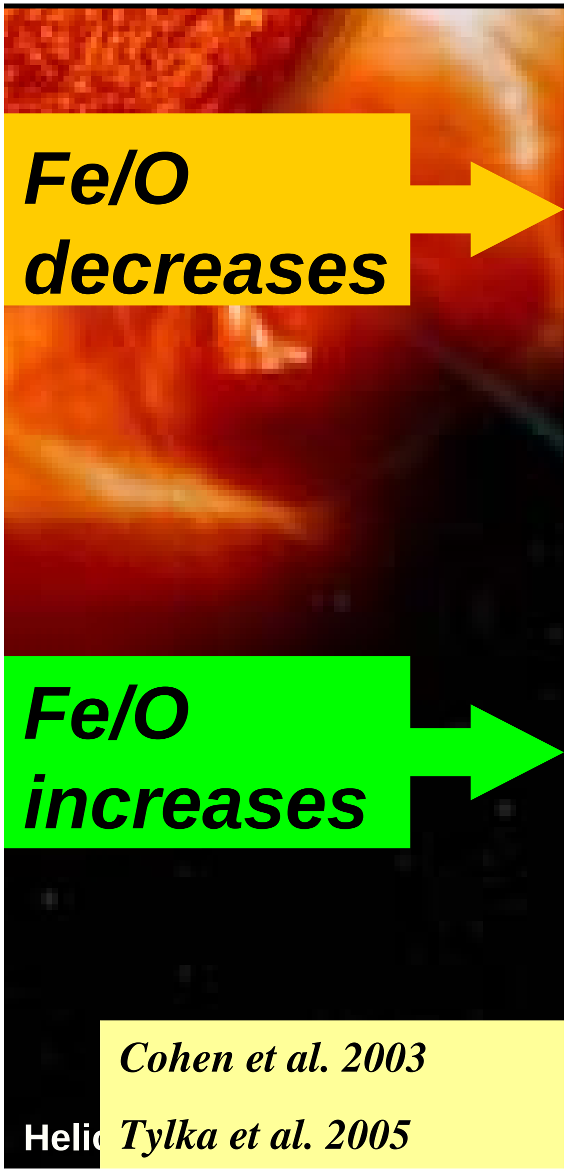
Popecki et al., 2003

Q(Fe) ~ 20 are rarely observed in SW



Galvin et al. (1995)

