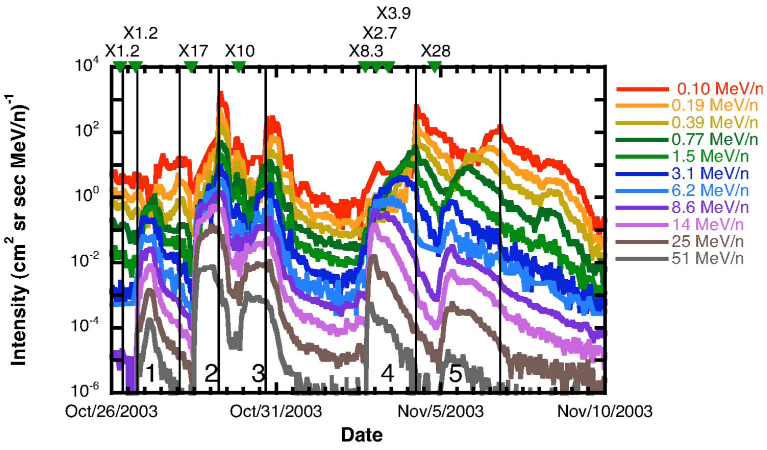
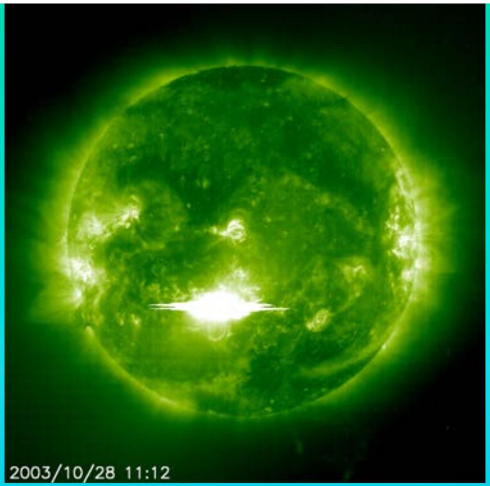
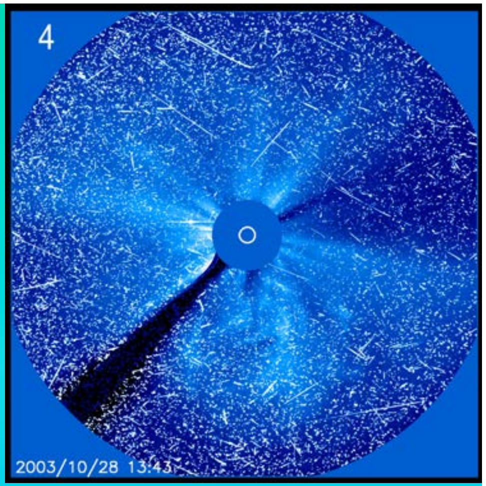


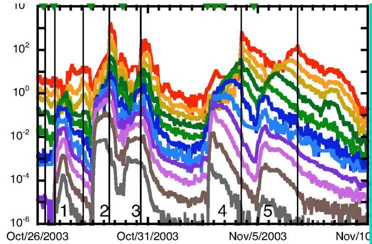




Solar Energetic Particles: What are they and Why do we care?

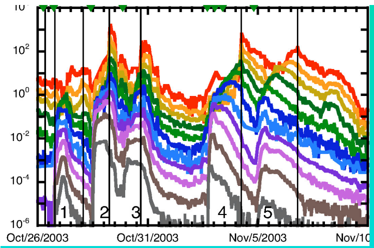
Christina Cohen

Caltech



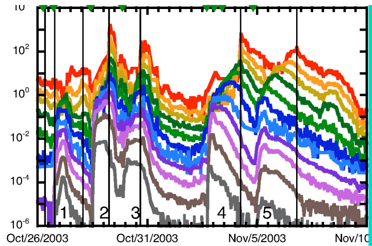
Outline

- What are SEPs?
  - And why do we care?
- Observational History
  - How are they measured?
  - How are they classified?
- Acceleration Mechanisms
  - Shock acceleration
  - Flare acceleration
- Problems with 2 classes
  - ACE observations
  - Explanations
- SEPs in 3-D
  - STEREO observations
  - Surprises
- Next Frontier



What are SEPs?

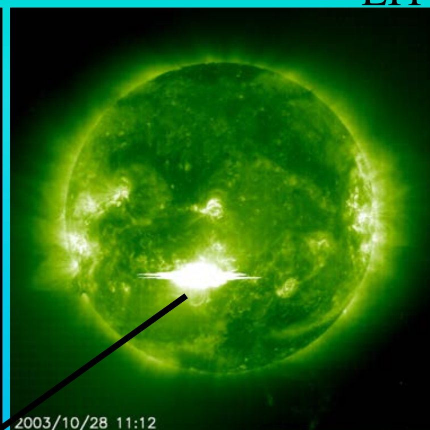
- Solar Energetic Particles
  - Solar = assumed to originate at the Sun
  - Energetic = historically above a few hundred keV/nuc
  - Particles = ions (mostly H, He like the Sun) + electrons
- Seen as increases in counting rates of ions (and/or electrons) of energies usually above 0.1 MeV/ nucleon



What are SEPs?

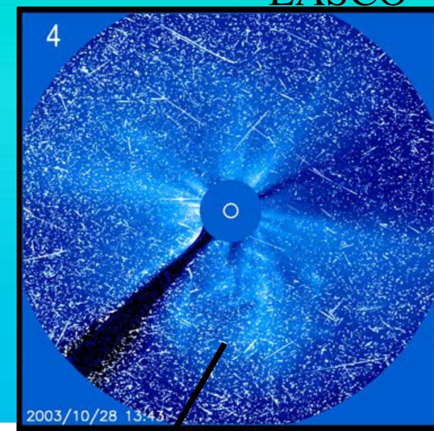
MDI

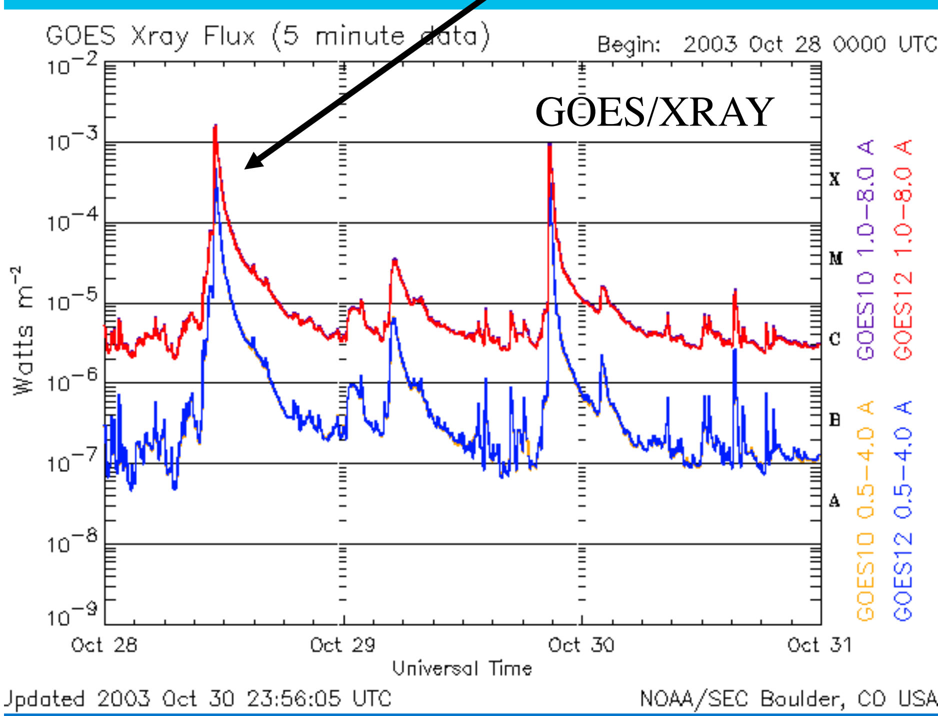
EIT

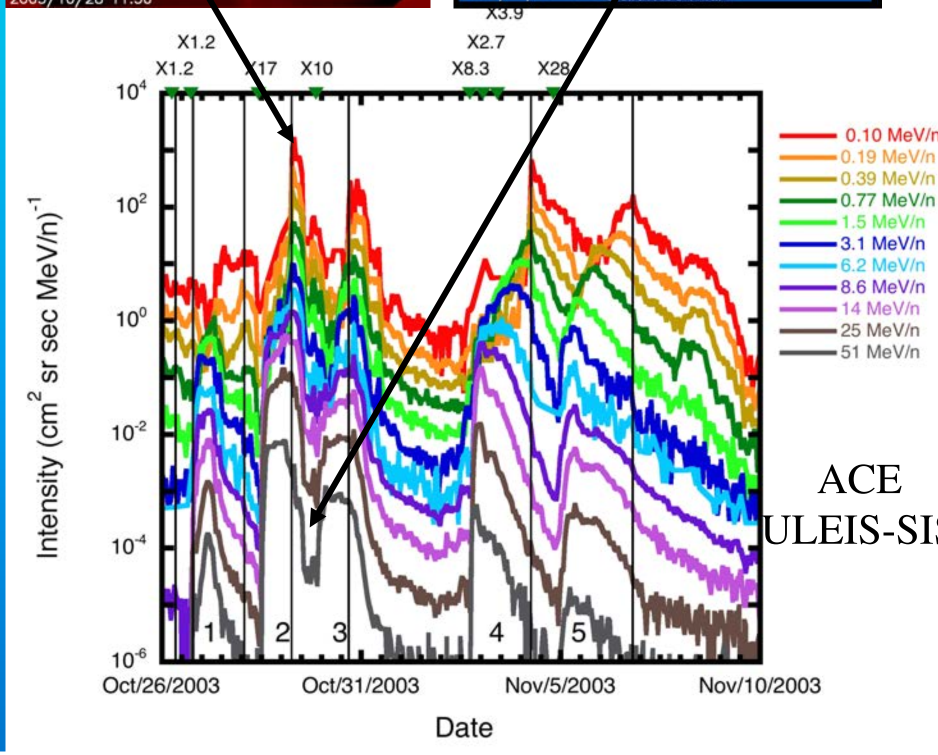


LASCO

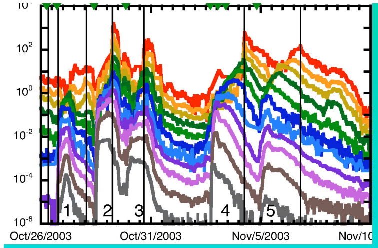
LASCO





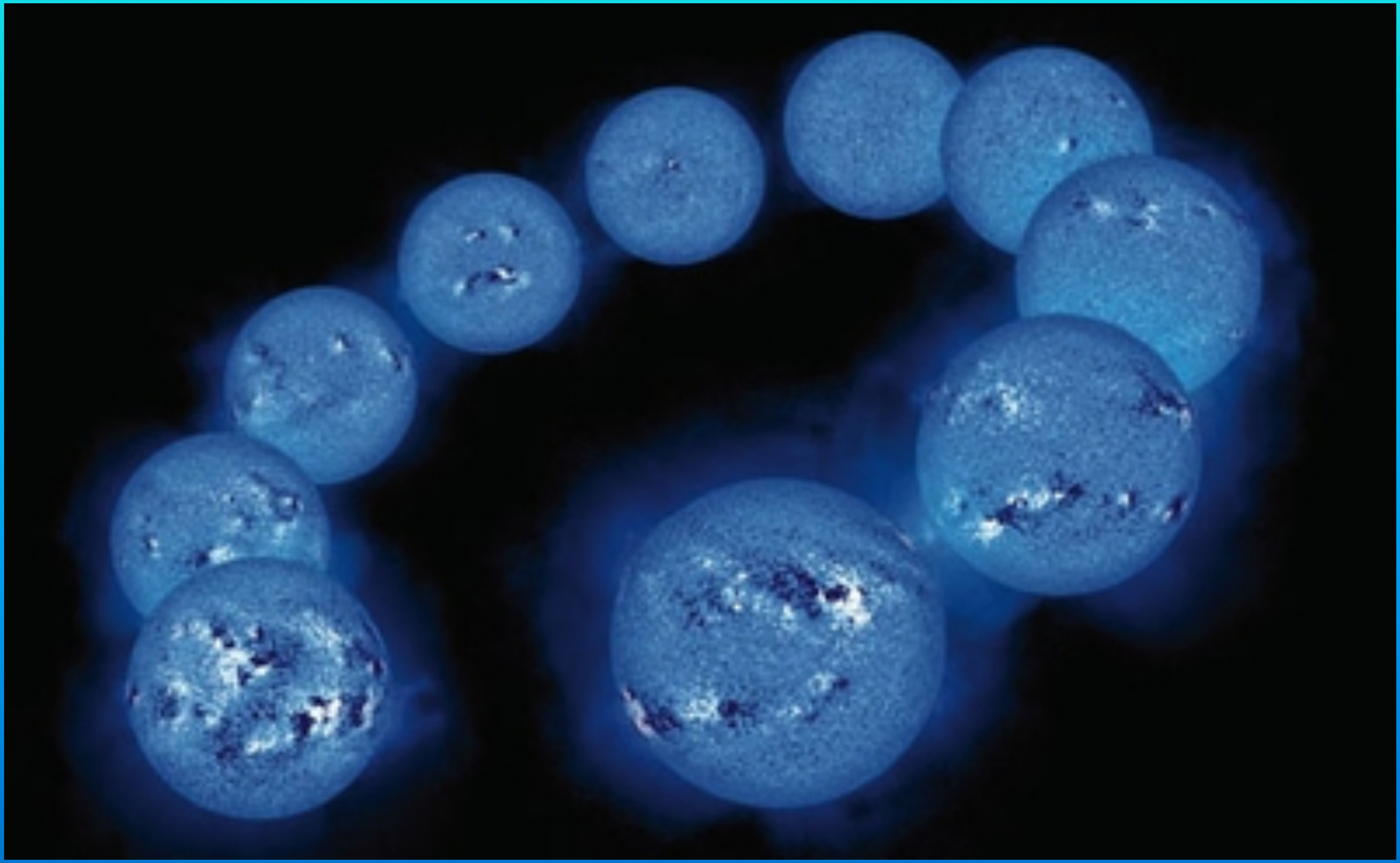


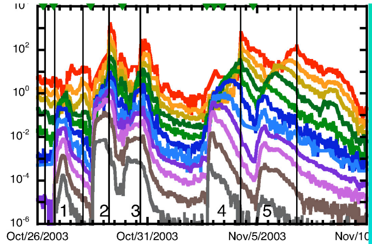
ACE
ULEIS-SIS



Solar Cycle

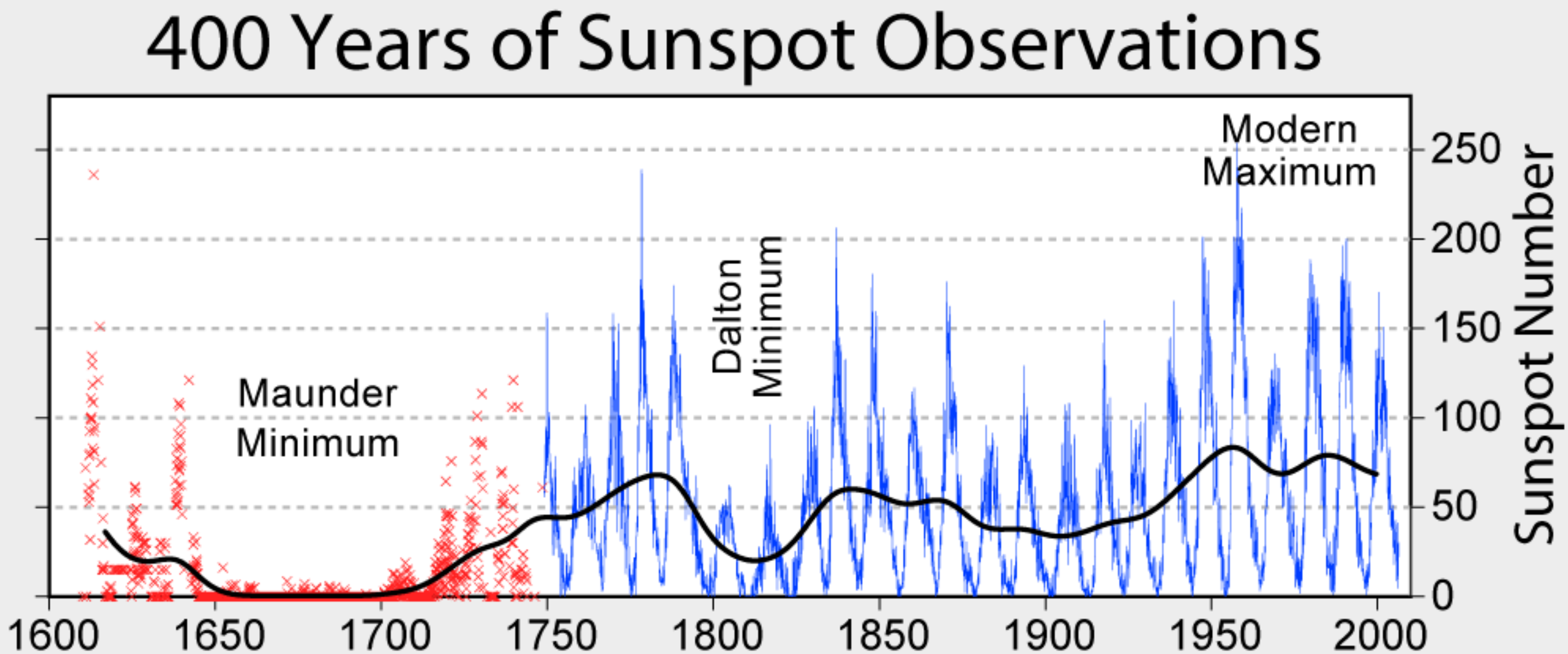
- The Sun's activity waxes and wanes over an 11-year cycle

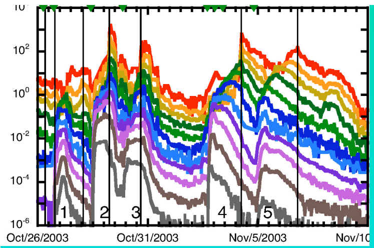




Solar Cycle

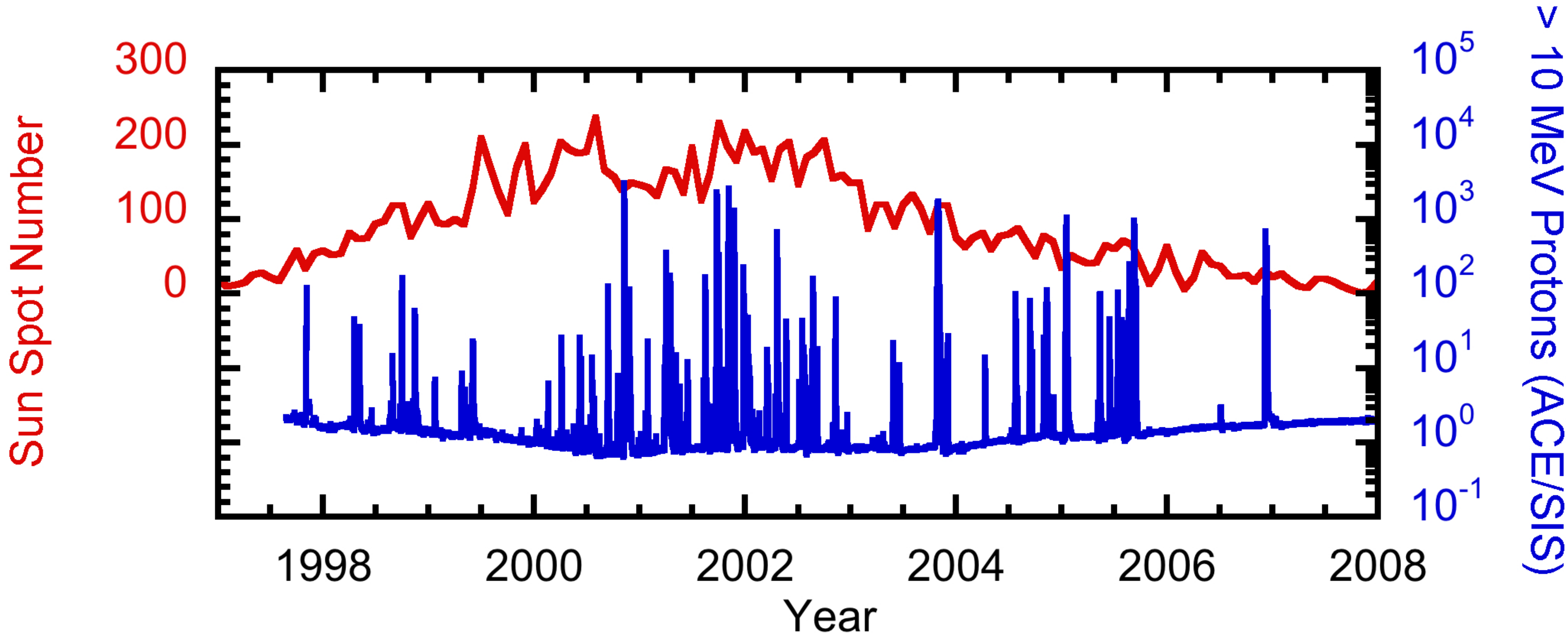
- The Sun's activity waxes and wanes over an 11-year cycle
- Sunspot number is the 'proxy'

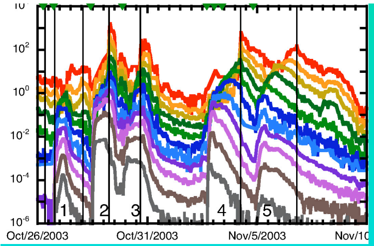




Solar Cycle

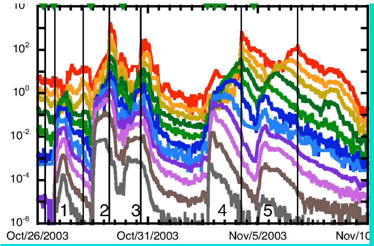
- The Sun's activity waxes and wanes over an 11-year cycle
- Sunspot number is the 'proxy'
- The frequency of SEP events is higher at solar maximum





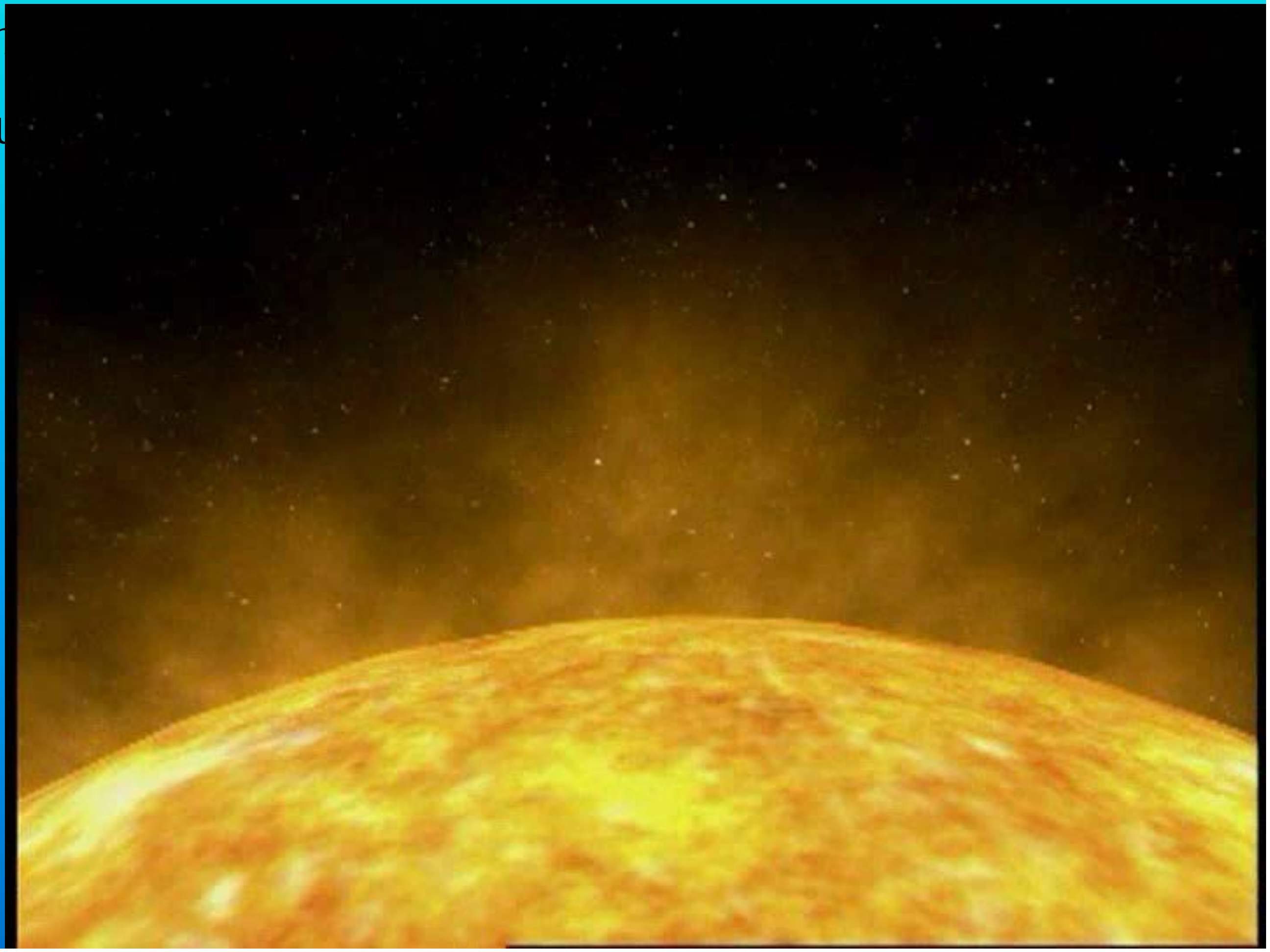
Why do we care about SEPs?

- A sample of the Sun
  - One of the most accurately measured solar samples
  - Abundances from spectroscopic measurements are limited
  - if we can just figure out the details of creating them and getting them here
- Space Weather

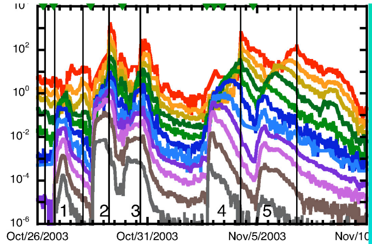


Why do we care about SEPs?