5.3 Heavy Ion Spectra

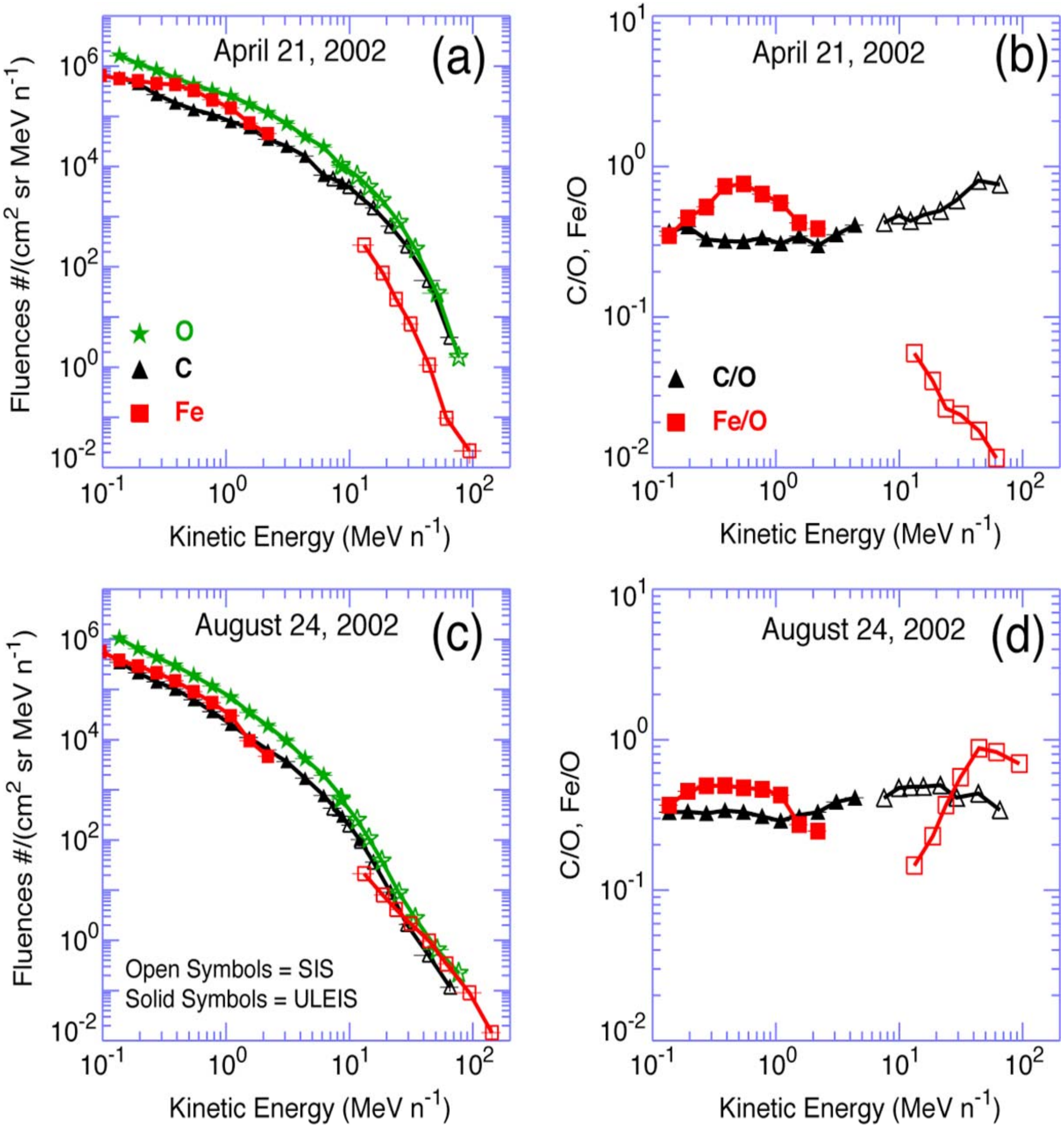


Fe/O decreases

Fe/O increases

Cohen et al. 2003

Tylka et al. 2005



5.3 Processes contributing to large SEPs

Seed Population

➔ Suprathermal material from flares, CME-driven shocks, heated solar wind etc. is re-accelerated by CME shocks

Seed population + Shock Geometry

➔ Quasi-perp shocks accelerate flare suprathermals, quasi-parallel shocks accelerate solar wind or coronal suprathermals

Direct Flare Scenario

➔ Flares and CME-driven shocks make contributions to large SEP events, contribution depends on flare size, CME shock strength, magnetic connection between flare and observer

Role of Scattering and Transport

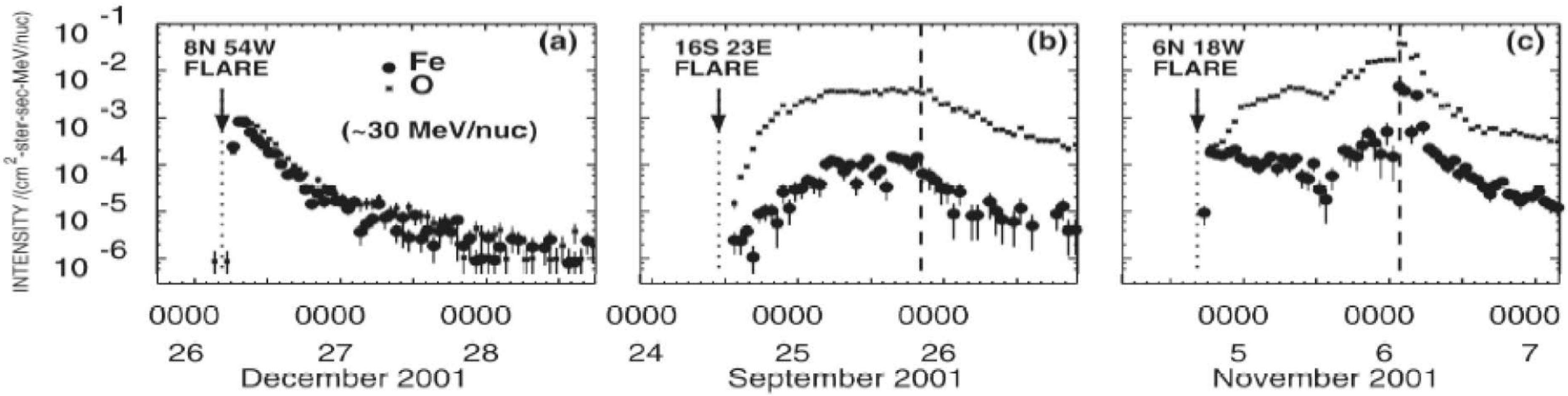
➔ Diffusion coefficient-dependent scattering during acceleration, escape, and transport