- A sample of the Sun
  - One of the most accurately measured solar samples
  - Abundances fron
  - if we can just figu
    them here
- Space Weather

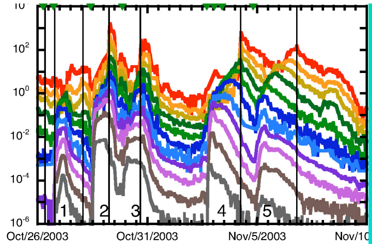


What History



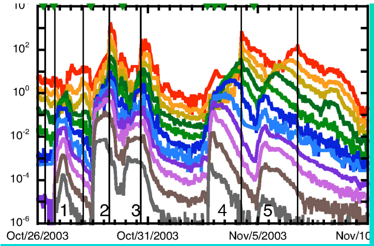
Why do we care about SEPs?

- A sample of the Sun
  - › One of the most accurately measured solar samples
  - › Abundances from spectroscopic measurements are limited
  - › if we can just figure out the details of creating them and getting them here
- Space Weather
  - › SEPs
    - Aurora
    - Radiation hazards
    - Satellite effects
  - › CMEs
    - Geomagnetic storms
    - Ground Induced Currents



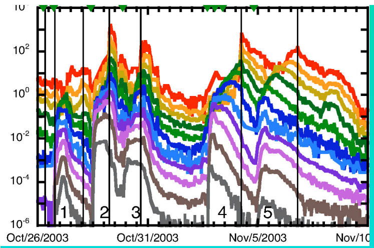
Aurora

- Energetic particles hitting the Earth's atmosphere excite atoms and create aurora



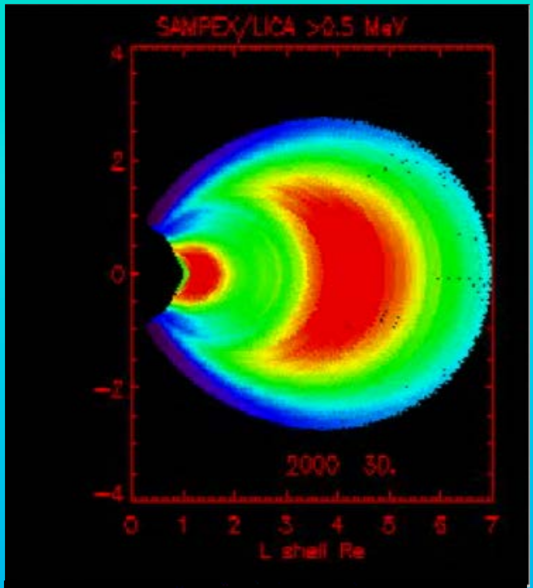
Aurora

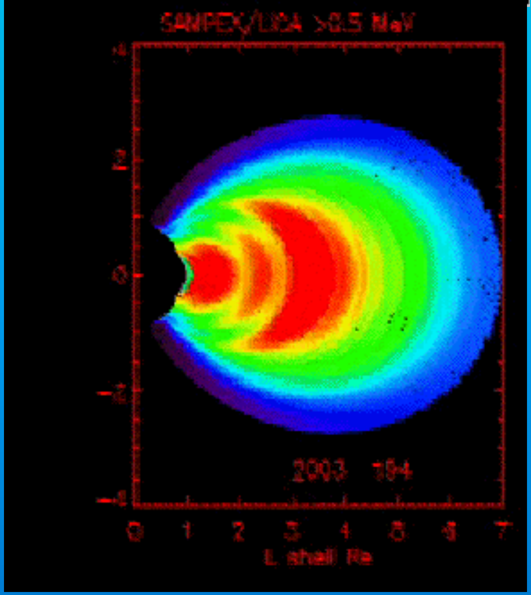
- Energetic particles hitting the Earth's atmosphere excite atoms and create aurora

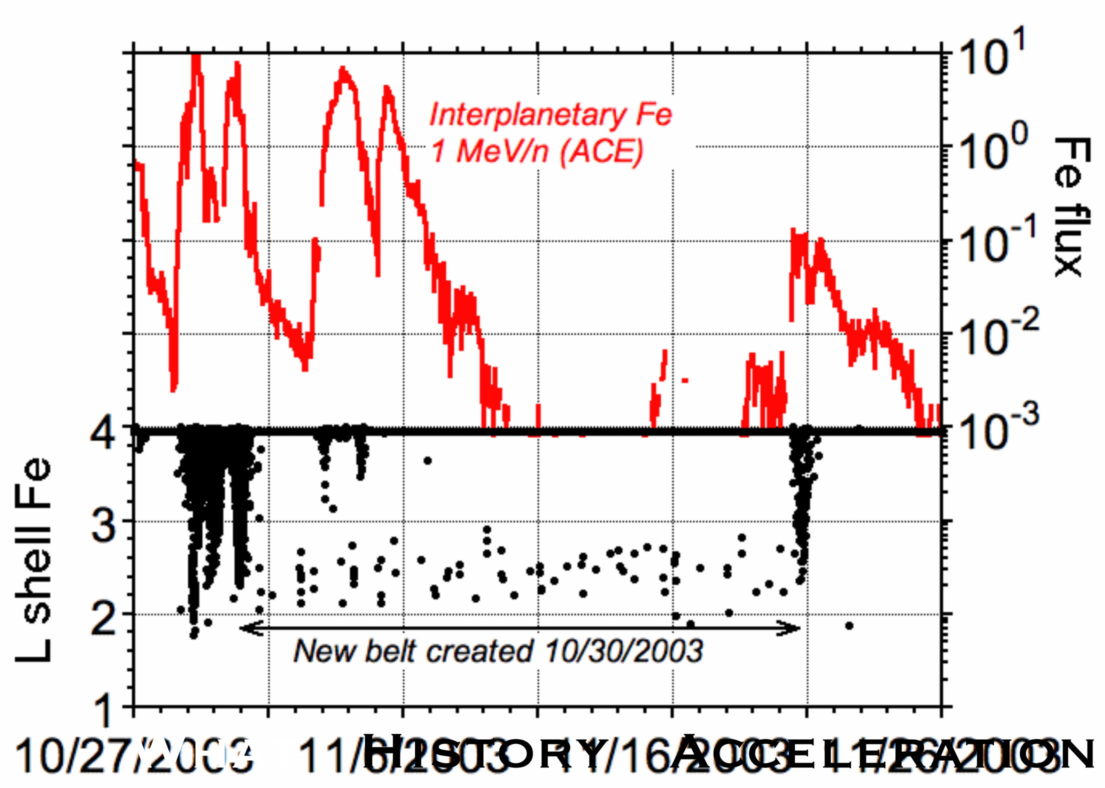


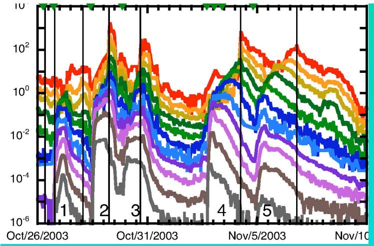
Earth Radiation Belts

- Energetic particles are trapped in belts around the Earth
- Radiation hazard for Earth-orbiting spacecraft



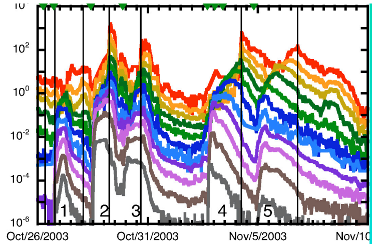






Satellite Effects

- Loss of data
- Spurious signals
  - False alarms, noise strobes, erroneous telemetry values
- Phantom commands
  - For example gain changes and attitude sensor errors
- Mission or sensor degradation
- Solar array degradation
- Safeholds
- Latchups
- Subsystem failure
  - Loss of a redundant system
- Mission Loss



Satellite Effects

April 2010

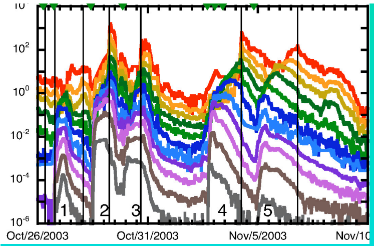
'Zombie' satellite runs amok in Earth's orbit

The out-of-control communications satellite Galaxy 15 is drifting into orbits occupied by other spacecraft.

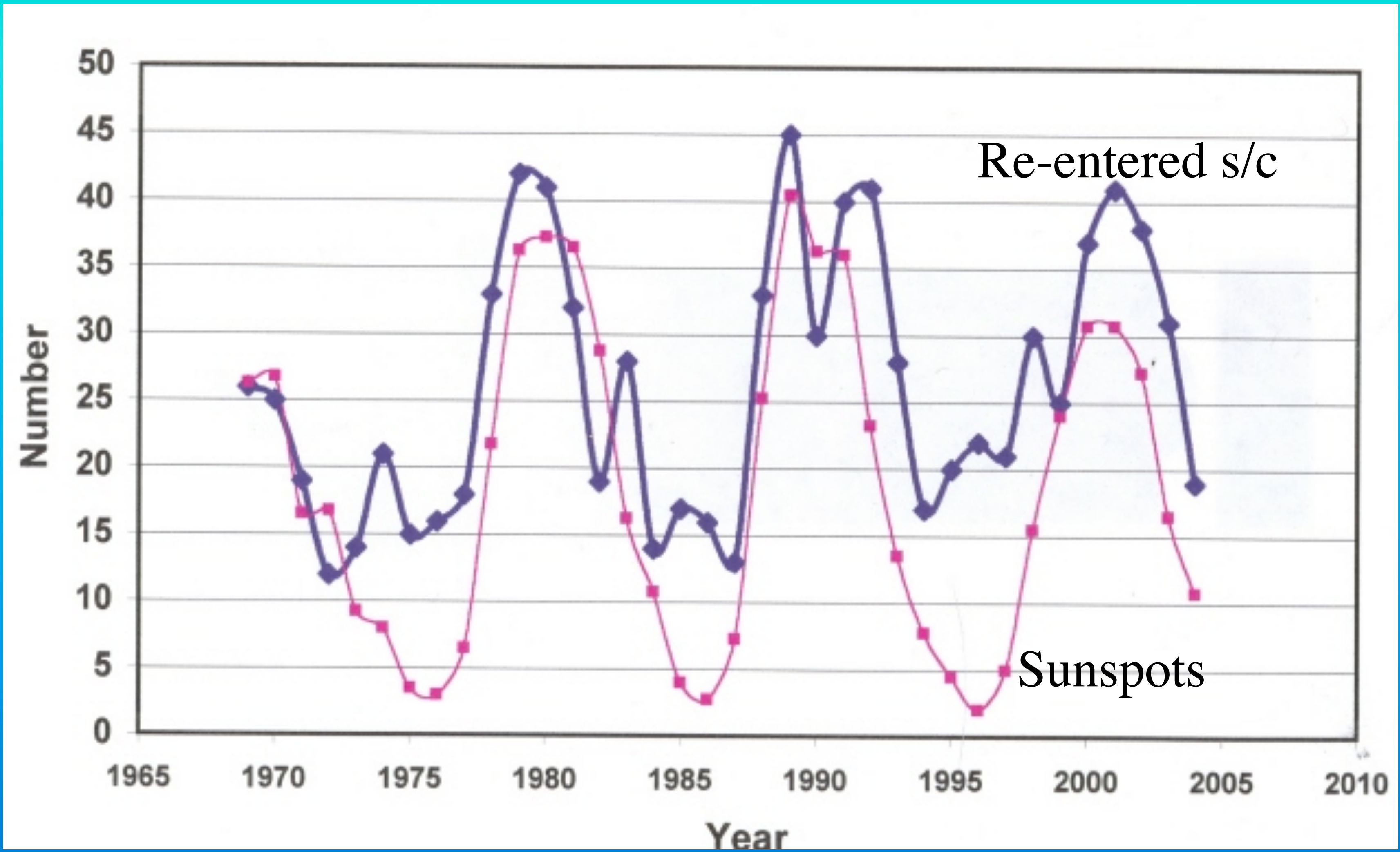
Intelsat's Galaxy 15 satellite launched in 2005 with an Ariane 5 rocket in Guyana. The communications satellite stopped responding last month, becoming a 'zombie' satellite that now threatens other spacecraft.

Newscom/File

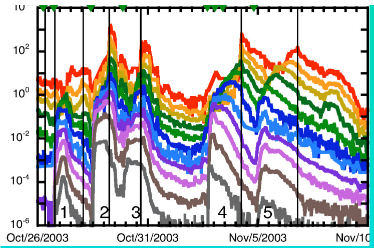
Enlarge



Satellite Effects



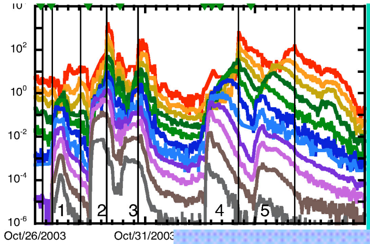
WHAT HISTORY ACCELERATION PROBLEMS 3D NEXT

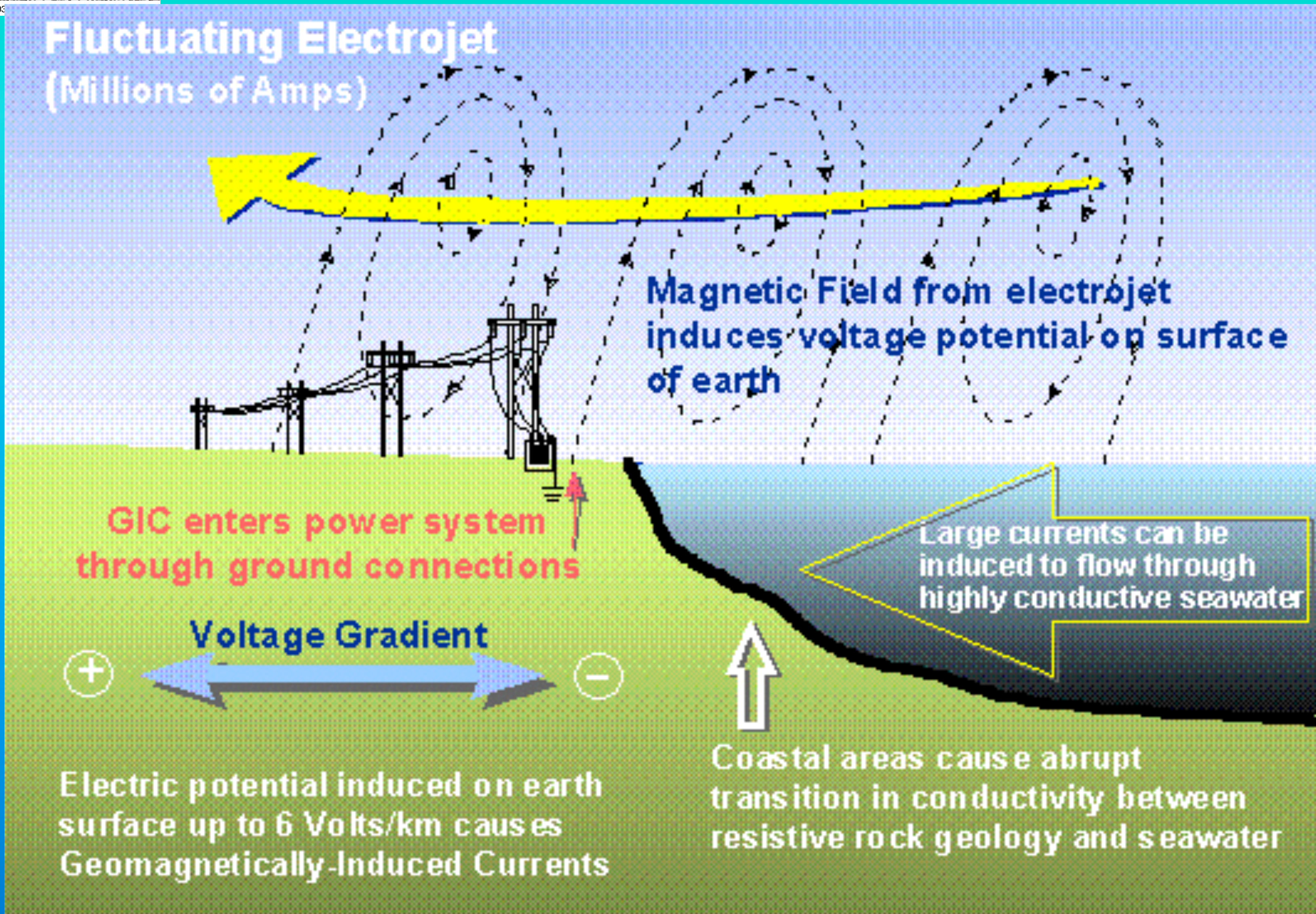


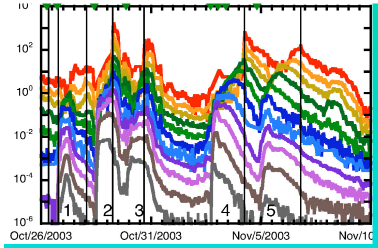
GICs & the Power Grid

- Geomagnetic Storms
  - Impact of the CME deforms the Earth's magnetic field
  - Induces currents in the power lines

GICs & the Power Grid



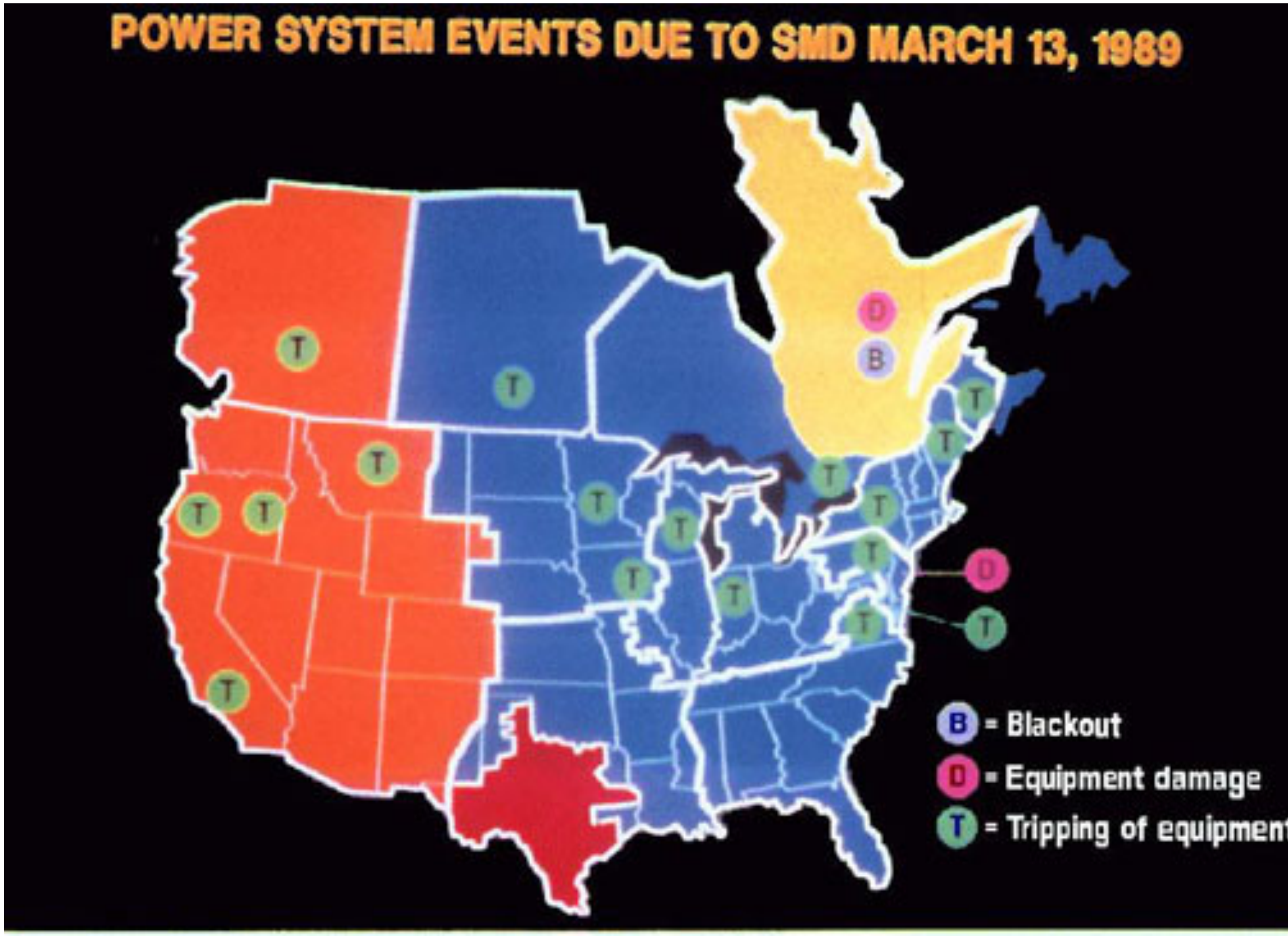




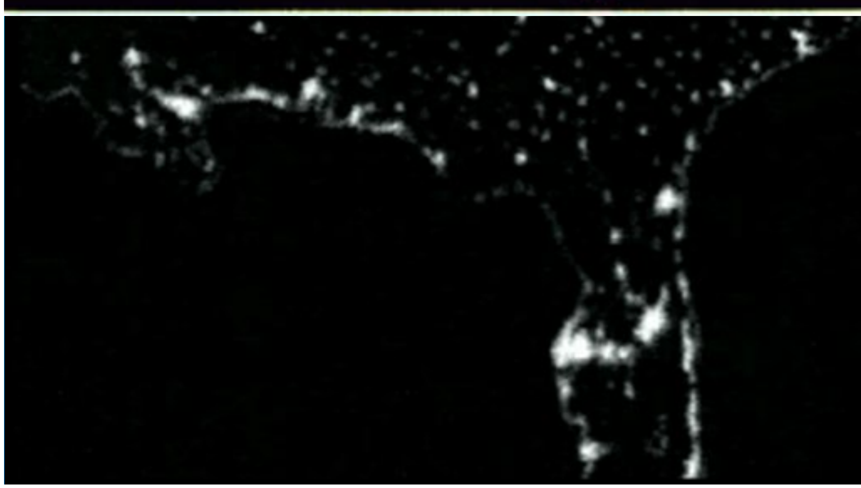
GICs & the Power Grid

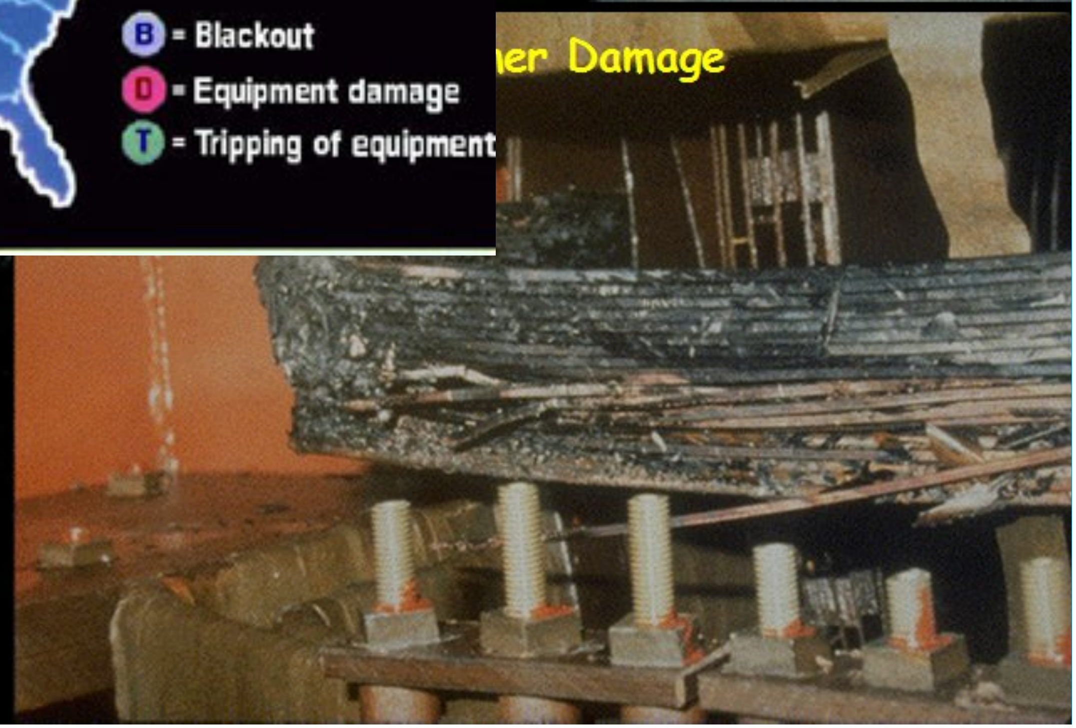
- Geomagnetic Storms
  - › Impact of the CME deforms the Earth's magnetic field
  - › Induces currents in the power lines
  - › Transformers aren't made to handle these high currents
    - Hydro Quebec lost power grid for 9 hours in March 1989
    - Current situation is even worse because of the large interconnectedness of today's power grid

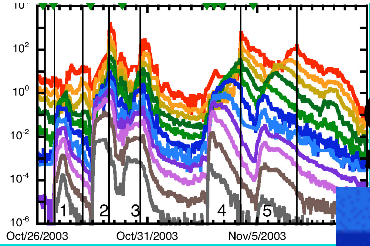
Geomagnetic Storm Effects
March 1989
Hydro Quebec Loses Electric Power for 9 Hours


POWER SYSTEM EVENTS DUE TO SMD MARCH 13, 1989
B = Blackout
D = Equipment damage
T = Tripping of equipment

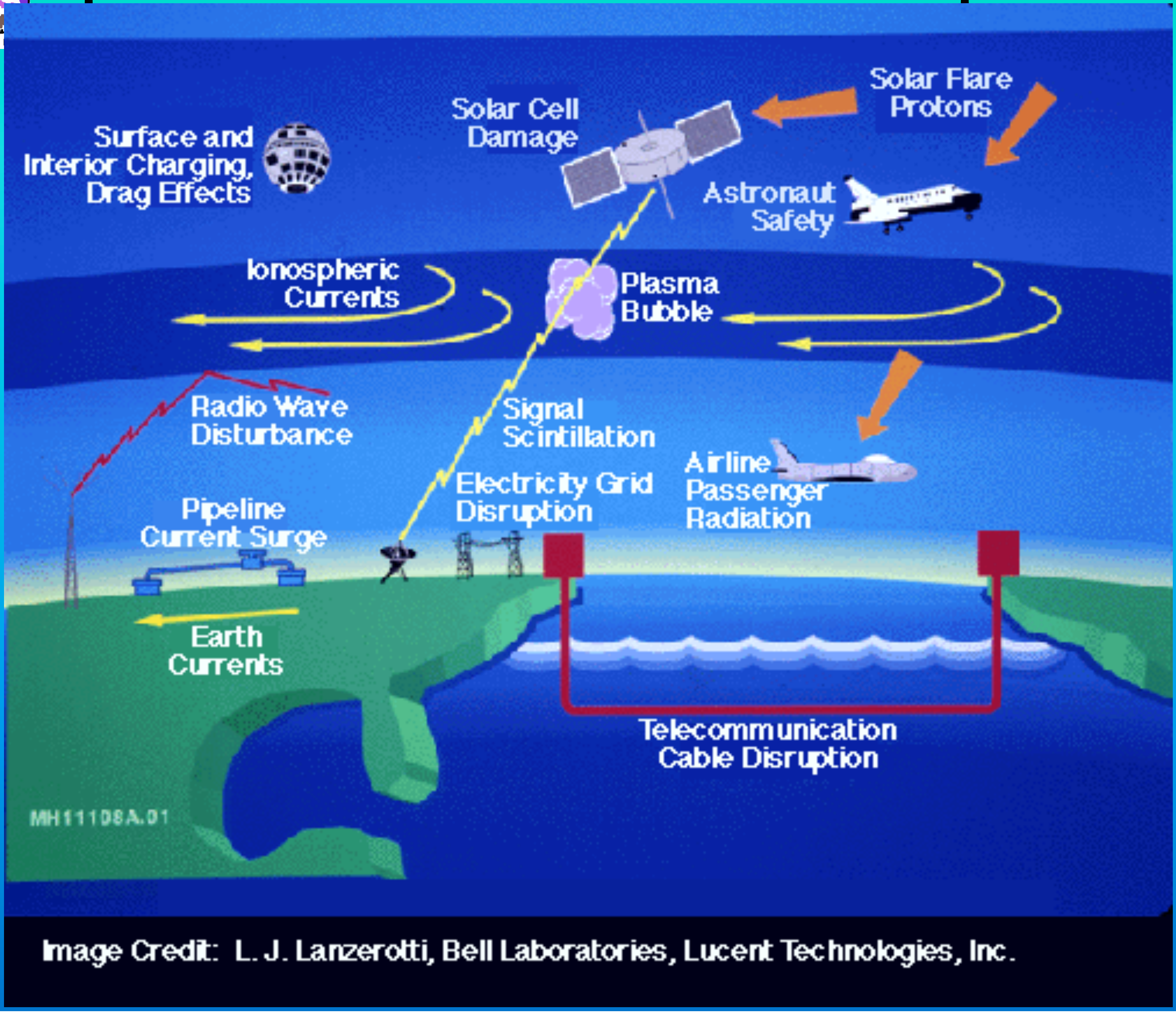

Electric Power
Transformer

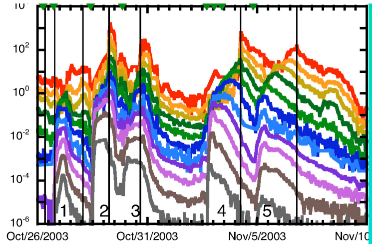



Damage



Space Weather Consequences

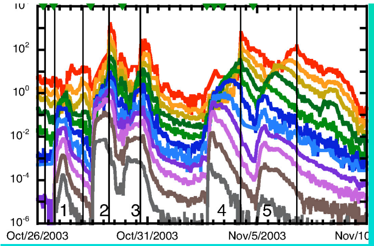




Space Weather Awareness

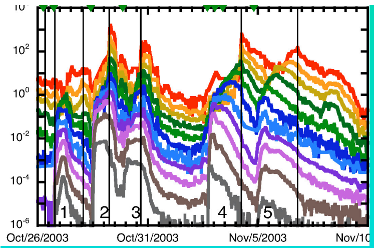
What History Acceleration Problems 3D Next


Oct/26/2003
Rain/
T'Storms
Severe
T'Storms
Possible
H
H
L
L
Rain/
T'Storms
T.S. Fay
NOAA
Weather Forecast for Friday, August 22, 2008
DOC/NOAA/NWS/NCEP/Hydrometeorological Prediction Center
Prepared by Fracasso based on HPC, SPC, and TPC forecasts.



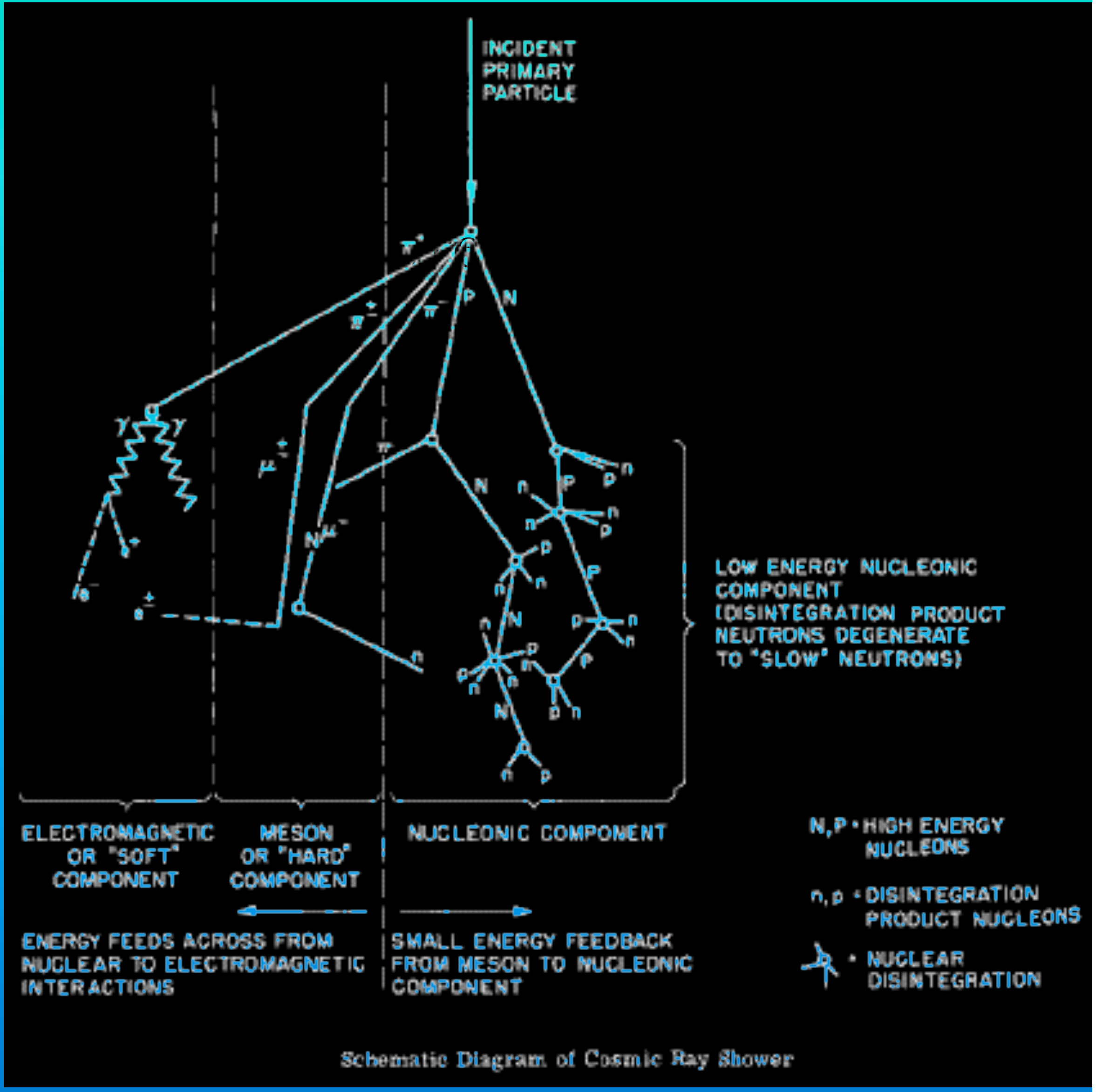
How are SEPs Measured?

- On the ground
  - neutron monitors (indirect measurement)

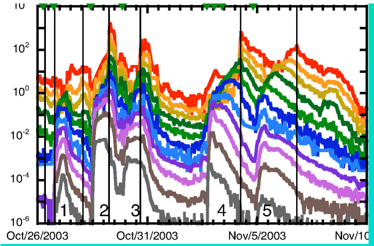


How are SEPs Measured?

- On the ground
  - › neutron monitors

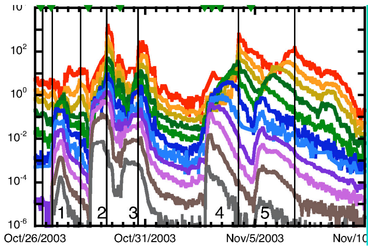


WHAT HISTORY ACCELERATION PROBLEMS 3D NEXT



How are SEPs Measured?

- On the ground
  - › neutron monitors (indirect measurement)
- In space (since early 1960s)
  - › first measurements (scintillation and Geiger counters)
  - › dE/dx vs E technique
    - Proportional counters
    - Solid state detectors

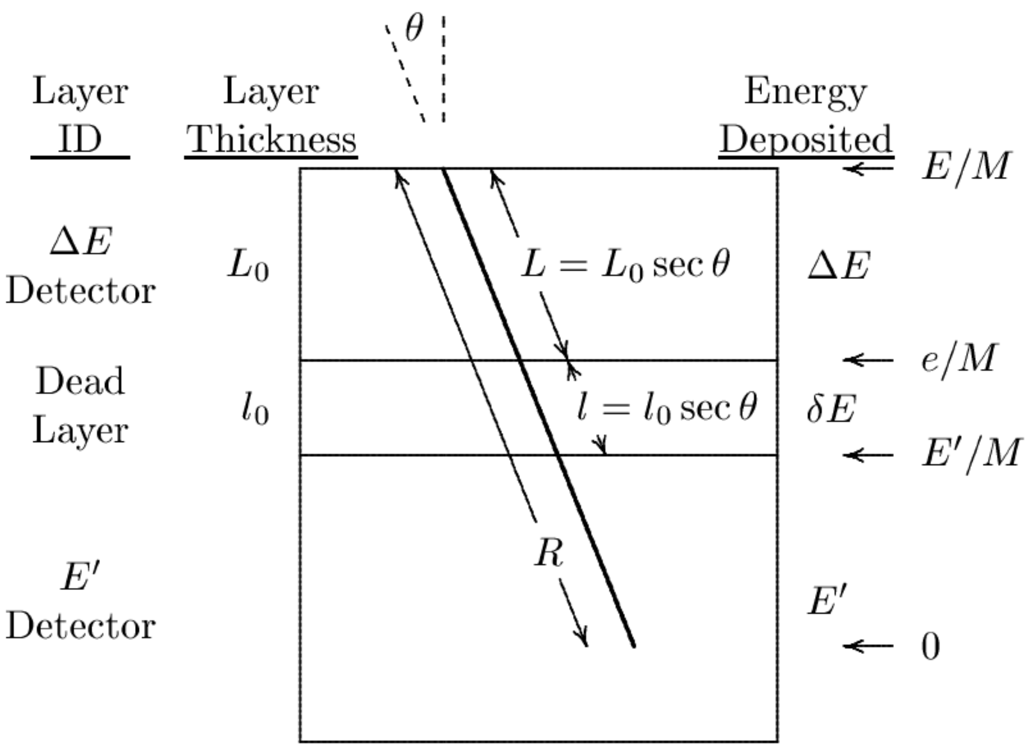


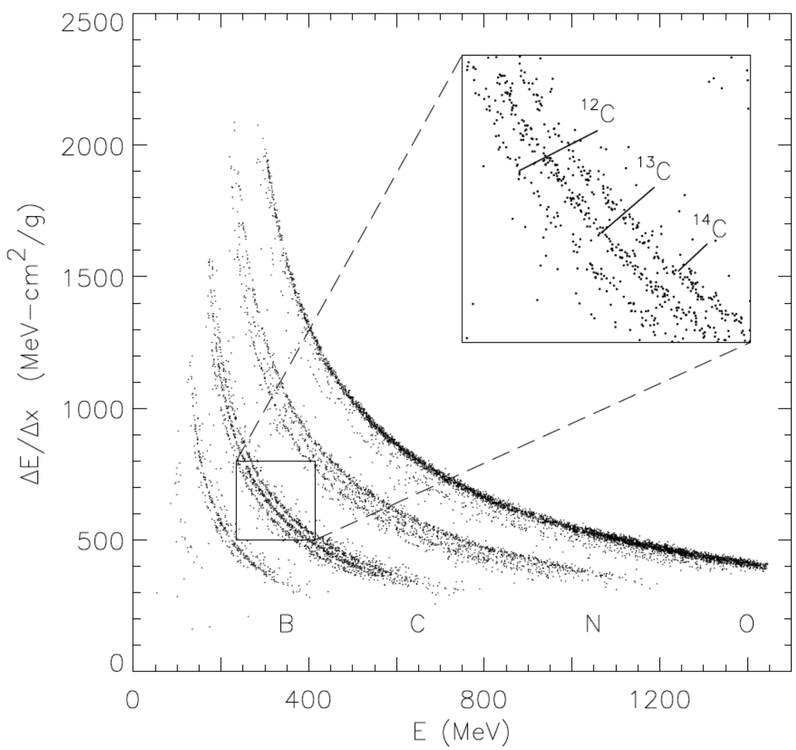
How are SEPs Measured?

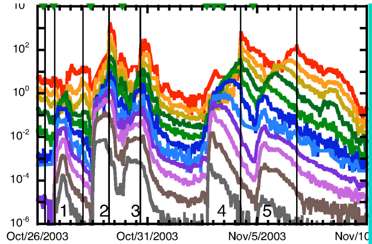
$$dE/dx \propto (Z/V)^2 \propto (MZ^2/E)$$

$$E\, dE/dx \propto Z^2 M$$

$$dE/dx \sim \Delta E/\ L = \Delta E/(L_0 \sec \vartheta)$$

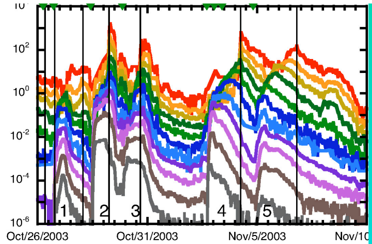






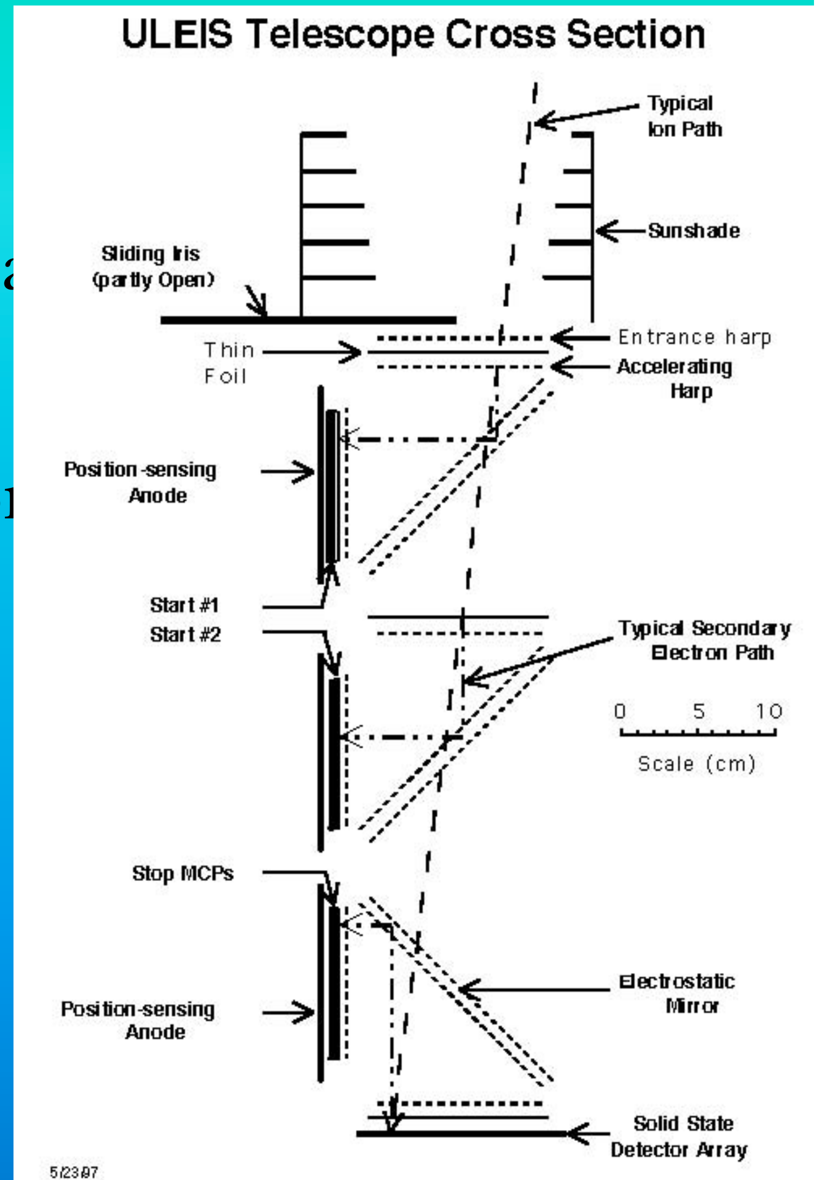
How are SEPs Measured?

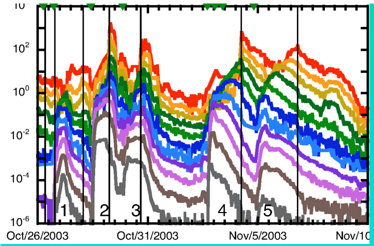
- On the ground
  - › neutron monitors (indirect measurement)
- In space (since early 1960s)
  - › first measurements (scintillation and Geiger counters)
  - › dE/dx vs E technique
    - Proportional counters
    - Solid state detectors
  - › Time of flight



How are SEPs Measured?

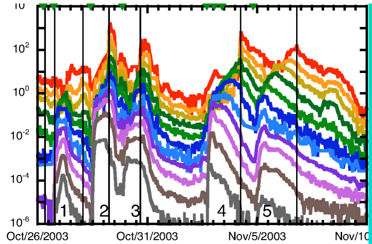
- On the ground
  - › neutron monitors (indirect mea
- In space (since early 1960s)
  - › first measurements (scintillatio
  - › dE/dx vs E technique
    - Proportional counters
    - Solid state detectors
  - › Time of flight





How are SEPs Measured?

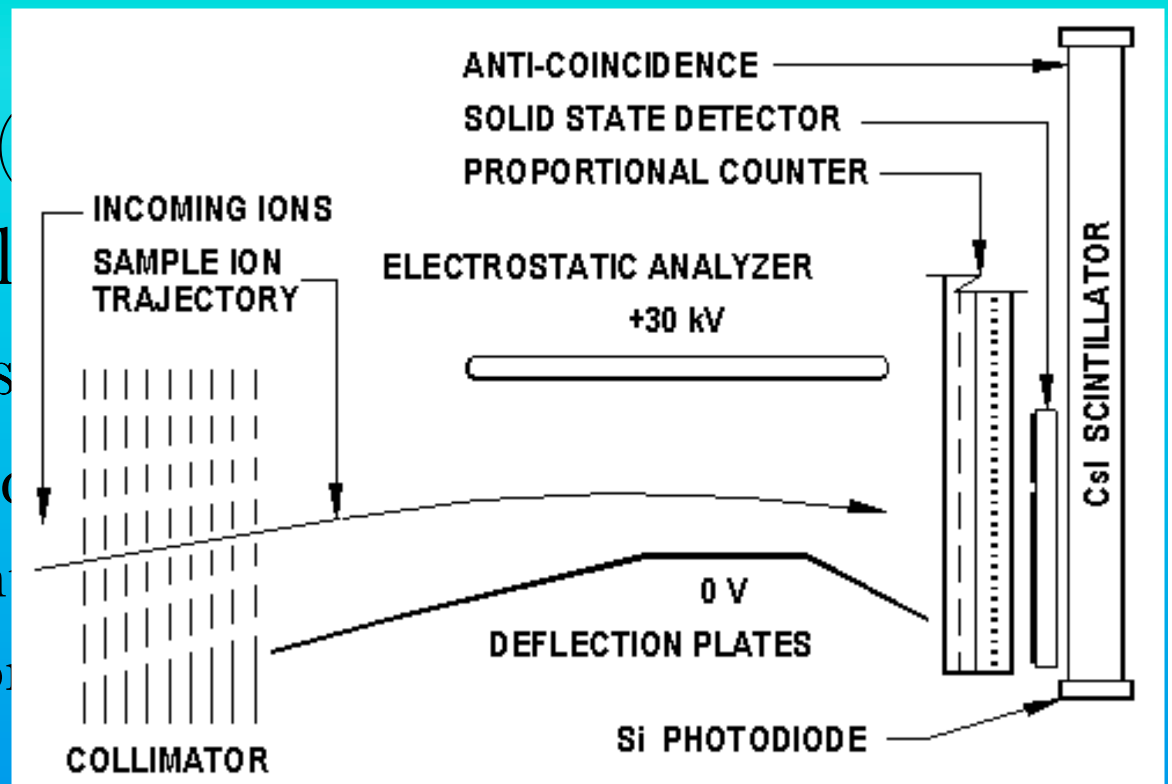
- On the ground
  - › neutron monitors (indirect measurement)
- In space (since early 1960s)
  - › first measurements (scintillation and Geiger counters)
  - › dE/dx vs E technique
    - Proportional counters
    - Solid state detectors
  - › Time of flight
  - › E/q + dE/dx vs E

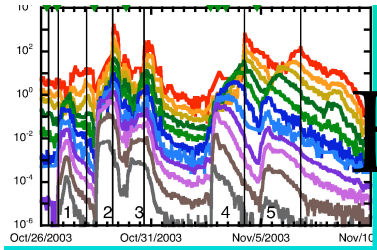


How are SEPs Measured?

- On the ground
  - › neutron monitors (
- In space (since earl
  - › first measurements
  - › dE/dx vs E technic
    - Proportional coun
    - Solid state detecto
  - › Time of flight
  - › E/q + dE/dx vs E

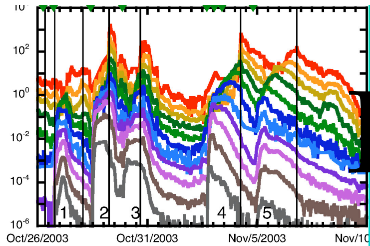
SEPICA





History of SEP Measurements

- First detection with connection to solar flare observation - Forbush 1946 in neutron monitor
- Timing related to gamma ray flare 1956 (most well studied)



History of SEP Measurements

- First detection w
observation - Fo
- Timing related t
(most well studie

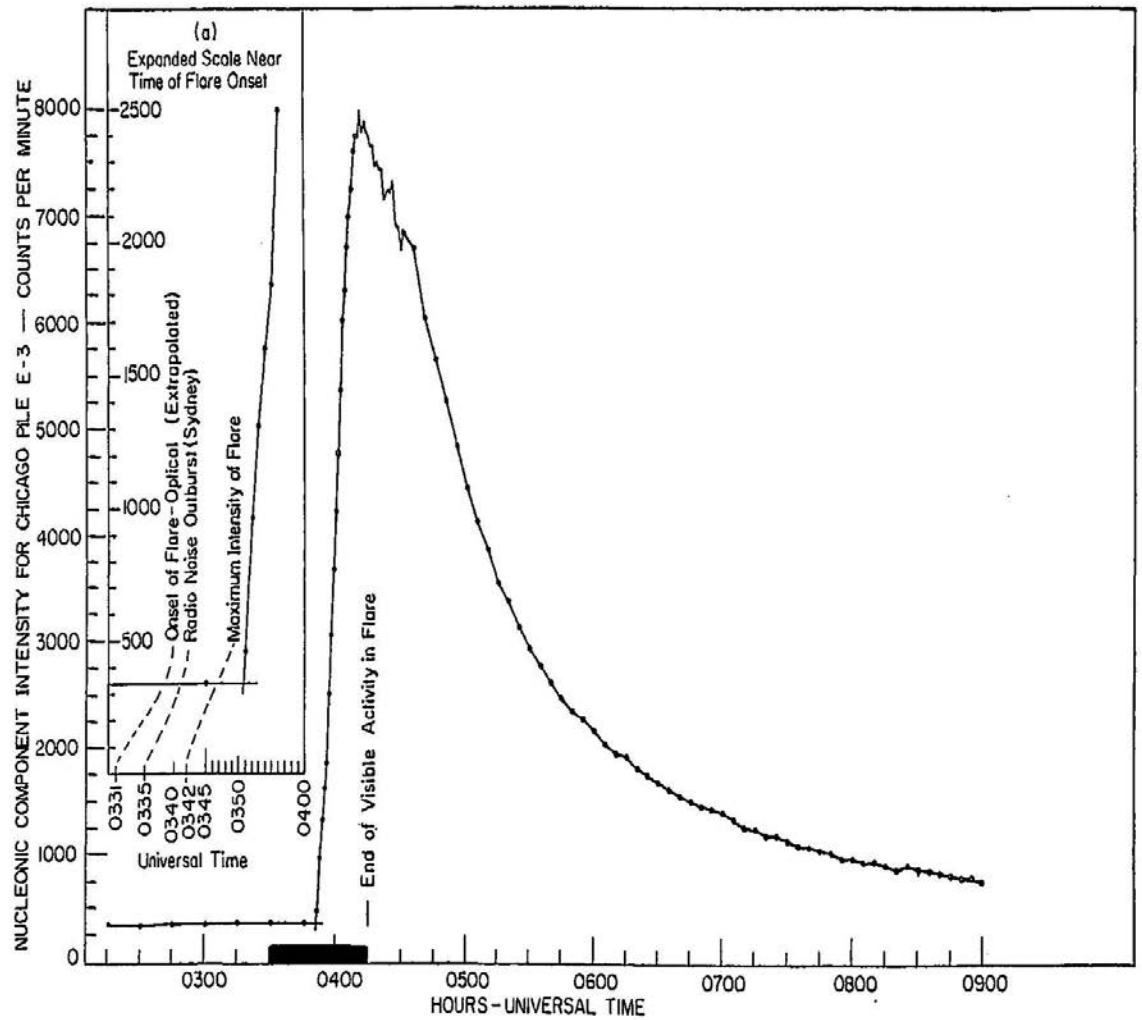
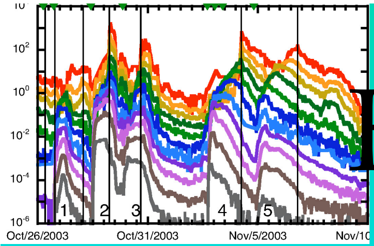


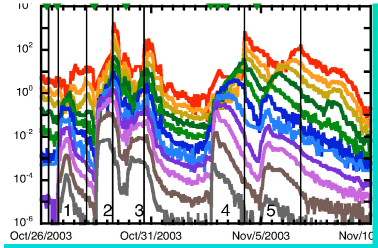
FIGURE 2. Chicago neutron monitor record of the ground level event of 23 February 1956 (adapted from 5).