5.4 Cane et al., 2003; 2006

Western events: High Fe/O => direct Flare population

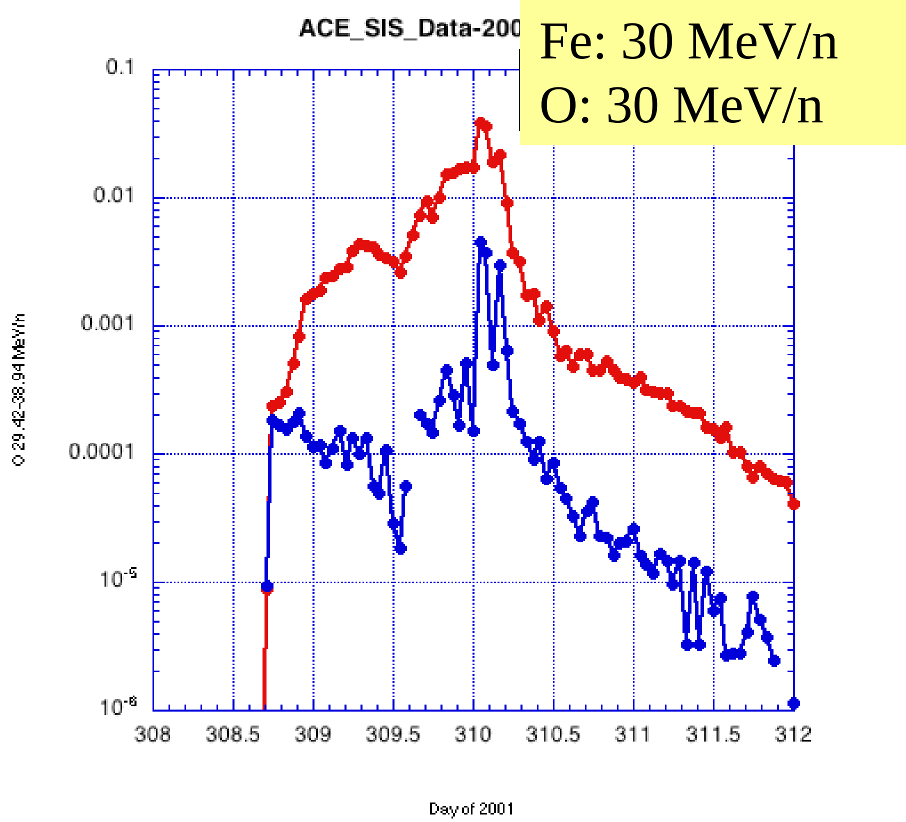
Eastern events: Fe/O< 0.2 => Shock-accelerated population