History of SEP Measurements

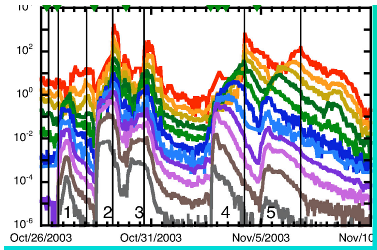
- First detection with connection to solar flare observation - Forbush 1946 in neutron monitor
- Timing related to gamma ray flare 1956 (most well studied)
- Better in space because can see them directly - space age
  - › intensity
  - › energy spectra
  - › composition

} Categorization



Categorization

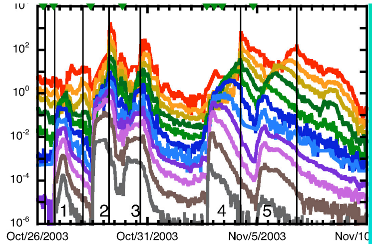
- At the same time…
  - › flares are being categorized by size, duration, emission wavelength
  - › radio emission is being categorized
  - › flares and radio emission combined to create…
- Two classes of flares
  - › Impulsive
  - › Gradual



Categorization

- Correlations with SEP characteristics results in a 2 class SEP system:

	Impulsive	Gradual
Flare Characteristics	Short duration Compact/Point Source	Long duration Large Source
Radio Characteristics	Type III/V	Type II/IV
Particle Characteristics	^3He, e^-, heavy ion rich short duration, small, limited longitude	SW like composition long duration, large, wide longitude



Categorization

Gradual   Impulsive

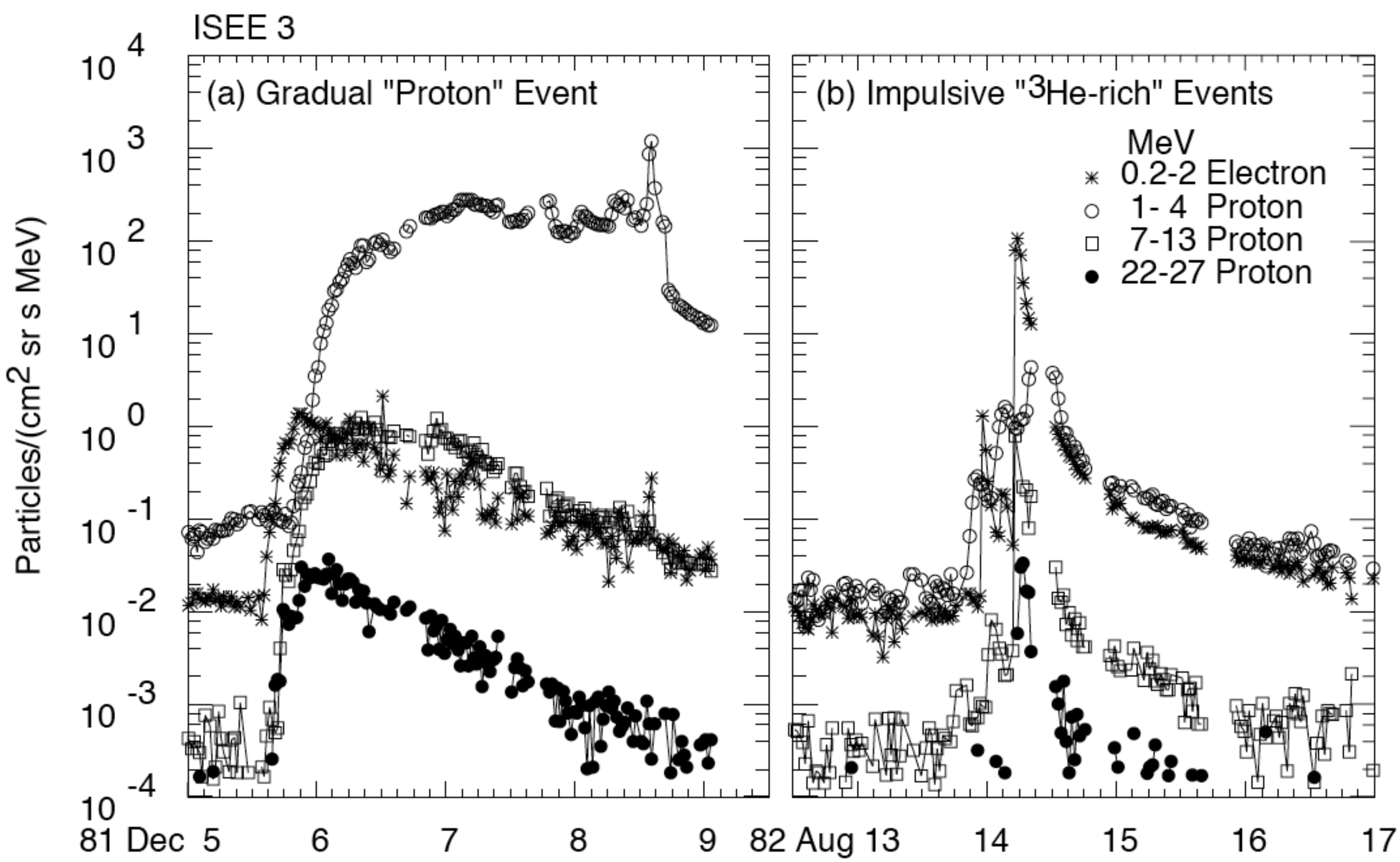
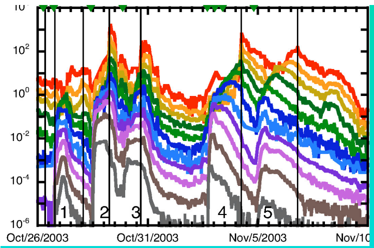
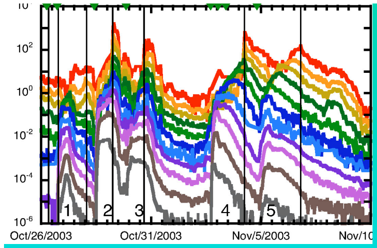


Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.



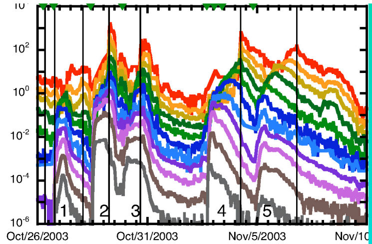
Paradigm Shift #1

- All SEPs created by flares
  - › slight problem with longitude distribution of gradual events
  - › ideas of storage, cross-field transport, lots of scattering in the interplanetary medium (not happy about this)
  - › Not a good correlation between interacting protons and SEP protons (SMM allowed gamma-ray measurements in space 1980)
- Enter Skylab and CME observations (1978)
  - › high correlation (96%) between gradual flares and CMEs
  - › CMEs can drive shocks and shocks can accelerate particles



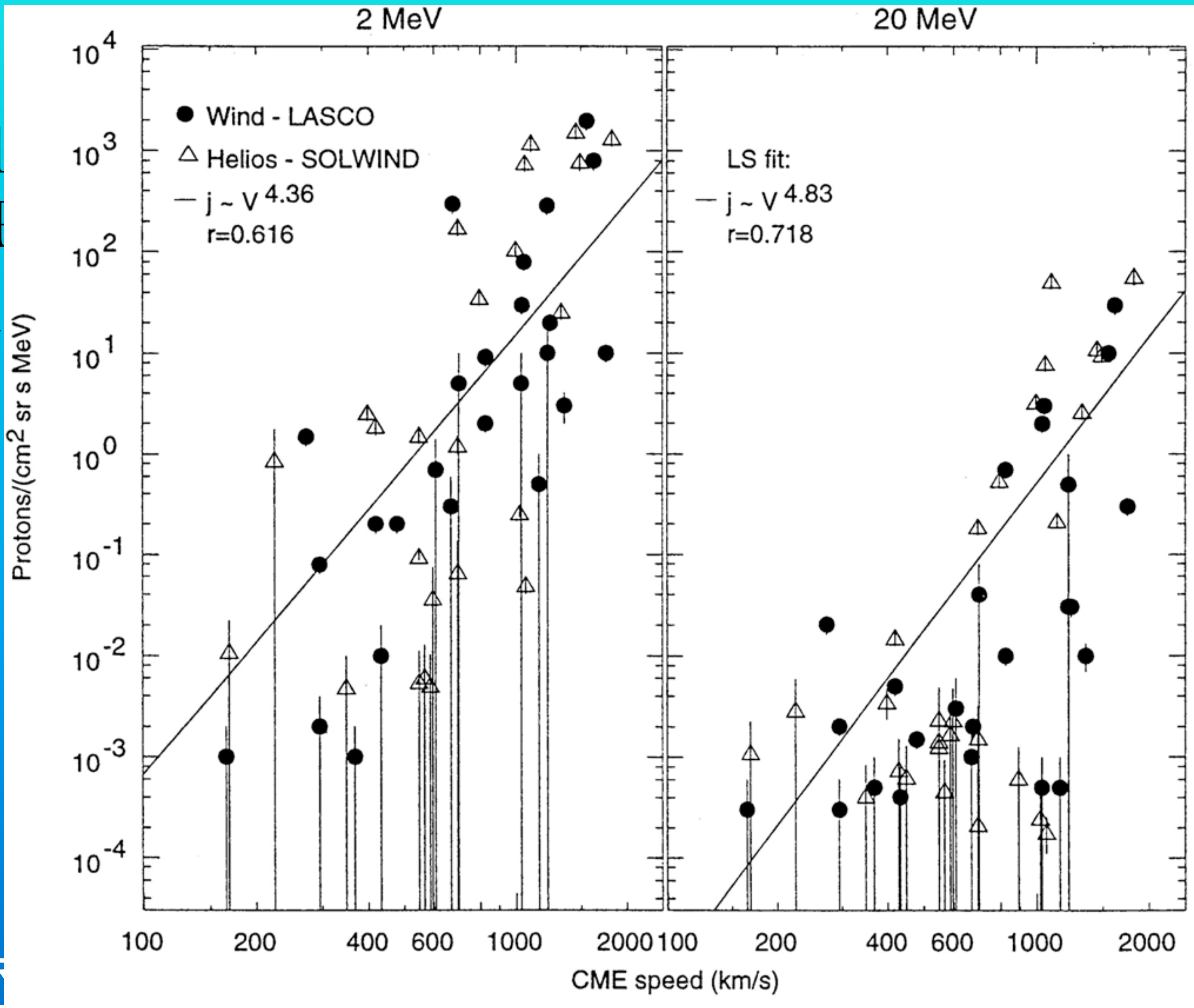
Paradigm Shift #1

- Nice things about CME-shock acceleration for gradual SEP events
  - CME angular size close to longitude distribution of gradual SEP events
  - Solves the cross-field transport 'problem'
  - Correlation between CME size/speed and SEP size

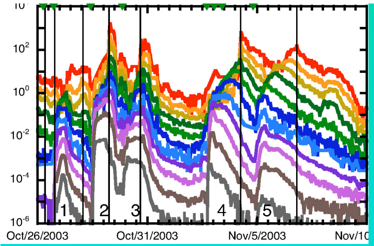


Paradigm Shift #1

- Nice things about CME-shock acceleration for gradual SEP
  - CME angul
    gradual SEI
  - Solves the c
  - Correlation

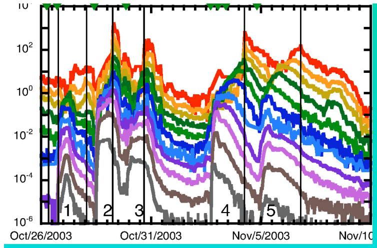


WHAT HISTOR



Paradigm Shift #1

- Nice things about CME-shock acceleration for gradual SEP events
  - CME angular size close to longitude distribution of gradual SEP events
  - Solves the cross-field transport 'problem'
  - Correlation between CME size/speed and SEP size
  - Found a gradual SEP event *with no flare* but with CME
  - Found CMEs did *not* occur with impulsive SEP events
  - Long acceleration in the IPM explained long duration of gradual SEP events (compared to short impulsive)



Paradigm Shift #1

- Had 1 acceleration mechanism for all SEP events
- Now have two independent acceleration mechanisms
  - › CME-driven shock acceleration => Gradual SEP events
  - › Impulsive flare acceleration => Impulsive SEP events

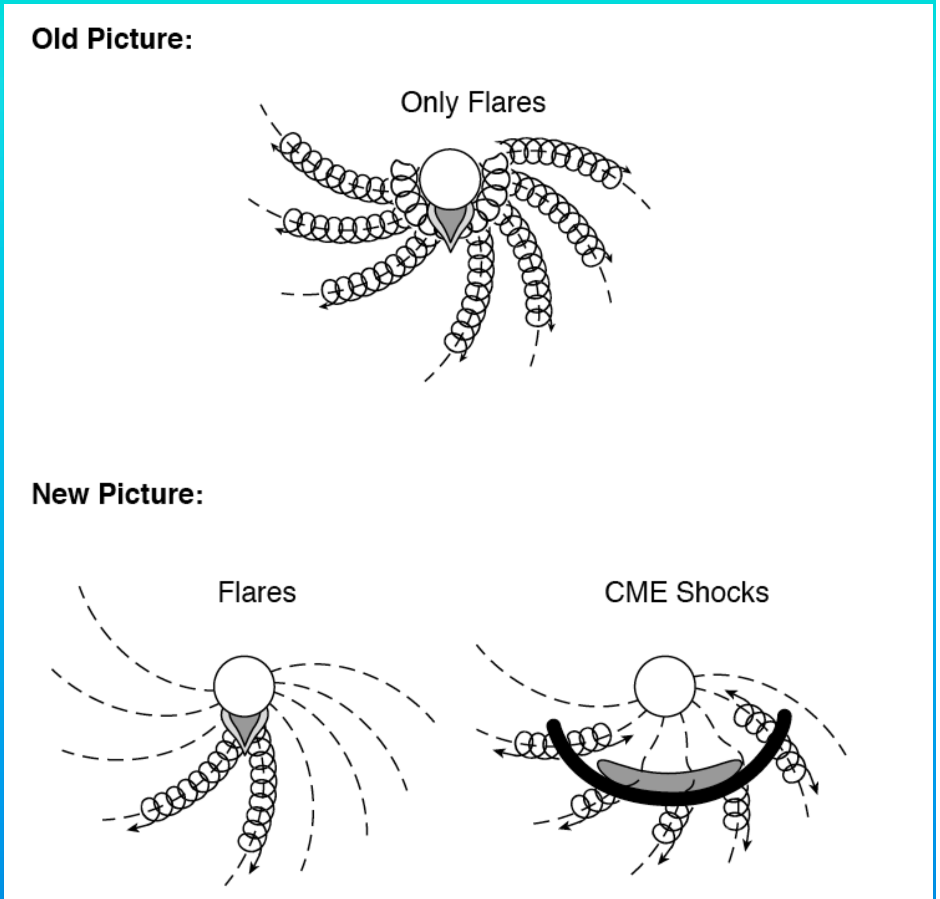
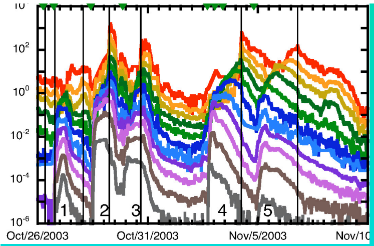


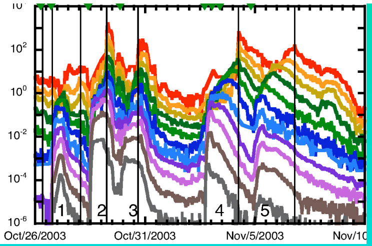
Figure 2.1. A paradigm shift.

Reames 1999



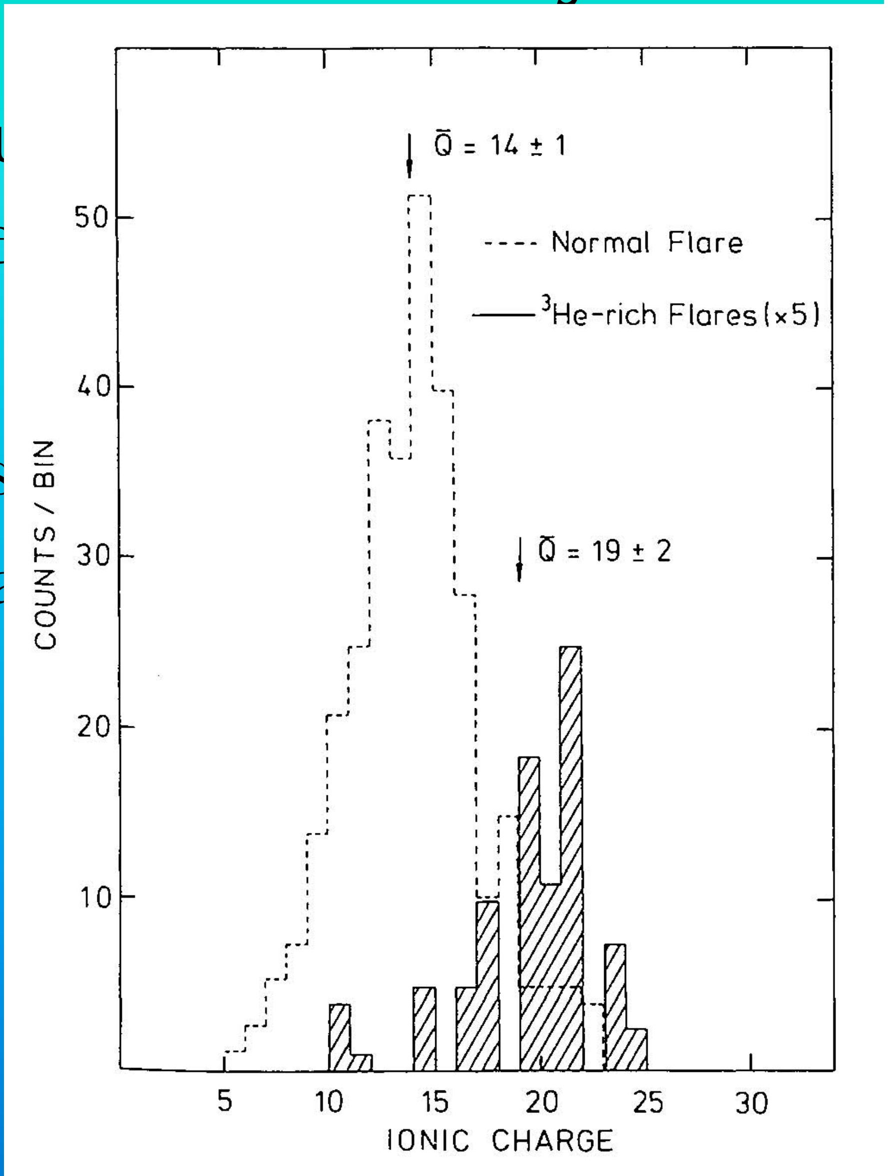
Two Class System

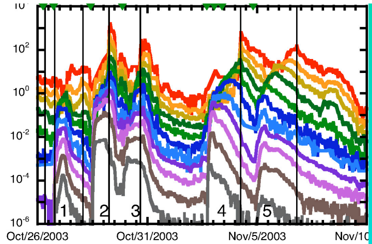
- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - › Big $^3He/^4He$ enhancements (Hseih & Simpson 1970)
  - › Klecker et al. 1984 finds charge state difference



Two Class System

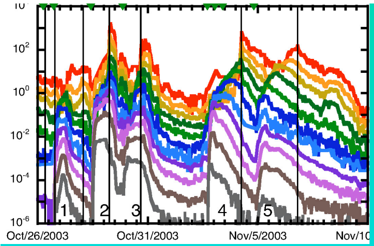
- Flurry of activity in SEP stu characteristics of two classe
- Impulsive
  - › Big $^3He/^4He$ enhancements
  - › Klecker et al. 1984 finds cha





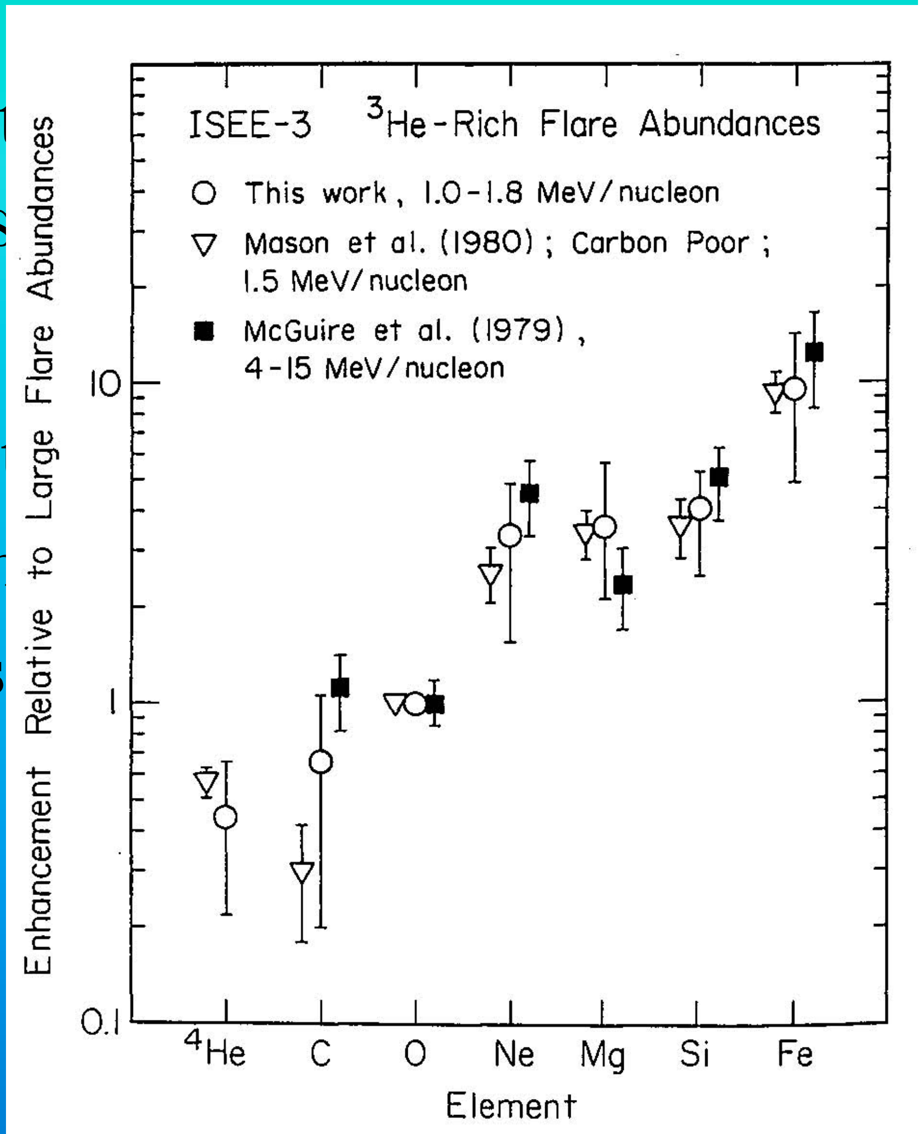
Two Class System

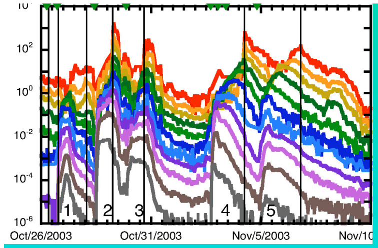
- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - Big $^3He/^4He$ enhancements (Hseih & Simpson 1970)
  - Klecker et al. 1984 finds charge state difference
  - Mason et al. 1986 finds systematic composition difference



Two Class System

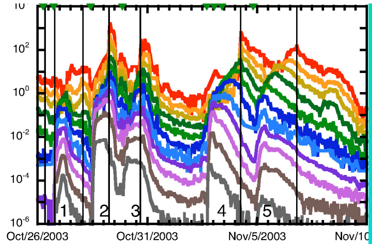
- Flurry of activity in SEP st
  characteristics of two class
- Impulsive
  - Big $^3He/^4He$ enhancemen
  - Klecker et al. 1984 finds ch
  - Mason et al. 1986 finds sys
    difference





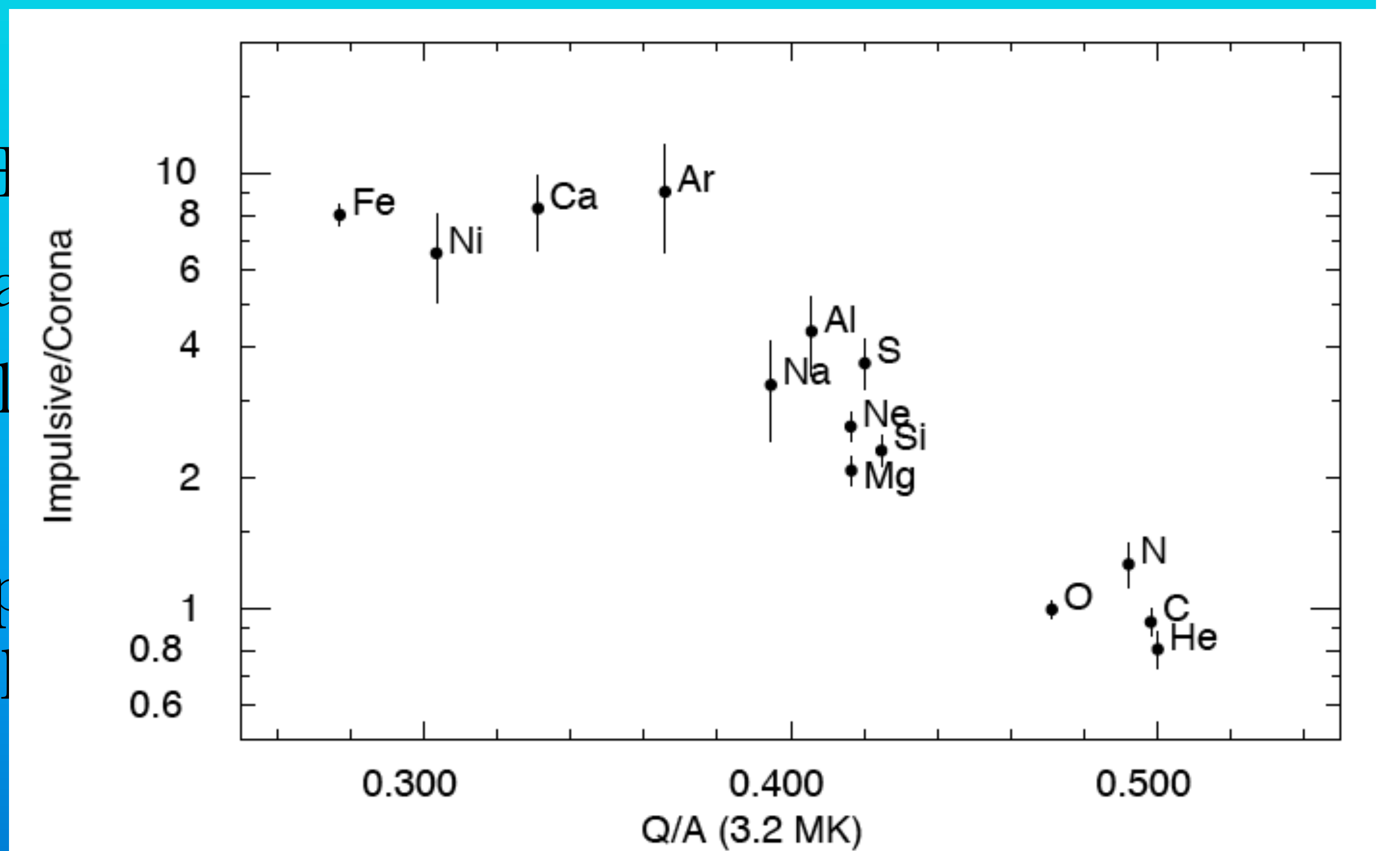
Two Class System

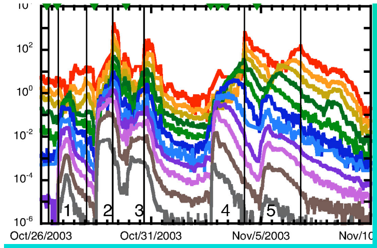
- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - Big $^3He/^4He$ enhancements (Hseih & Simpson 1970)
  - Klecker et al. 1984 finds charge state difference
  - Mason et al. 1986 finds systematic composition difference
  - Reames explains charge and composition characteristics in terms of low altitude



Two Class System

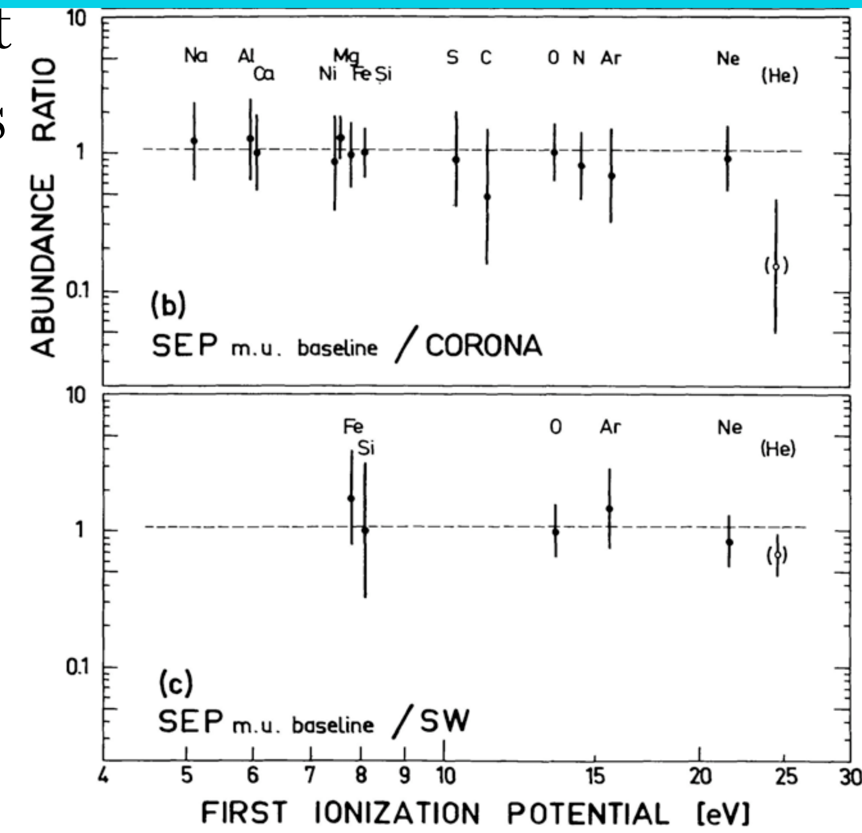
- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - Big $^{3}He/^{4}H$
  - Klecker et a
  - Mason et al difference
  - Reames exp in terms of I

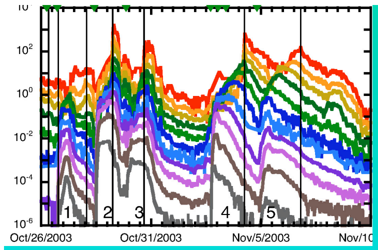




Two Class System

- Gradual
  - All flare material is like impulsive SEP material but gradual SEP material looks like the solar wind
    - composition
    - charge states





Two Class System

- The 1990s standard 2 class system table

Two Groups =>	Impulsive Flare acceleration	Gradual Shock acceleration
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
Q_{Fe}	~20	~14
Duration	Hours	Days
X-rays	Impulsive	Gradual
Coronagraph	--	CME (96%)

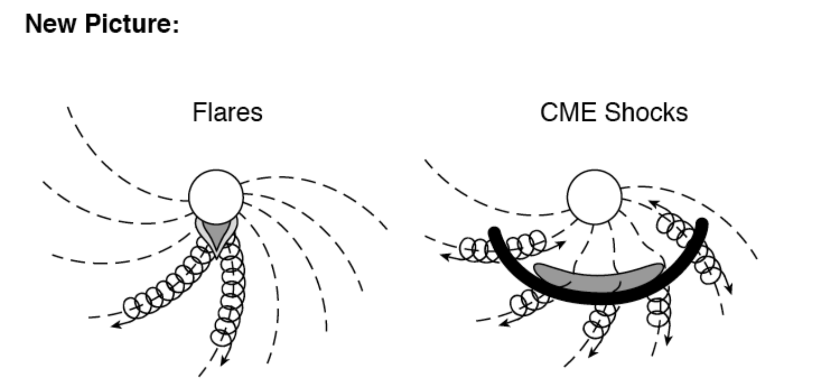
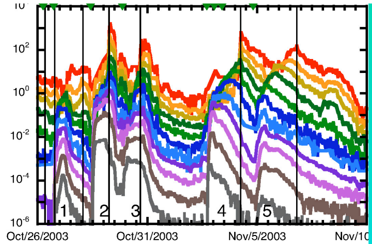


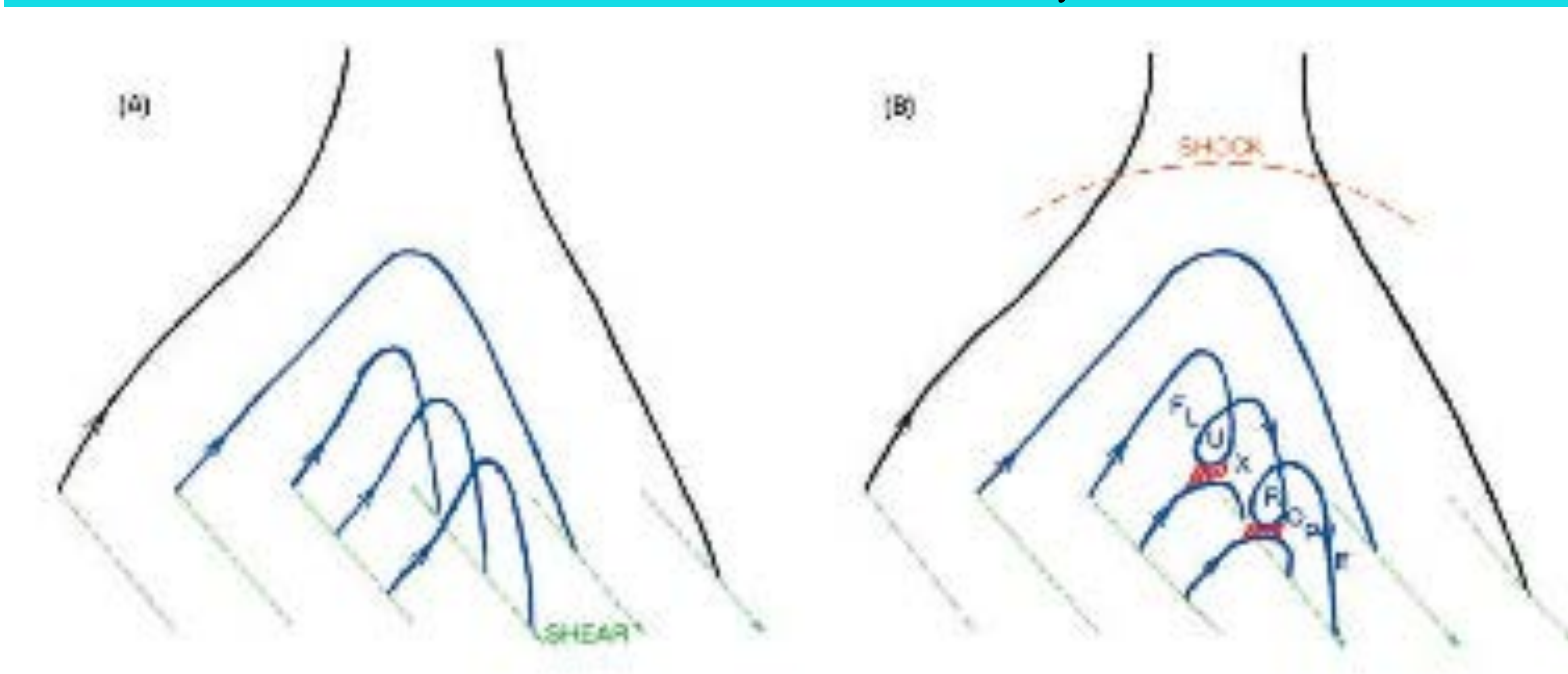
Figure 2.1. A paradigm shift. Reames 1999

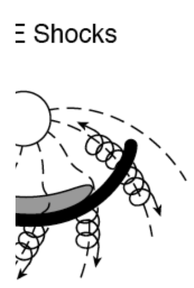
Big Point to remember:
» the two classes are *exclusive*



Two Class System

- The 1990s standard 2 class system table





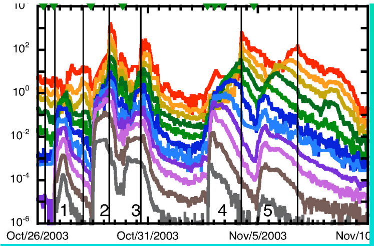
eames 1999

r:

exclusive

X-rays	Impulsive	Gradual
Coronagraph	--	CME (96%)

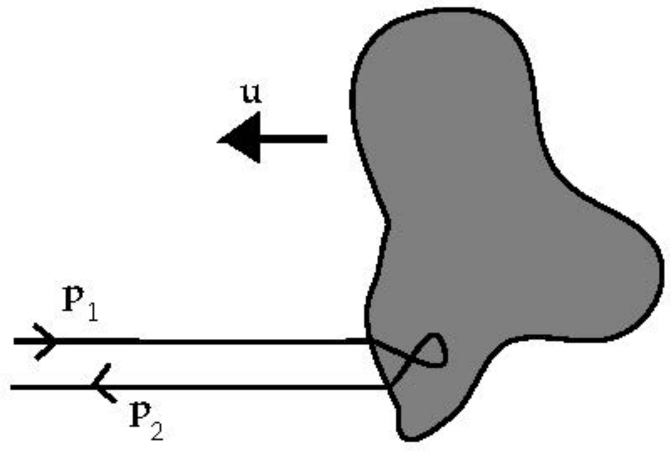
Flare particles in gradual events do not escape into the IPM because of closed field lines behind the CME



SEP Acceleration

- Wave-particle interactions
  - Scattering with MHD turbulence

$$v_1' = v_1 - u \qquad v_2' = v_2 - u$$

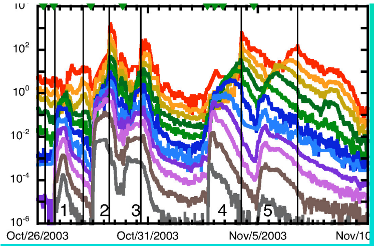


Inelastic collision

$$v_2' = -v_1' \qquad v_2 = 2u - v_1$$

Energy change

$$\Delta E = \frac{1}{2} m(v_2^2 - v_1^2) = 2m(u^2 - v_1 u)$$



SEP Acceleration

- Wave-particle interactions
  - Scattering with MHD turbulence

$$v_1' = v_1 - u \qquad v_2' = v_2 - u$$

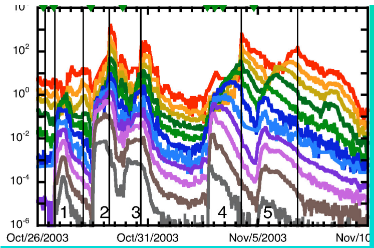
Inelastic collision

$$v_2' = -v_1' \qquad v_2 = 2u - v_1$$

Energy change

$$\Delta E = \frac{1}{2} m (v_2^2 - v_1^2) = 2m(u^2 - v_1 u)$$

This term is negative for head-on collisions and positive for overtaking collisions.



SEP Acceleration

- Wave-particle interactions
  - Scattering with MHD turbulence

$$v_1' = v_1 - u \qquad v_2' = v_2 - u$$

Inelastic collision

$$v_2' = -v_1' \qquad v_2 = 2u - v_1$$

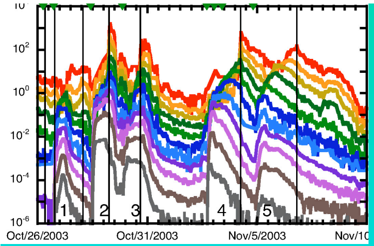
Energy change

$$\Delta E = \frac{1}{2}m(v_2^2 - v_1^2) = 2m(u^2 - v_1 u)$$

Second-order Fermi process

This term is negative for head-on collisions and positive for overtaking collisions.

If head-on and overtaking collisions are about the same this term cancels but still have a net energy gain.



SEP Acceleration

- Wave-particle interactions
  - Scattering with MHD turbulence

$$v_1' = v_1 - u \qquad v_2' = v_2 - u$$

Inelastic collision

$$v_2' = -v_1' \qquad v_2 = 2u - v_1$$

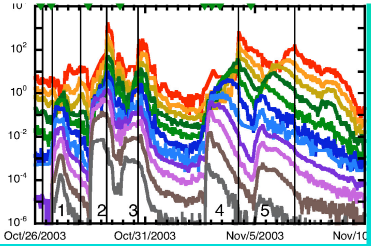
Energy change

$$\Delta E = \frac{1}{2}m(v_2^2 - v_1^2) = 2m(u^2 - v_1 u)$$

First-order Fermi process

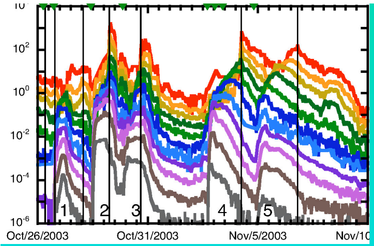
This term is negative for head-on collisions and positive for overtaking collisions.

If *v*>>*u* then this term dominates. But head-on collisions are more likely than overtaking collisions so usually net E gain



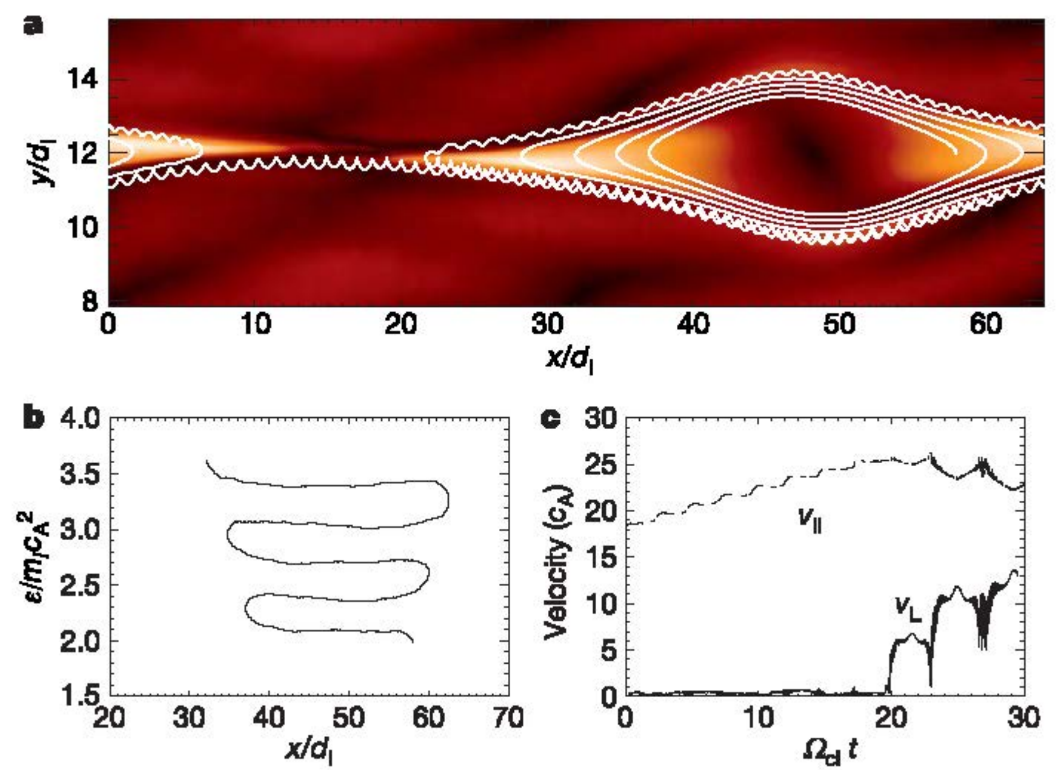
SEP Acceleration

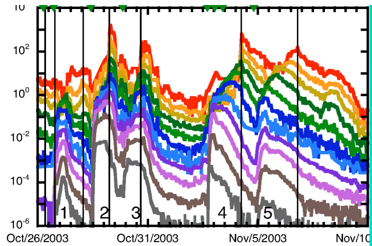
- Flare acceleration
  - › Wave-particle interactions -> Stochastic acceleration
    - Second-order Fermi process – energy gain ~ u^2
  - › One model involves 'cascading' resonance
    - Waves interact with particles of particular Q/M
    - As they give energy to particles, they resonate with higher Q/M particles
    - Fe gets enhanced before Ne-Si, Ne-Si before CNO, etc
    - ^{3}He is a special case and is preferentially heated first
    - Hasn't been compared to observations
  - › Parallel propagating waves
    - Compared to ^{3}He and ^{4}He observations



SEP Acceleration

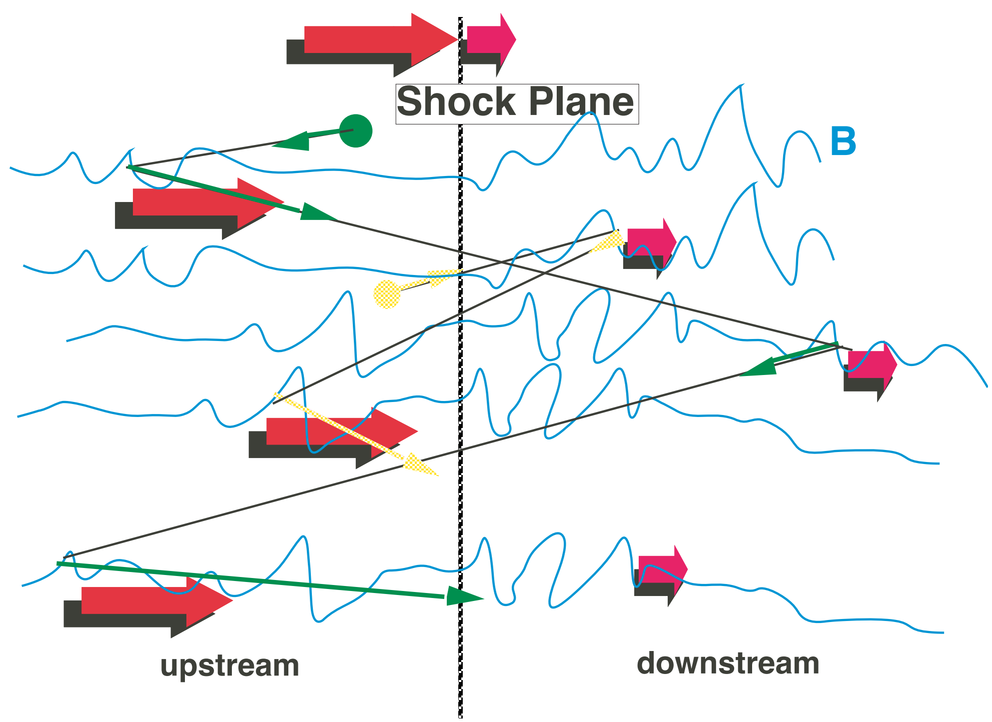
- Flare acceleration
  - › Contracting magnetic islands
    - As islands contract, ion/e- bounces between edges
    - Multiple island encounters needed to get high energies
    - First-order Fermi process
    - Comparisons to observations still to be done
- Problem is hard to know conditions at the Sun





SEP Acceleration

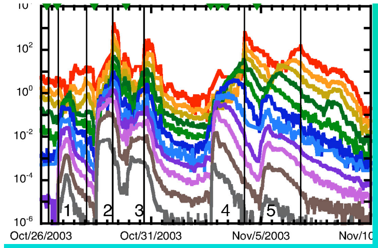
- Shock acceleration
  - Converging ‘mirrors’
  - Always gain energy
  - First-order Fermi
    Energy gain ~ ΔV
- CMEs can drive shocks
- Easily testable with observations



= Fermi Acceleration

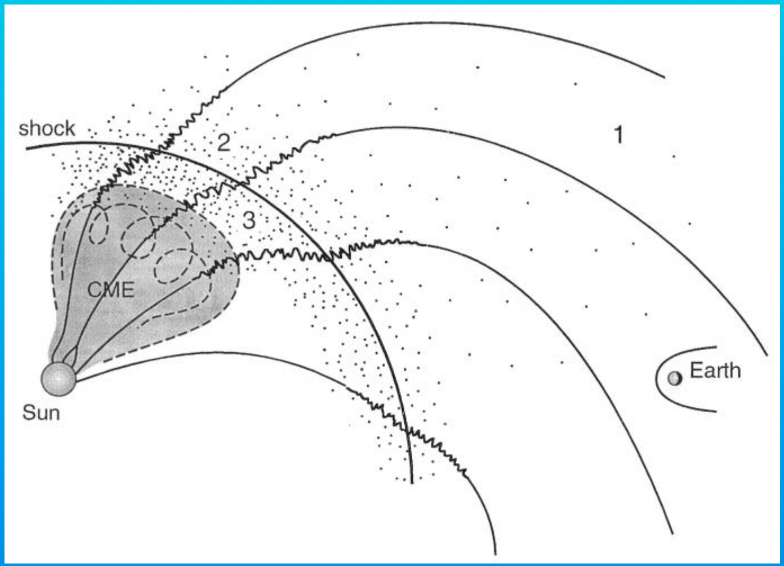
momentum gain in 1 cycle:

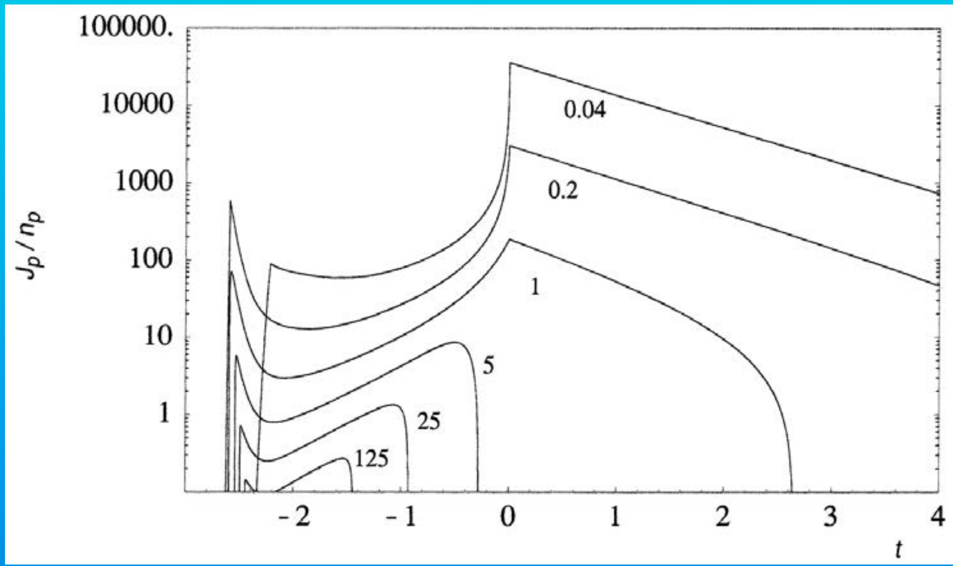
$\Delta p = 2m * (V_{upstream} - V_{downstream})$



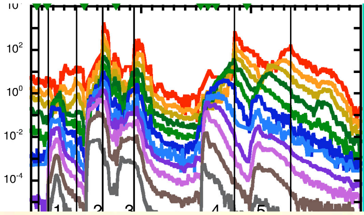
SEP Acceleration

- Lee 2005 is currently the definitive work on shock acceleration for gradual SEP events
  - › Makes predictions about time profiles and spectra that can be tested with observations

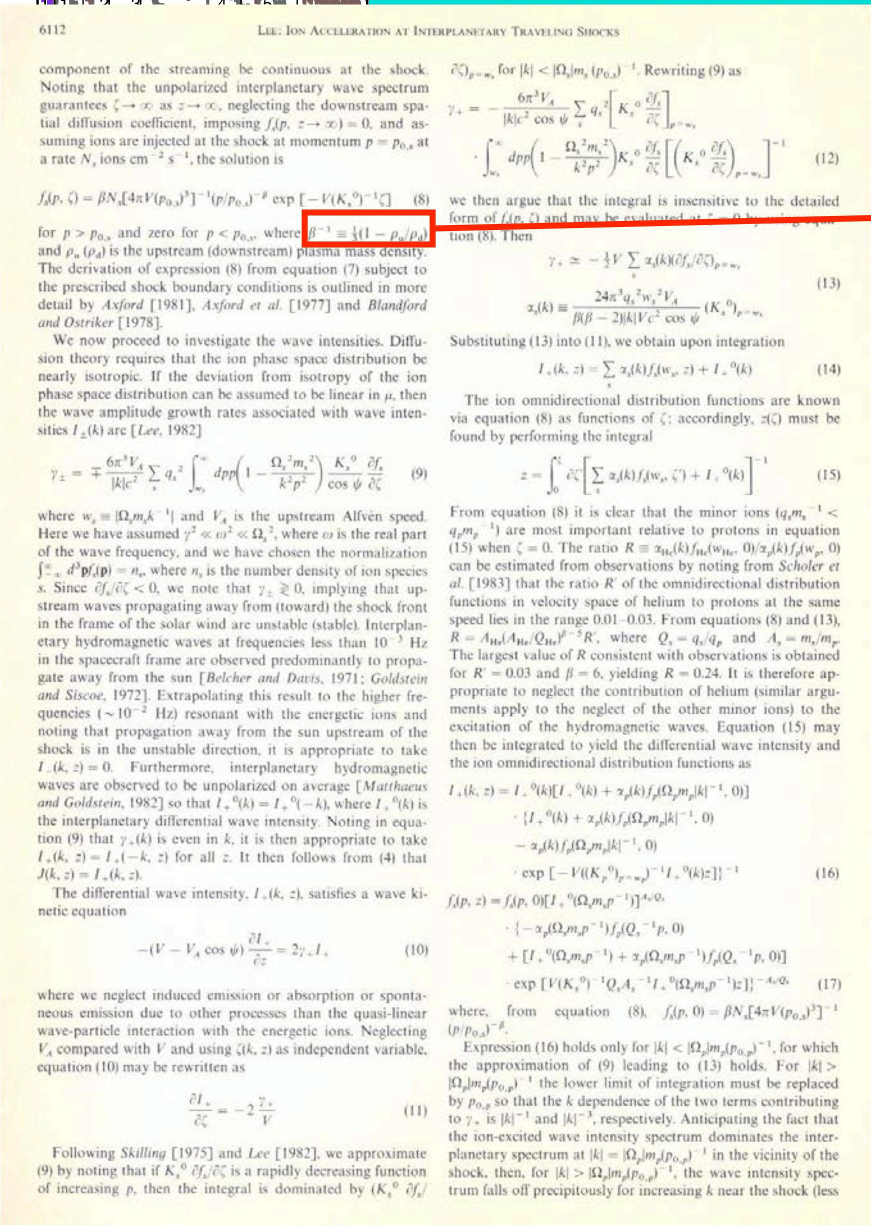




- But a paper with 105 equations tends to scare experimenters into using something more simple…



SEP Acceleration



component of the streaming be continuous at the shock. Noting that the unpolarized interplanetary wave spectrum guarantees $\zeta \to \infty$ as $z \to \infty$, neglecting the downstream spatial diffusion coefficient, imposing $f_s(p, z \to \infty) = 0$, and assuming ions are injected at the shock at momentum $p = p_{0,s}$ at a rate N_s ions cm^{-2} s^{-1}, the solution is

$$f_s(p, \zeta) = \beta N_s [4\pi V (p_{0,s})^3]^{-1} (p/p_{0,s})^{-\beta} \exp[-V(K_s^0)^{-1}\zeta] \quad (8)$$

for $p > p_{0,s}$ and zero for $p < p_{0,s}$, where $\beta^{-1} \equiv \frac{1}{3}(1 - \rho_u/\rho_d)$ and ρ_u (ρ_d) is the upstream (downstream) plasma mass density. The derivation of expression (8) from equation (7) subject to the prescribed shock boundary conditions is outlined in more detail by *Axford* [1981], *Axford et al.* [1977] and *Blandford and Ostriker* [1978].