Central Meridian Events: High Fe/O followed by lower Fe/O at shock = Flare+shock

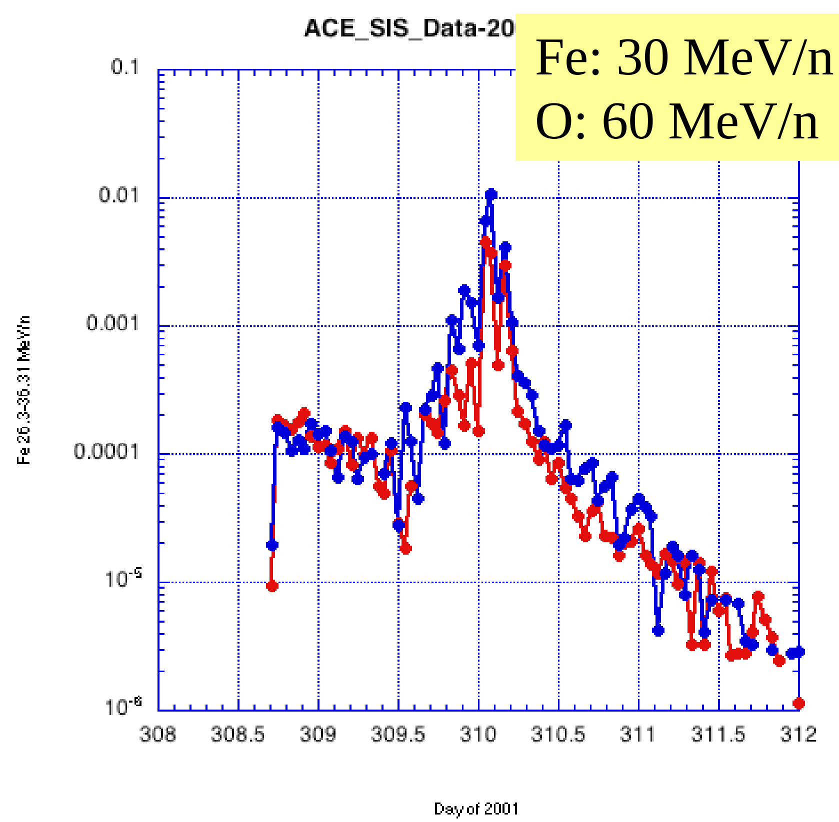


5.4 Time-profiles

November 4, 2001 => 2 component event of Cane et al., 2006



Fe: 30 MeV/n
O: 30 MeV/n



Fe: 30 MeV/n
O: 60 MeV/n

O, Fe At same MeV/n

O has ~twice the kin. energy as Fe

5.5 Kappa-dominated spectra and time profiles

- **Time-intensity profiles for Fe are similar to those of O at twice the energy/nucleon in ~75% of the events**

  => Temporal variations of Fe/O vanish

- **A simple mechanism that could give this effect is a time intensity profile dominated by transport scattering, where**

$$\kappa_{//} = \frac{1}{3} v \lambda_{//} = C v \left(\frac{A}{Q} \right)^{\gamma} \qquad (36b)$$

5.6 Status of Large SEP events

Property	*70-90's*	*Emerging Picture*	*Future Challenges*
Source Material	Ambient corona, solar wind	Suprathermals from flares, large SEPs, other?	Identify & characterize sources Investigate effects on injection and acceleration
Acceleration	CME shocks	Confirmed upto ~100 MeV/n. >100 MeV/n (?)	Require 2-step process Effects of injection, shock geometry Combine with CME models
Transport	Diffusive	M/Q-dependent; affects spectra, abundances, time-profiles	Characterize effects of turbulence and scattering in the corona and IP medium

6 Lecture Summary

- **SEP Observations**
  - **Key Heliospheric Particle Population**
  - **1990's - Two-classes of SEPs**
    - **Flare-related or impulsive**
    - **CME-shock accelerated or gradual**
  - **Recent Observations**
    - **Distinction between impulsive and gradual is blurred**
    - **A single model cannot account for e-s, heavy and UH heavy ions, 3He in the impulsive SEPs**
    - **Flares and CME shocks both contribute to large SEPs**
- **Theory**
  - **Interplanetary Transport**
    - **Diffusion in space, pitch-angle, and momentum, wave-particle interactions, convection, focusing in diverging magnetic fields, transport equations, Observations - Fits with transport equations**
  - **Particle Acceleration**
    - **Direct Electric Fields, Shock drift acceleration, diffusive shock acceleration, stochastic acceleration, self-generated turbulence**

- Joint Graduate Program between University of Texas, San Antonio (UTSA) and Southwest Research Institute (SwRI) in Space Physics
- Students in the Masters and PhD programs have access to SwRI's world-class space physics laboratory facilities
- Dissertation work includes hands-on training and active participation in the design and development of space flight hardware
- ~20-30 Fellowships available for Spring and Fall 2008.