We now proceed to investigate the wave intensities. Diffusion theory requires that the ion phase space distribution be nearly isotropic. If the deviation from isotropy of the ion phase space distribution can be assumed to be linear in μ, then the wave amplitude growth rates associated with wave intensities $I_\pm(k)$ are [*Lee*, 1982]

$$\gamma_\pm = \mp \frac{6\pi^3 V_A}{|k|c^2} \sum_s q_s^2 \int_{w_s}^{\infty} dpp\left(1 - \frac{\Omega_s^2 m_s^2}{k^2 p^2}\right) \frac{K_s^0}{\cos\psi} \frac{\partial f_s}{\partial \zeta} \quad (9)$$

where $w_s \equiv |\Omega_s m_s k^{-1}|$ and V_A is the upstream Alfvén speed. Here we have assumed $\gamma^2 \ll \omega^2 \ll \Omega_s^2$, where ω is the real part of the wave frequency, and we have chosen the normalization $\int_{-\infty}^{\infty} d^3\mathbf{p} f_s(\mathbf{p}) = n_s$, where n_s is the number density of ion species s. Since $\partial f_s/\partial\zeta < 0$, we note that $\gamma_\pm \gtrless 0$, implying that upstream waves propagating away from (toward) the shock front in the frame of the solar wind are unstable (stable). Interplanetary hydromagnetic waves at frequencies less than 10^{-3} Hz in the spacecraft frame are observed predominantly to propagate away from the sun [*Belcher and Davis*, 1971; *Goldstein and Siscoe*, 1972]. Extrapolating this result to the higher frequencies ($\sim 10^{-2}$ Hz) resonant with the energetic ions and noting that propagation away from the sun upstream of the shock is in the unstable direction, it is appropriate to take $I_-(k, z) = 0$. Furthermore, interplanetary hydromagnetic waves are observed to be unpolarized on average [*Matthaeus and Goldstein*, 1982] so that $I_+^0(k) = I_+^0(-k)$, where $I_+^0(k)$ is the interplanetary differential wave intensity. Noting in equation (9) that $\gamma_+(k)$ is even in k, it is then appropriate to take $I_+(k, z) = I_+(-k, z)$ for all z. It then follows from (4) that $J(k, z) = I_+(k, z)$.

The differential wave intensity, $I_+(k, z)$, satisfies a wave kinetic equation

$$-(V - V_A \cos\psi) \frac{\partial I_+}{\partial z} = 2\gamma_+ I_+ \quad (10)$$

where we neglect induced emission or absorption or spontaneous emission due to other processes than the quasi-linear wave-particle interaction with the energetic ions. Neglecting V_A compared with V and using $\zeta(k, z)$ as independent variable, equation (10) may be rewritten as

$$\frac{\partial I_+}{\partial \zeta} = -2\frac{\gamma_+}{V} \quad (11)$$

Following *Skilling* [1975] and *Lee* [1982], we approximate (9) by noting that if $K_s^0\, \partial f_s/\partial\zeta$ is a rapidly decreasing function of increasing p, then the integral is dominated by $(K_s^0\, \partial f_s/\partial\zeta)_{p=w_s}$ for $|k| < |\Omega_s| m_s (p_{0,s})^{-1}$. Rewriting (9) as

$$\gamma_+ = -\frac{6\pi^3 V_A}{|k|c^2 \cos\psi} \sum_s q_s^2 \left[K_s^0 \frac{\partial f_s}{\partial\zeta}\right]_{p=w_s} \cdot \int_{w_s}^{\infty} dpp\left(1 - \frac{\Omega_s^2 m_s^2}{k^2 p^2}\right) K_s^0 \frac{\partial f_s}{\partial\zeta}\left[\left(K_s^0 \frac{\partial f_s}{\partial\zeta}\right)_{p=w_s}\right]^{-1} \quad (12)$$

we then argue that the integral is insensitive to the detailed form of $f_s(p, \zeta)$ and may be evaluated at $\zeta = 0$ by using equation (8). Then

$$\gamma_+ \simeq -\tfrac{1}{2} V \sum_s \alpha_s(k) (\partial f_s/\partial\zeta)_{p=w_s}$$

$$\alpha_s(k) \equiv \frac{24\pi^3 q_s^2 w_s^2 V_A}{\beta(\beta - 2)|k| V c^2 \cos\psi} (K_s^0)_{p=w_s} \quad (13)$$

Substituting (13) into (11), we obtain upon integration

$$I_+(k, z) = \sum_s \alpha_s(k) f_s(w_s, z) + I_+^0(k) \quad (14)$$

The ion omnidirectional distribution functions are known via equation (8) as functions of ζ; accordingly, $z(\zeta)$ must be found by performing the integral

$$z = \int_0^{\zeta} \partial\zeta' \left[\sum_s \alpha_s(k) f_s(w_s, \zeta') + I_+^0(k)\right]^{-1} \quad (15)$$

From equation (8) it is clear that the minor ions ($q_s m_s^{-1} < q_p m_p^{-1}$) are most important relative to protons in equation (15) when $\zeta = 0$. The ratio $R \equiv \alpha_{He}(k) f_{He}(w_{He}, 0)/\alpha_p(k) f_p(w_p, 0)$ can be estimated from observations by noting from *Scholer et al.* [1983] that the ratio R' of the omnidirectional distribution functions in velocity space of helium to protons at the same speed lies in the range 0.01–0.03. From equations (8) and (13), $R = A_{He}(A_{He}/Q_{He})^{\beta-5} R'$, where $Q_s = q_s/q_p$ and $A_s = m_s/m_p$. The largest value of R consistent with observations is obtained for $R' = 0.03$ and $\beta = 6$, yielding $R = 0.24$. It is therefore appropriate to neglect the contribution of helium (similar arguments apply to the neglect of the other minor ions) to the excitation of the hydromagnetic waves. Equation (15) may then be integrated to yield the differential wave intensity and the ion omnidirectional distribution functions as

$$I_+(k, z) = I_+^0(k)[I_+^0(k) + \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0)] \cdot \{I_+^0(k) + \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0) - \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0) \cdot \exp[-V((K_p^0)_{p=w_p})^{-1} I_+^0(k) z]\}^{-1} \quad (16)$$

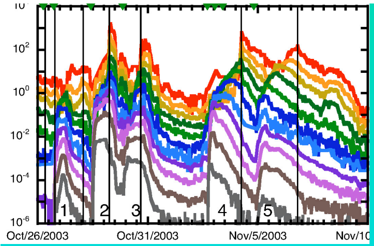
$$f_s(p, z) = f_s(p, 0)[I_+^0(\Omega_s m_s p^{-1})]^{A_s/Q_s} \cdot \{-\alpha_p(\Omega_s m_s p^{-1}) f_p(Q_s^{-1} p, 0) + [I_+^0(\Omega_s m_s p^{-1}) + \alpha_p(\Omega_s m_s p^{-1}) f_p(Q_s^{-1} p, 0)] \cdot \exp[V(K_s^0)^{-1} Q_s A_s^{-1} I_+^0(\Omega_s m_s p^{-1}) z]\}^{-A_s/Q_s} \quad (17)$$

where, from equation (8), $f_s(p, 0) = \beta N_s [4\pi V (p_{0,s})^3]^{-1} (p/p_{0,s})^{-\beta}$.

Expression (16) holds only for $|k| < |\Omega_p| m_p (p_{0,p})^{-1}$, for which the approximation of (9) leading to (13) holds. For $|k| > |\Omega_p| m_p (p_{0,p})^{-1}$ the lower limit of integration must be replaced by $p_{0,p}$ so that the k dependence of the two terms contributing to γ_+ is $|k|^{-1}$ and $|k|^{-3}$, respectively. Anticipating the fact that the ion-excited wave intensity spectrum dominates the interplanetary spectrum at $|k| = |\Omega_p| m_p (p_{0,p})^{-1}$ in the vicinity of the shock, then, for $|k| > |\Omega_p| m_p (p_{0,p})^{-1}$, the wave intensity spectrum falls off precipitously for increasing k near the shock (less

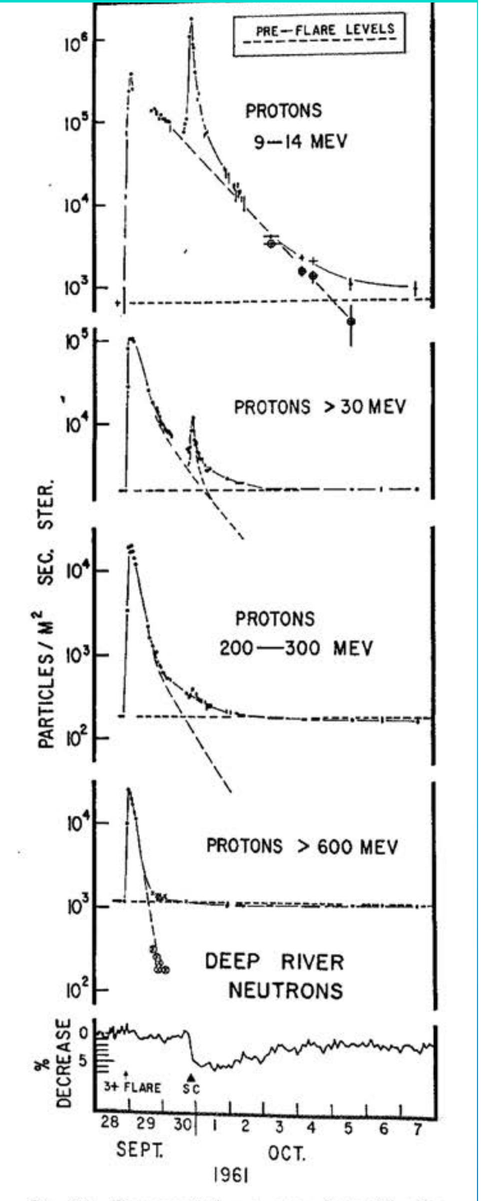
$$\beta^{-1} \equiv \tfrac{1}{3}(1 - \rho_u/\rho_d)$$

- Prediction of SEP spectrum
  - Power-law
  - Simple relationship between spectral index and shock compression ratio
  - Independent of particle species

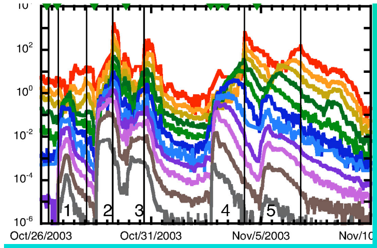


Shocks and ESPs

- Bryant 1962, Explorer 12, 9/30/61
  - Associated with Forbush decrease and geomagnetic storm → 'Energetic Storm Particles'
- Determined that they are 'locally' shock accelerated particles (1970s)
  - 2 categories: classic and spike
  - 2 acceleration mechanisms
- Nice because can also measure shock parameters

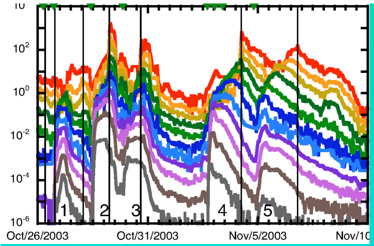


What History Acceleration Problems 3D Next



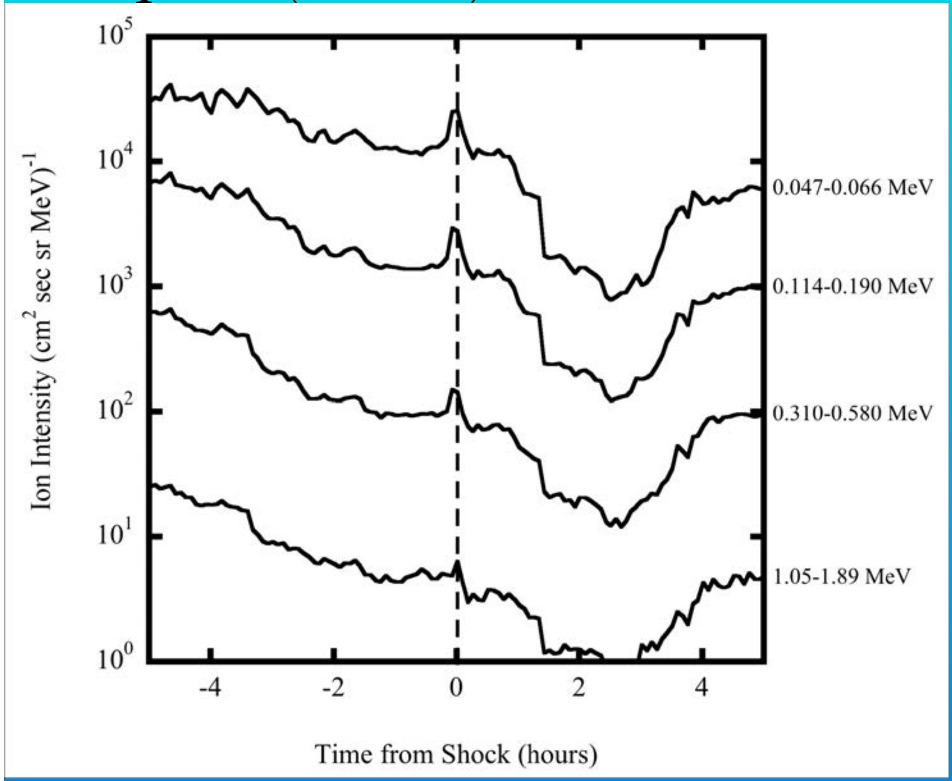
ESP and Spike Events

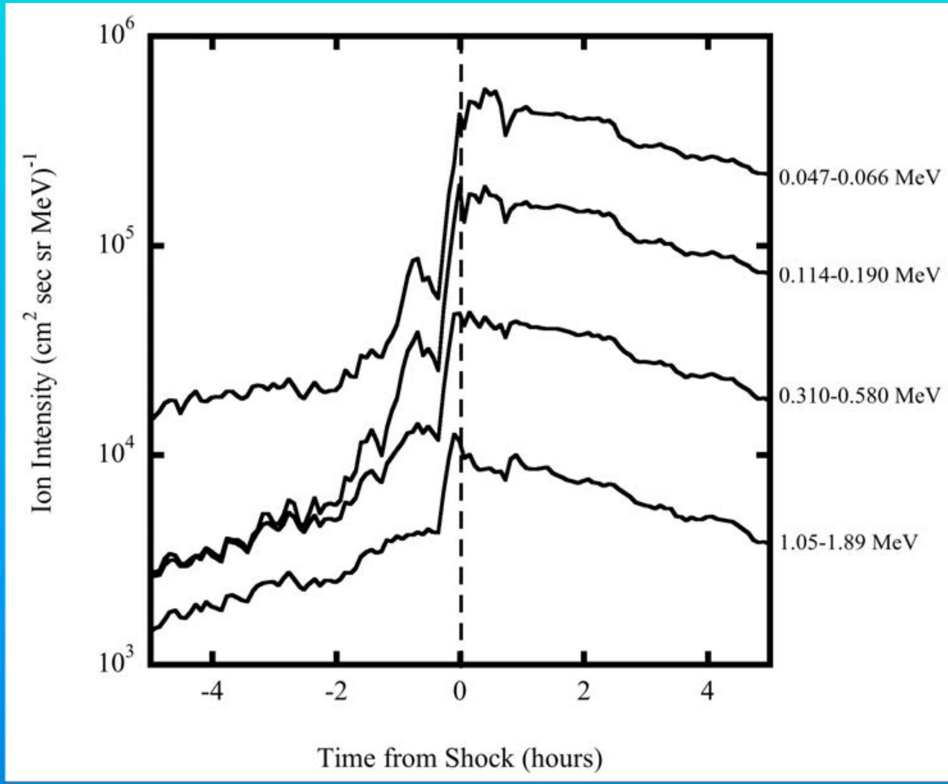
- Spike (LESP)
  - Duration of 5-20 minutes
  - Arrival within 5-10 minutes of shock
  - Rarely exceeds 5 MeV
- ESP
  - Duration of several hours
  - Arrival maybe ahead or behind shock
  - May extend to ~20 MeV

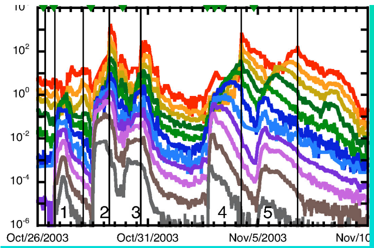


ESP and Spike Events

- Spike (LESP)
- ESP



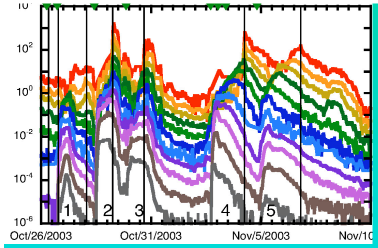




ESP and Spike Events

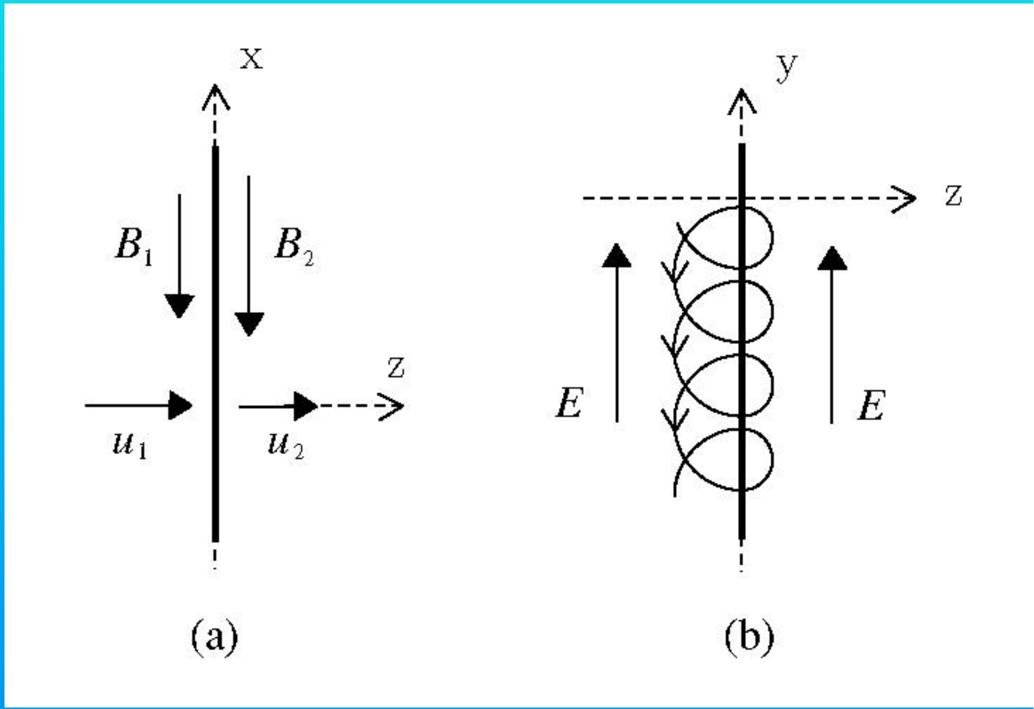
- Spike (LESP)
  - Duration of 5-20 minutes
  - Arrival within 5-10 minutes of shock
  - Rarely exceeds 5 MeV
  - Shock drift acceleration at quasi-perpendicular shocks

- ESP
  - Duration of several hours
  - Arrival maybe ahead or behind shock
  - May extend to ~20 MeV
  - Diffusive shock acceleration at oblique or quasi-parallel shocks

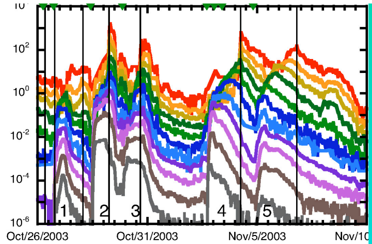


ESP and Spike Events

- Spike (LESP)
  - Duration of 5-20 minutes
  - Arrival within 5-10 minutes of shock
  - Rarely exceeds 5 MeV
  - Shock drift acceleration at quasi-perpendicular shocks
  - Hard to stay there so short lived

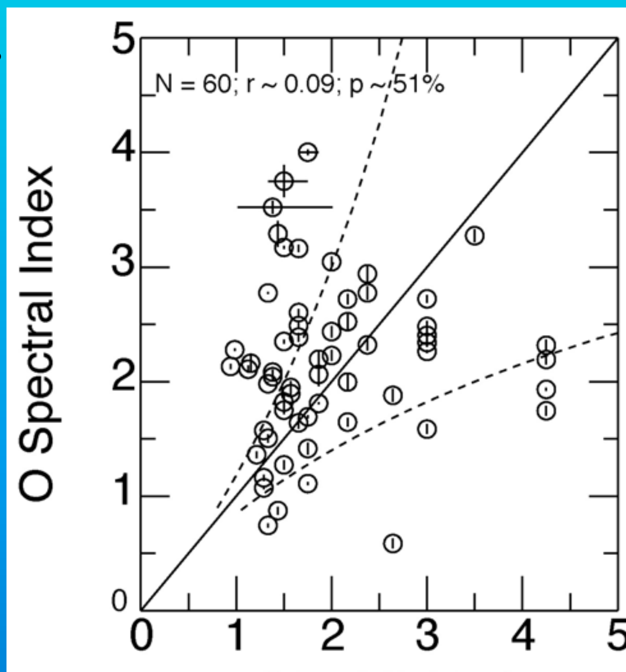


shocks

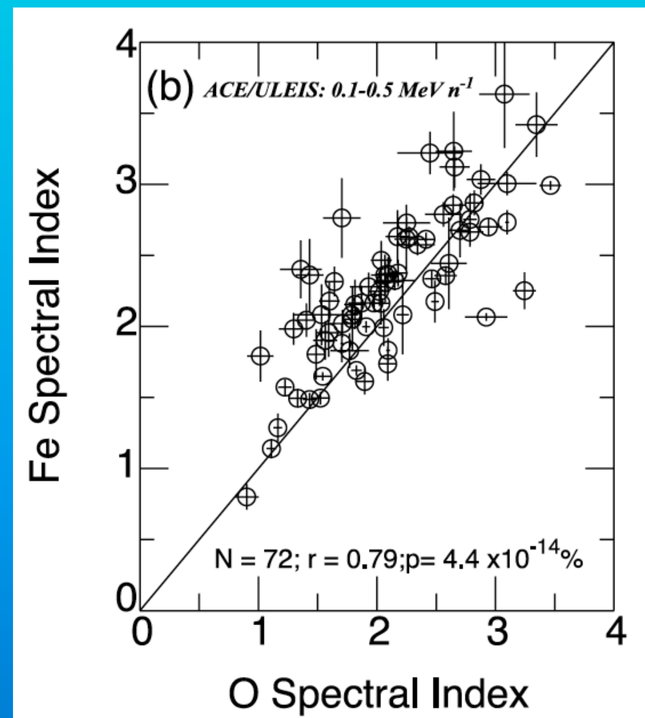


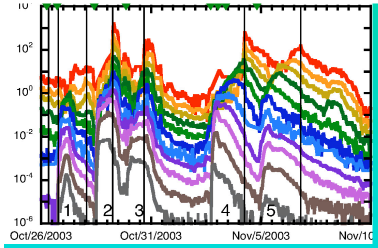
Shock Theory and Observations

- Late 1970s produced simple 1-D shock theory
- Although Lee (1983) cautioned against blindly applying this to all energies, experimenters did anyway…



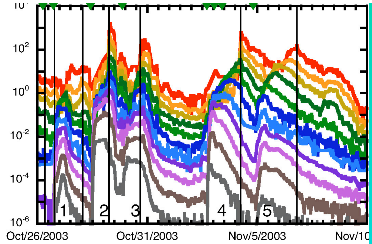
Desai et al. 2004





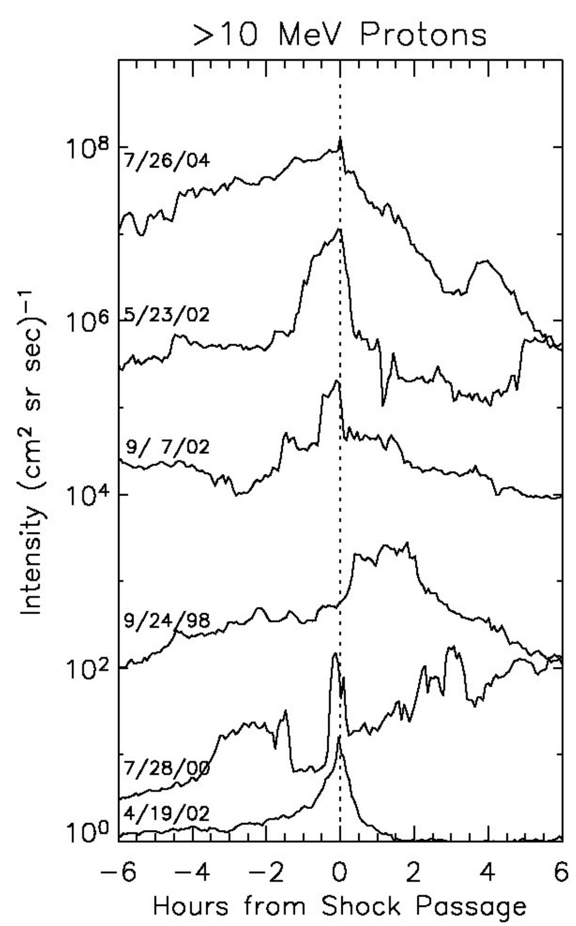
Shock Theory and Observations

- Late 1970s produced simple 1-D shock theory
- Although Lee (1983) cautioned against blindly applying this to all energies and all events, experimenters did anyway…
  - And found agreement was not so good
  - Lee has suggestions as to why (as any good theorist would)



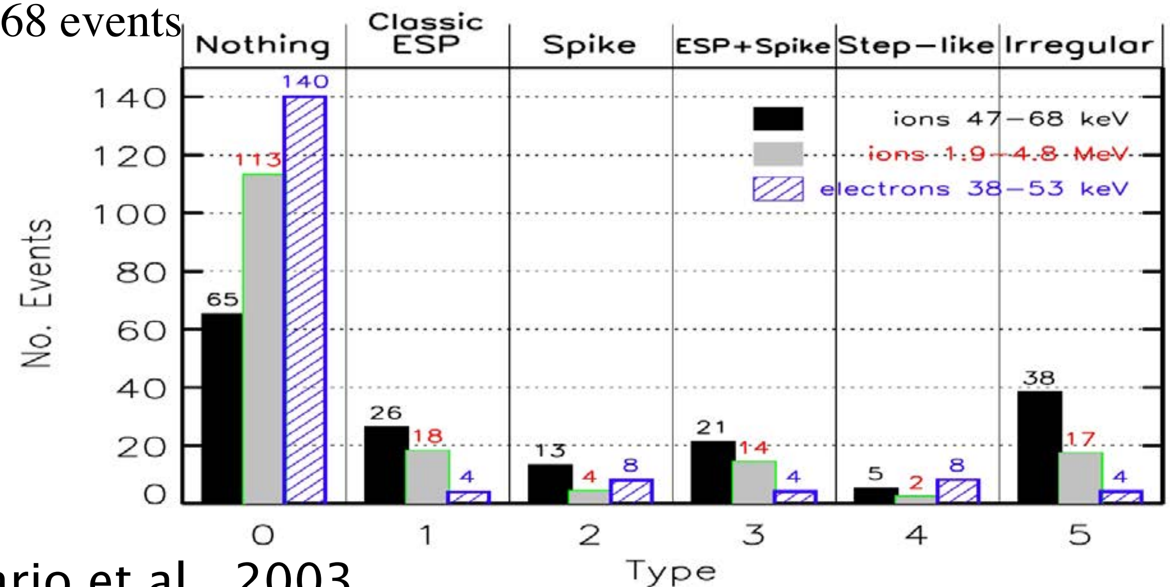
Shock Theory and Observations

- ESP events are extremely variable

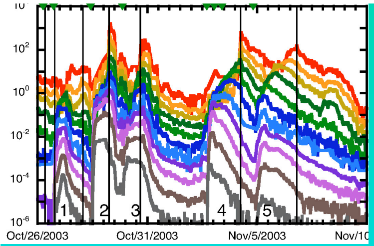


Cohen et al. 2005

168 events

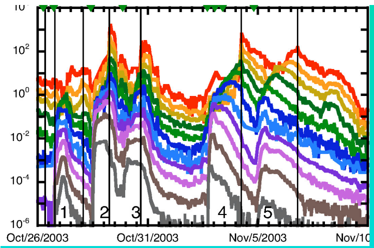


Lario et al., 2003



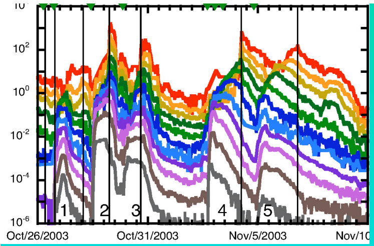
Shock Theory and Observations

- ESP events are extremely variable and we aren't careful about which ones the theory applies to
  - Not initially hard spectra
  - Not quasi-perpendicular shocks
  - Not being transported (rather than accelerated)
- Correct frame of mind
  - Need to evaluate the compression ratio in the wave frame not the plasma frame



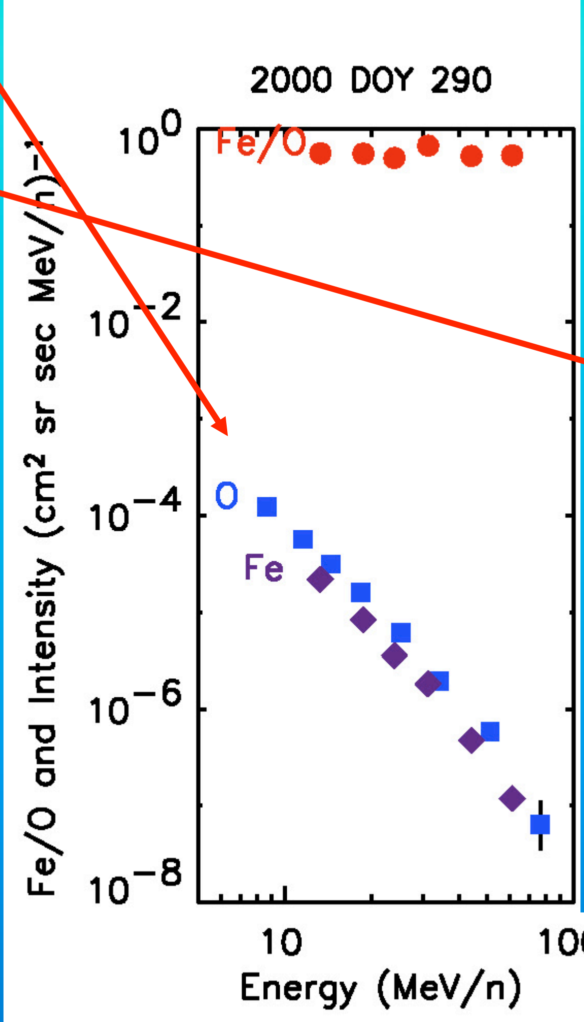
SEP Acceleration

- Complications with SEP events
  - › Effects of escaping the shock region
  - › Effects of transport (diffusion)
  - › Evolution of the shock (orientation, strength, etc)

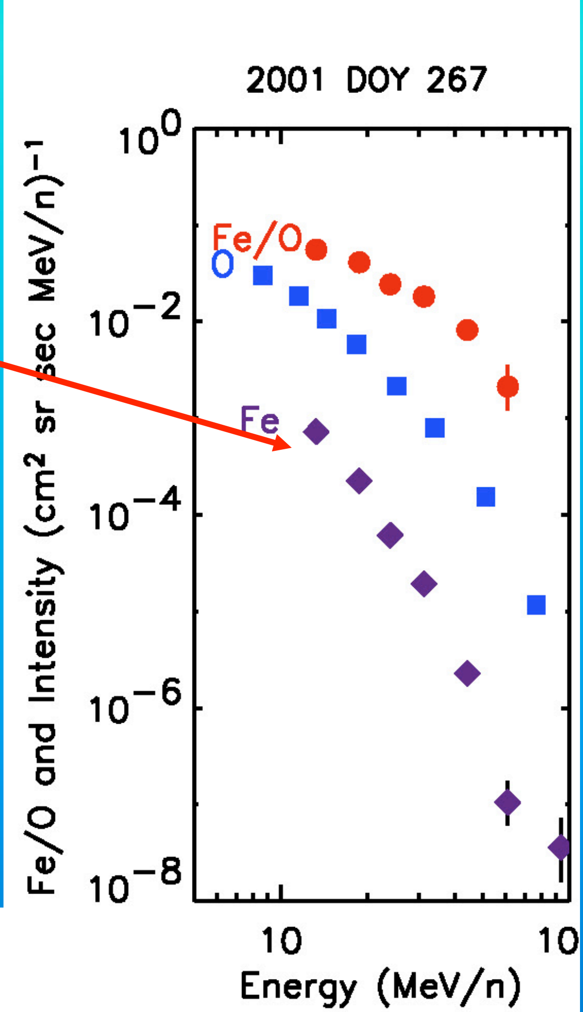


Diffusion Effects

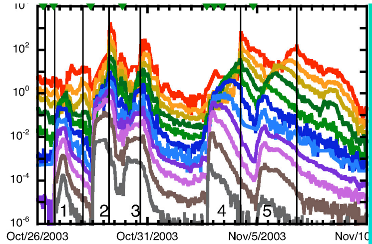
- Although shock theory predicts this
- We often see this



Cohen et al. 2002



Cohen et al. 2002



Diffusion Effects

- Although shock theory predicts this
- We often see this
- Signature of diffusion

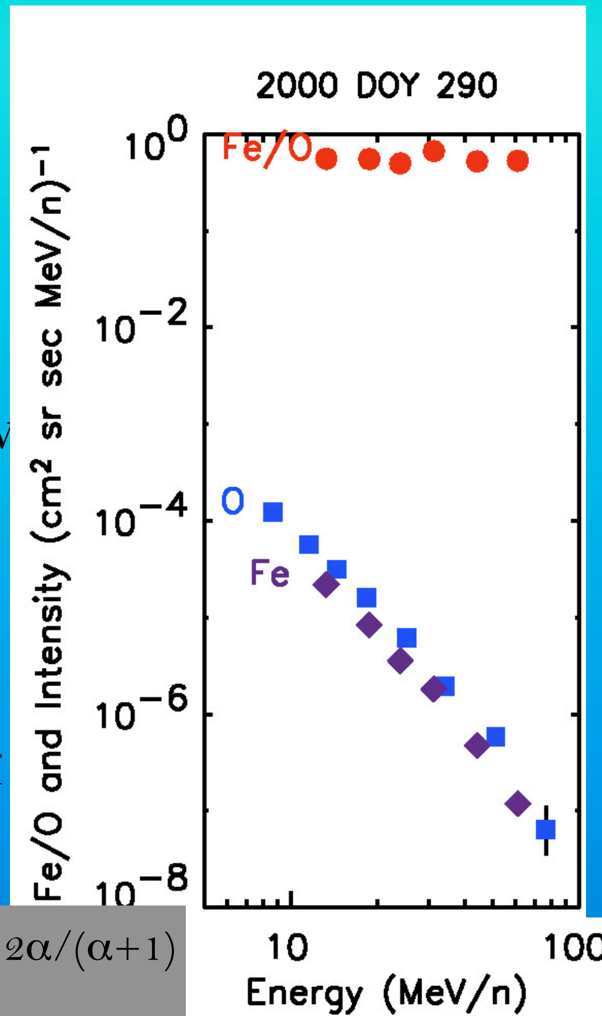
$$\kappa = 1/3 \, v \, \lambda$$

- Assume λ is a power-law in rigidity

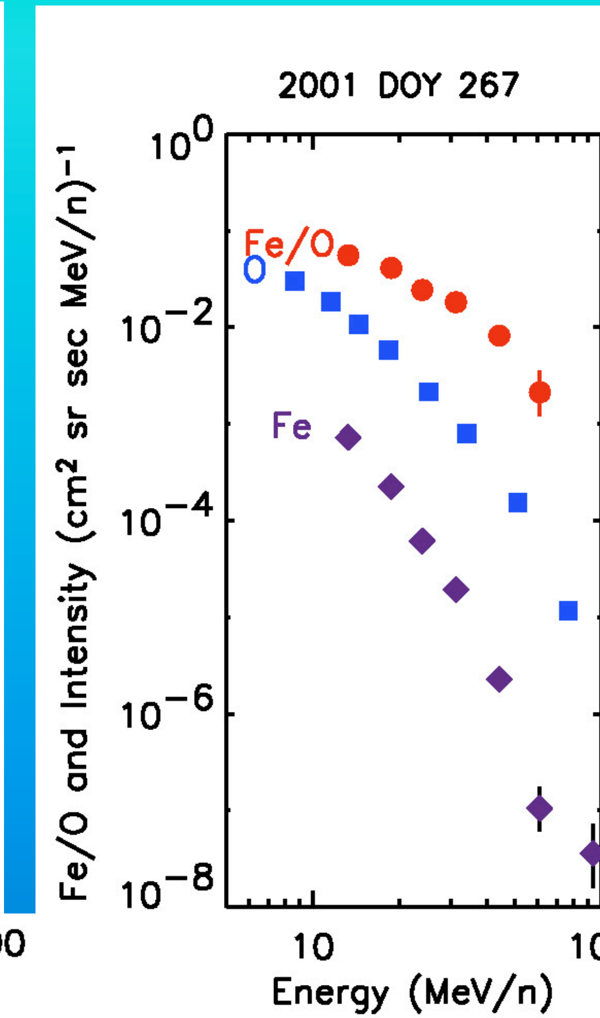
$$\kappa \sim (M/Q)^{\alpha} E^{(\alpha+1)/2}$$

- Break energies should occur at same value of κ

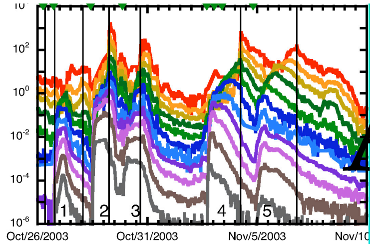
$$E_1/E_2 = [(Q/M)_1/(Q/M)_2]^{2\alpha/(\alpha+1)}$$



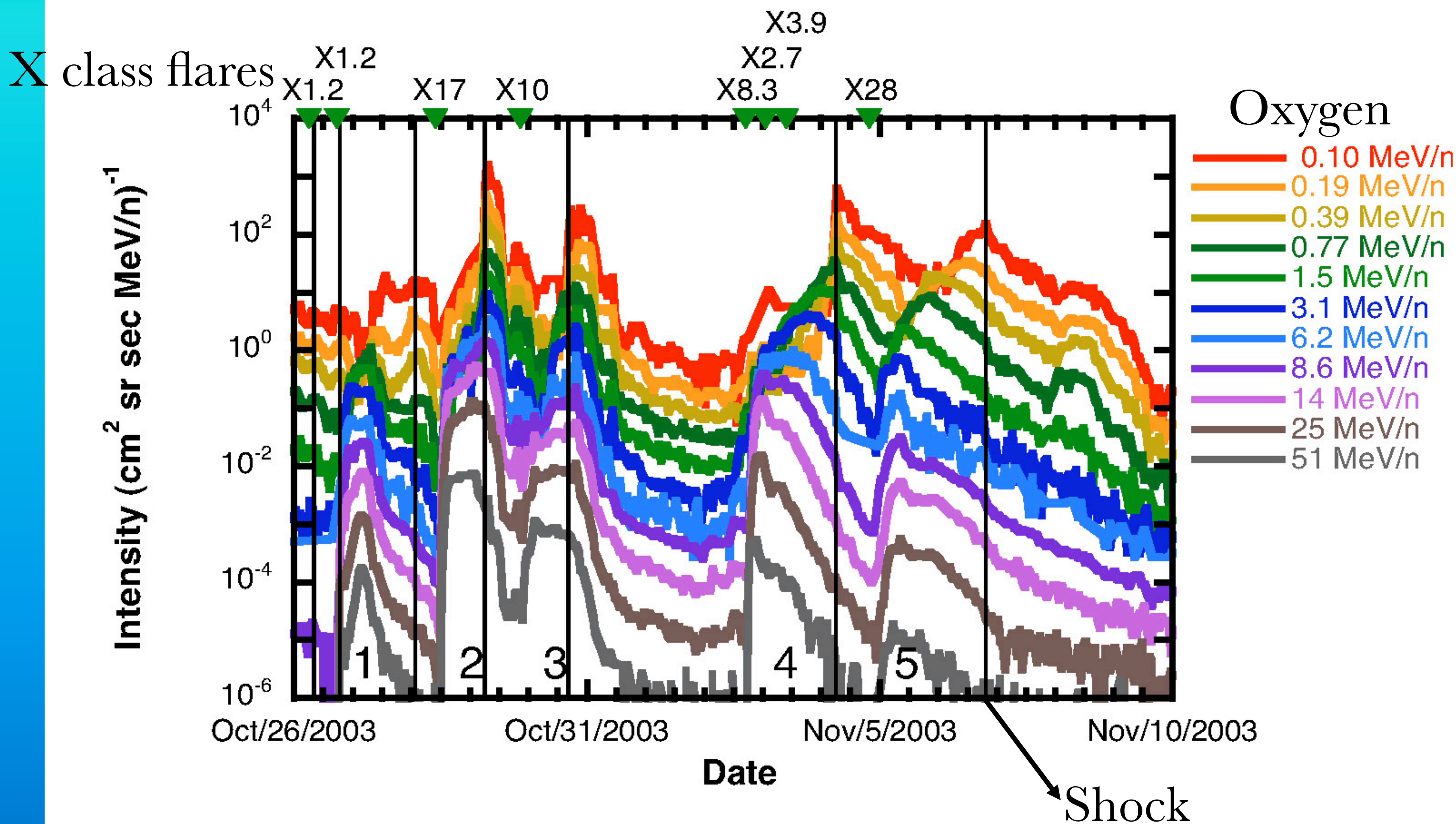
Cohen et al. 2002

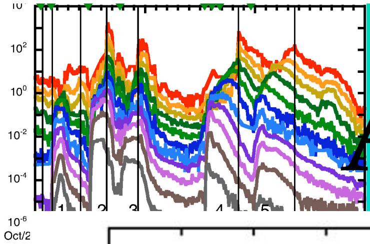


Cohen et al. 2002

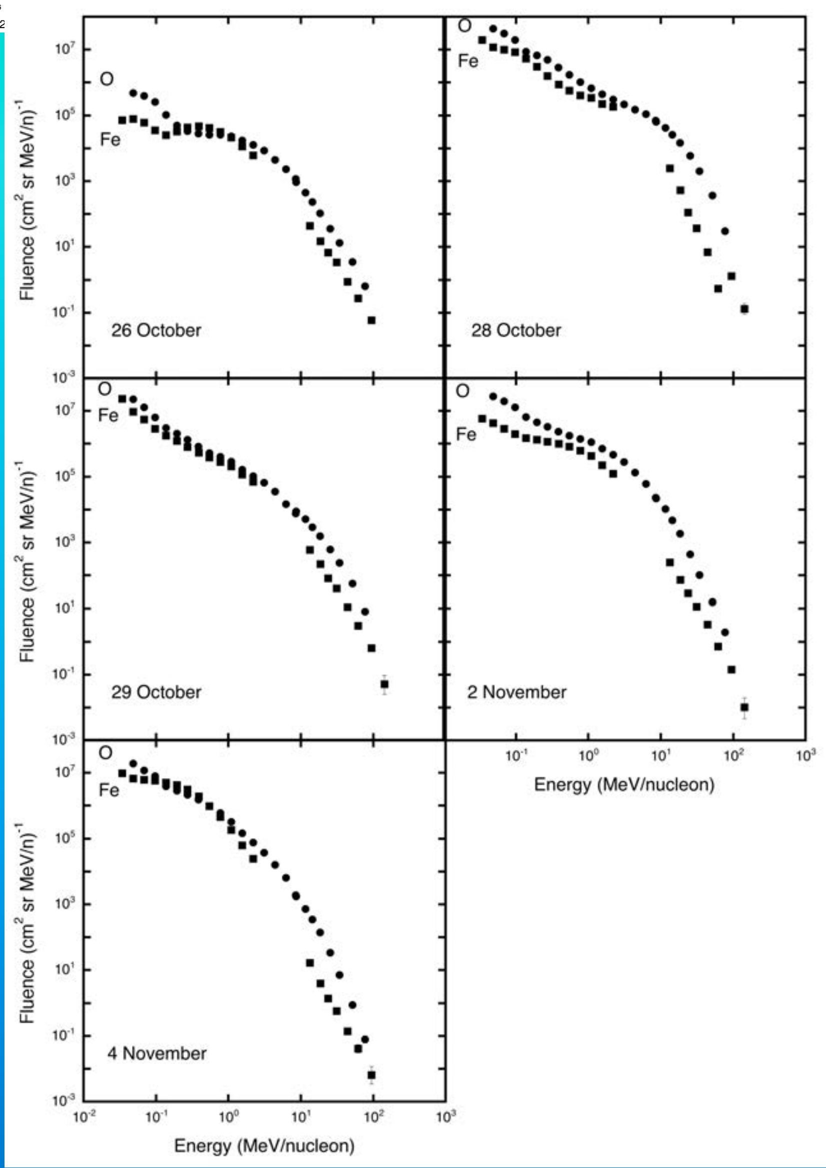


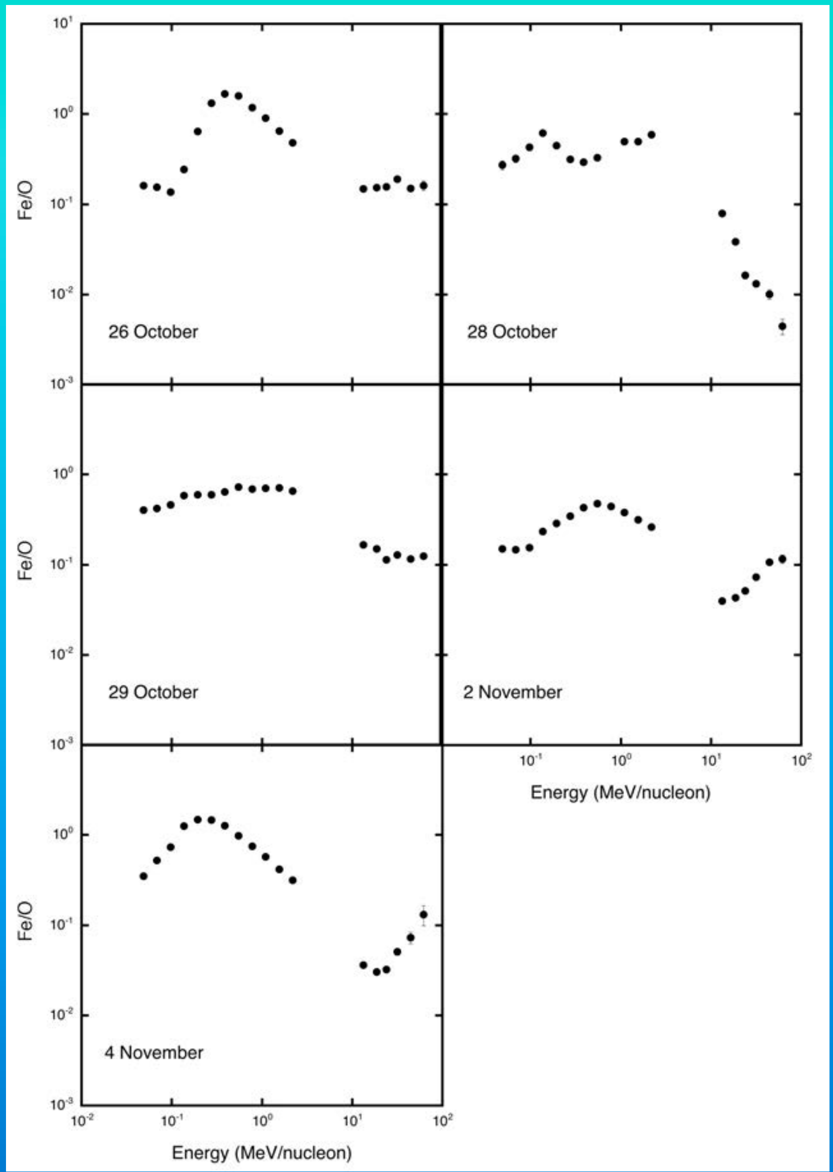
Application to Big SEP Events



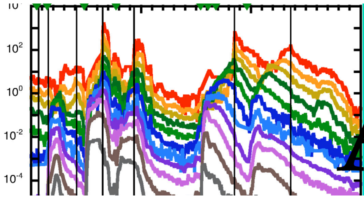


Application to Big SEP Events

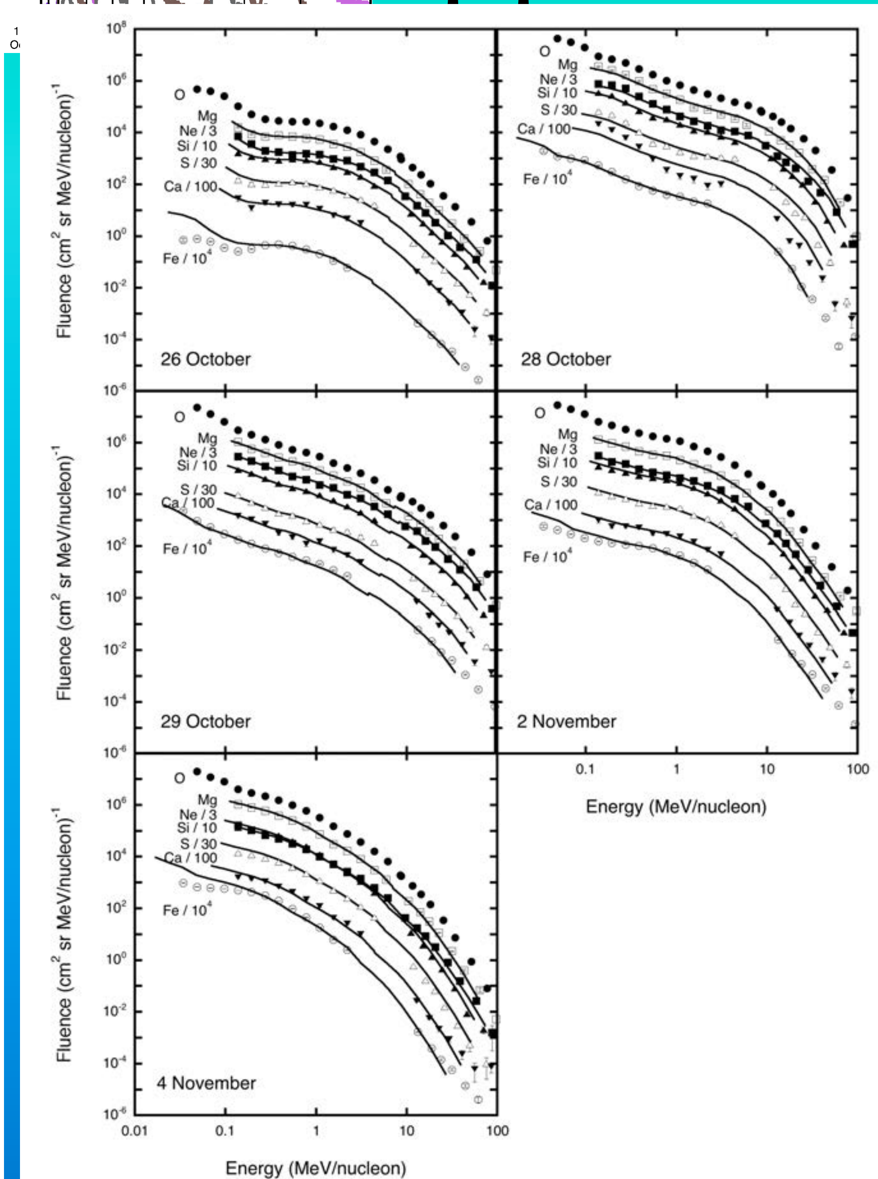


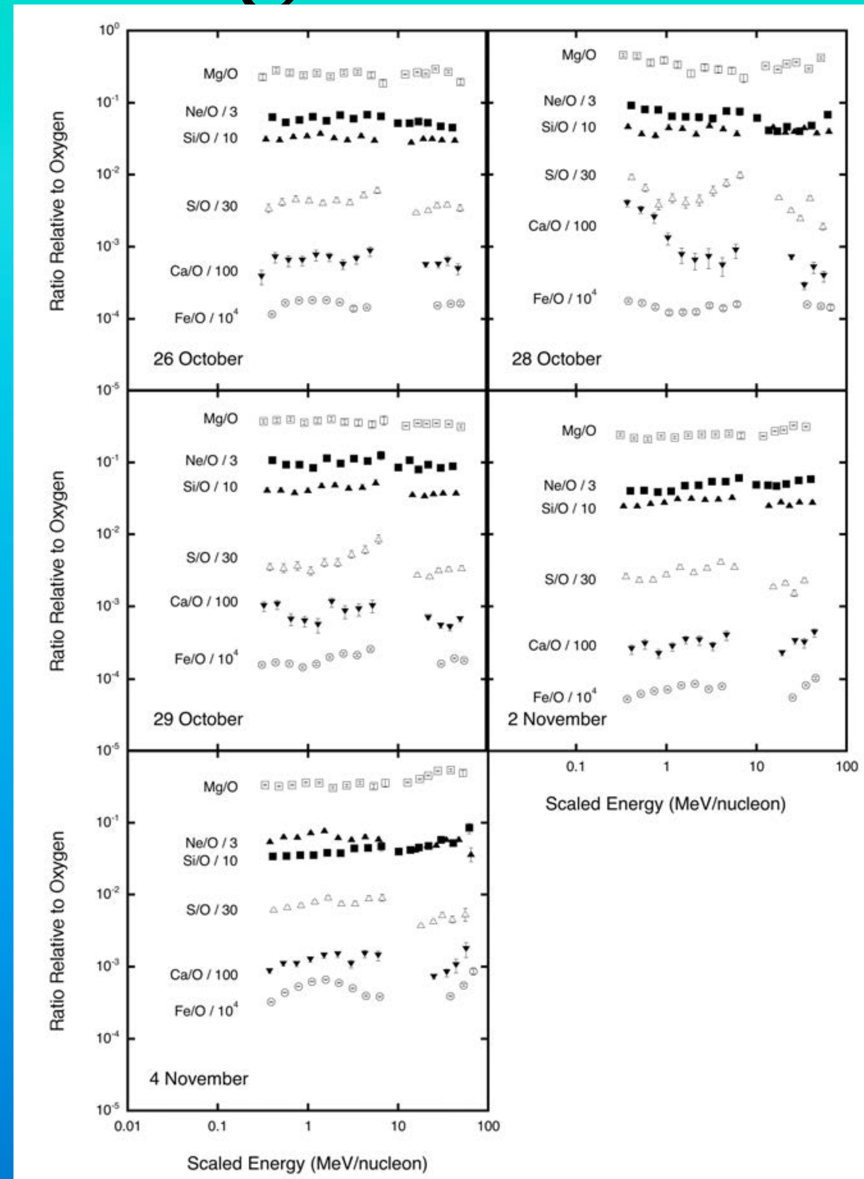


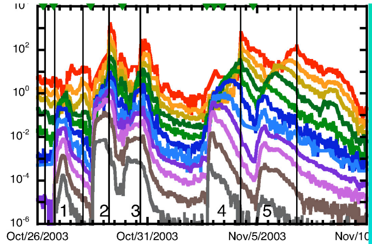
What History Acceleration Problems 3D Next



Application to Big SEP Events

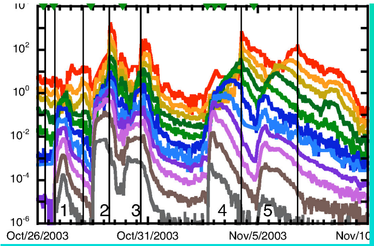






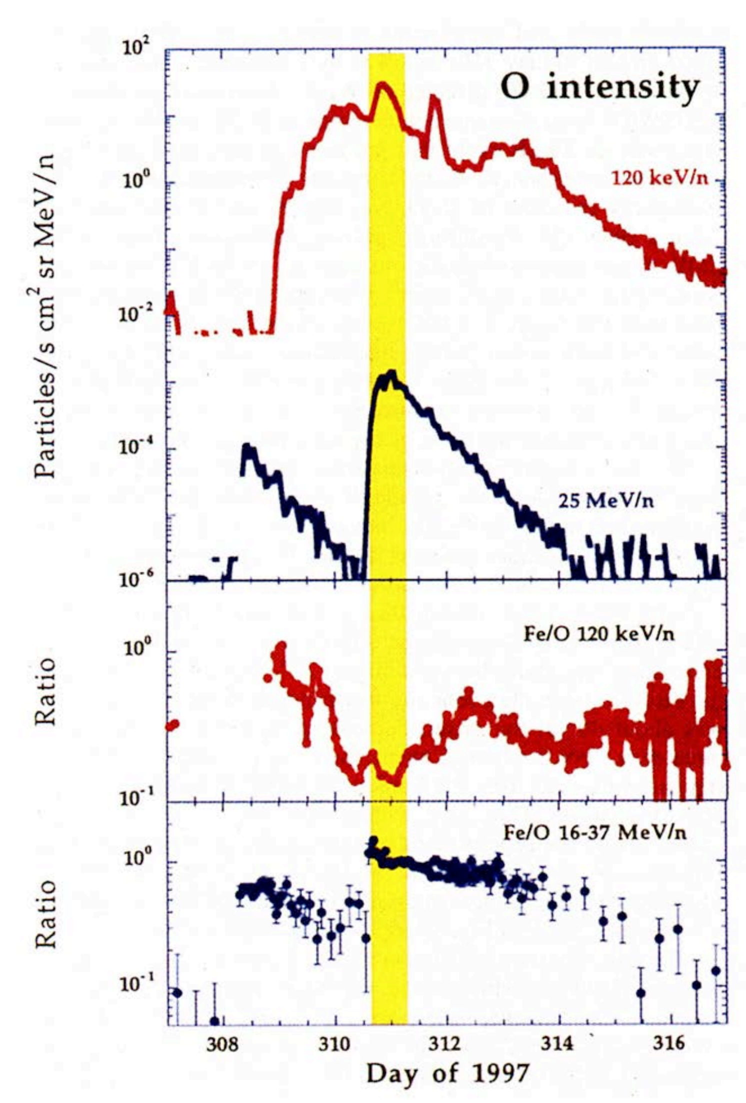
Problems with 2 Classes

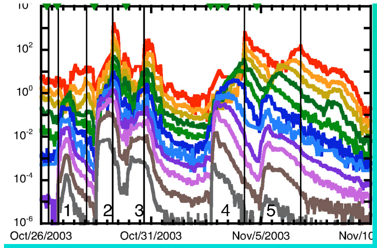
- ACE launches August 1997
  - › Suite of high-tech instruments to study heavy ions in SEP events over 3 orders of magnitude in energy (.1-100 MeV/n)
    - Elemental Composition (ULEIS+SIS)
    - Isotopic Composition (ULEIS+SIS)
    - Charge State Composition (SEPICA)
  - › In November 1997, ACE observes first gradual SEP events
    - Composition does not look as it should...



Problems with 2 Classes

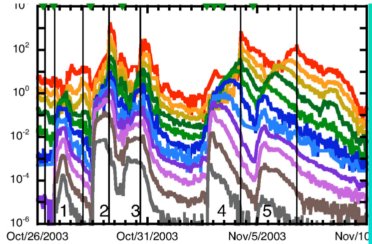
- ACE launches August 1997
  - › Suite of high-tech instruments t SEP events over 3 orders of ma (.1-100 MeV/n)
    - Elemental Composition (ULEIS+
    - Isotopic Composition (ULEIS+S
    - Charge State Composition (SEPI
  - › In November 1997, ACE obser events
    - Composition does not look as it s





Problems with 2 Classes

- Within the first year, ACE observes many more of these enriched-Fe events
  - Composition from C-Ni looks impulsive (12-60 MeV/n)
  - Enhancements of ^{3}He (not at impulsive levels)



Problems with 2 Classes

- Within the first year, ACE ob

ks

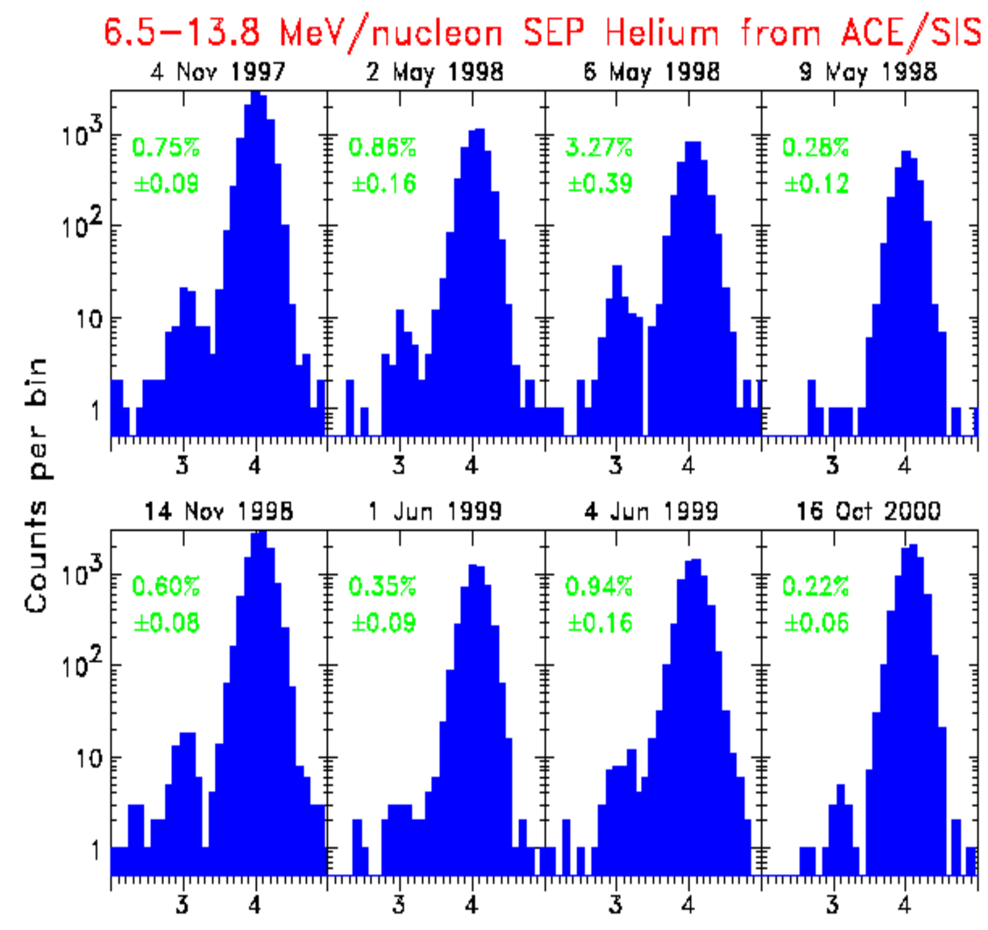
at i

e st

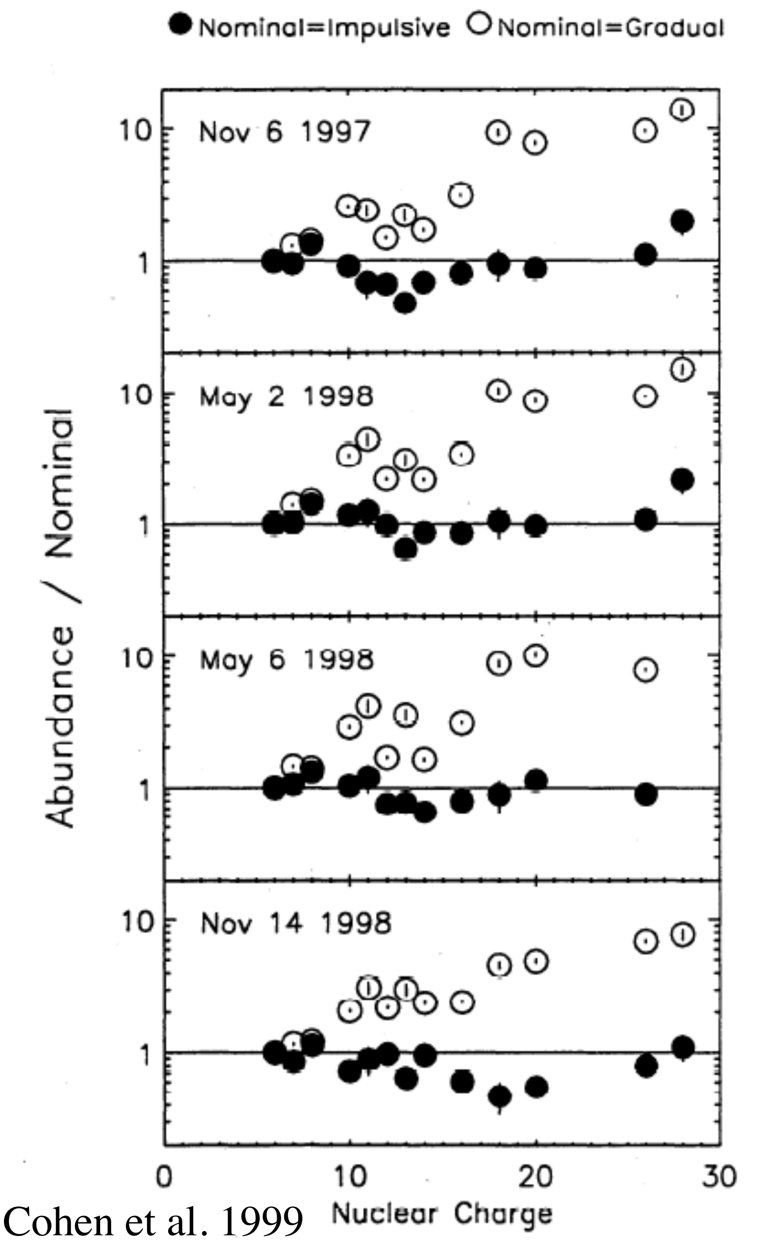
que

ke

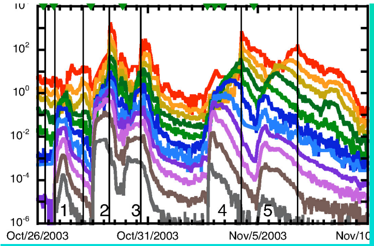
ON



Leske et al.



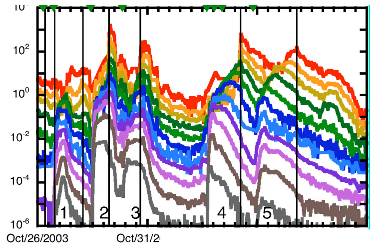
Cohen et al. 1999

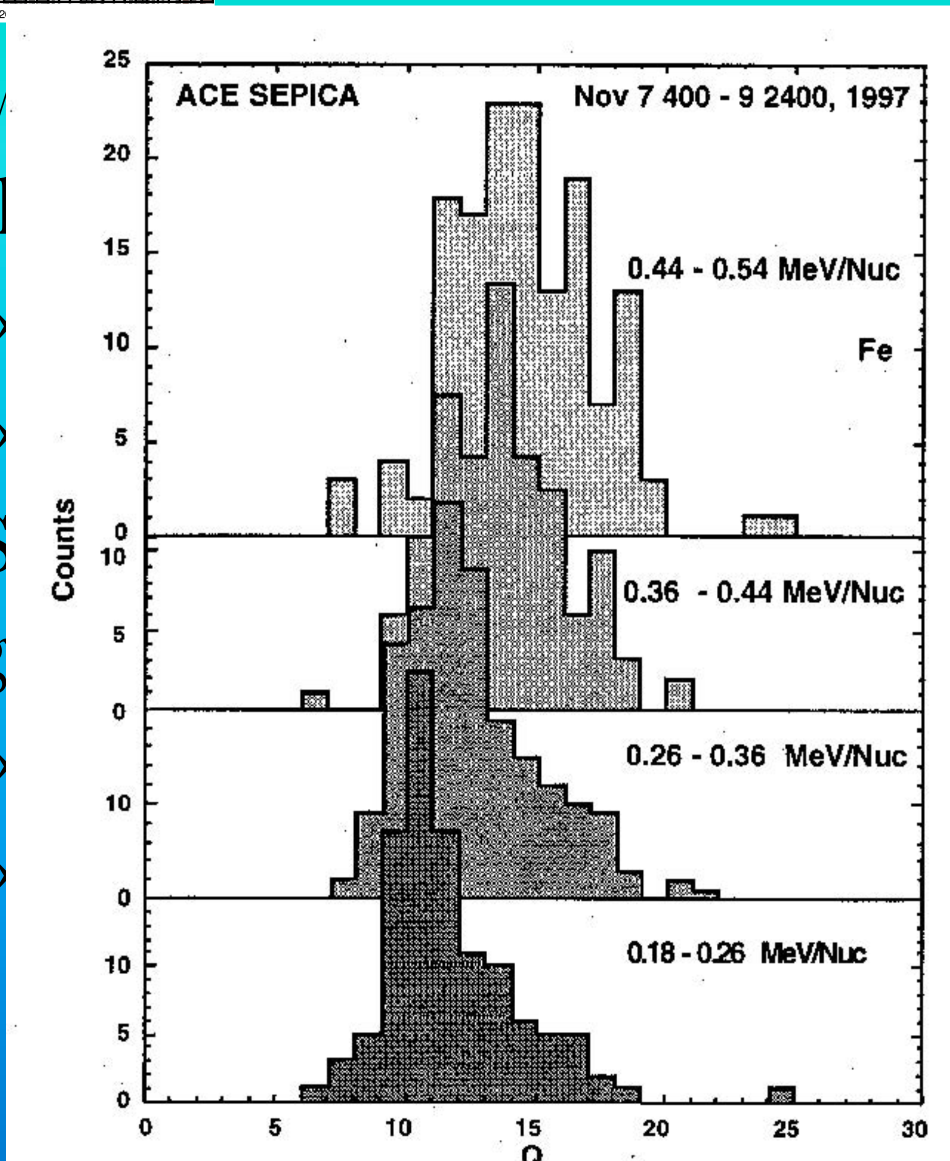


Problems with 2 Classes

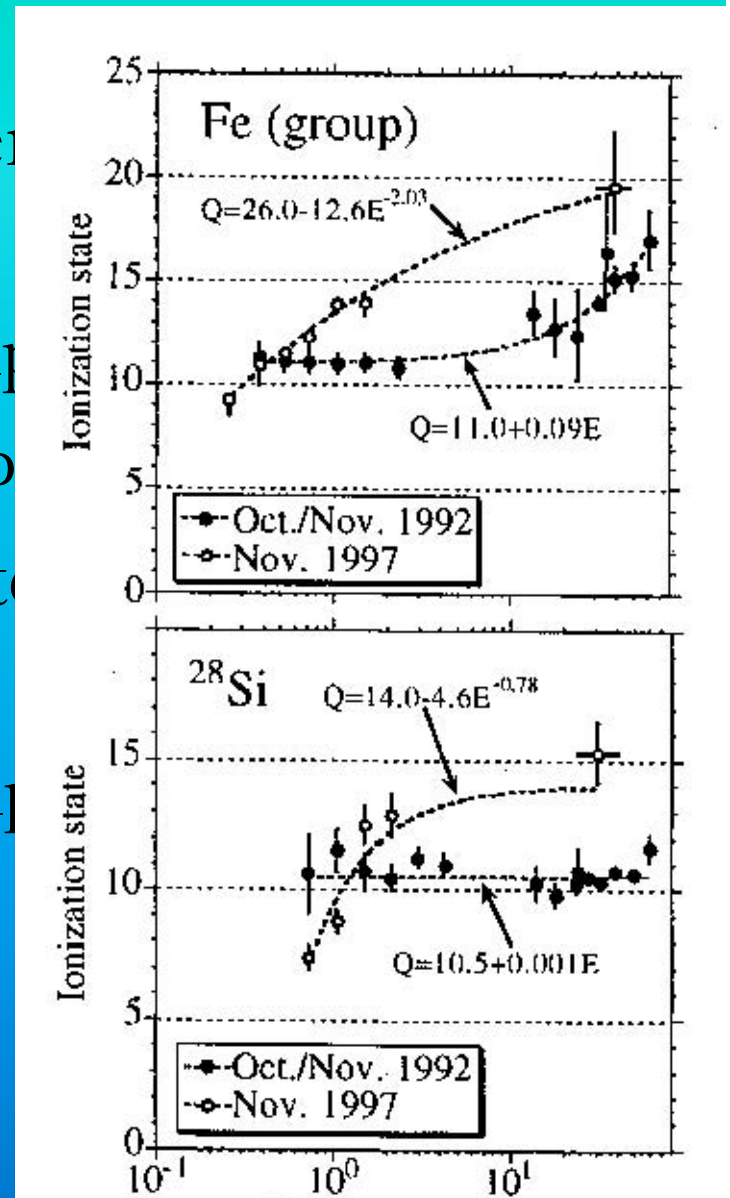
- Within the first year, ACE observes many more of these enriched-Fe events
  - Composition from C-Ni looks impulsive (12-60 MeV/n)
  - Enhancements of ^{3}He (not at impulsive levels)
- SAMPEX measures charge states with geomagnetic cutoff technique
  - At 30 MeV/n Q_{Fe} is ~20 (like impulsive)
  - Q_{Fe} is *energy dependent*

Problems with 2 Classes

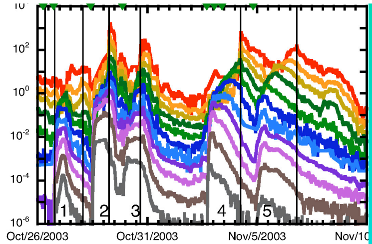




Moebius et al. 1999

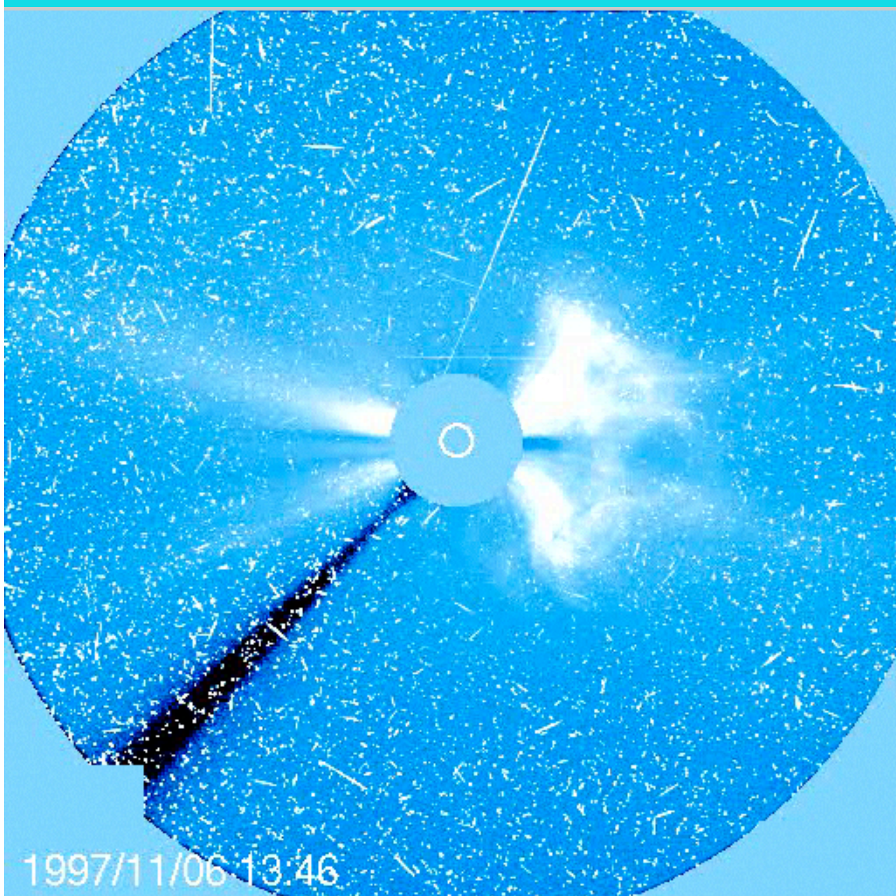


Mazur et al., 1999

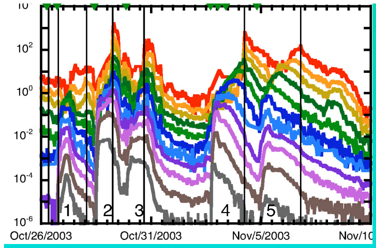


Problems with 2 Classes

- How should we classify these events?

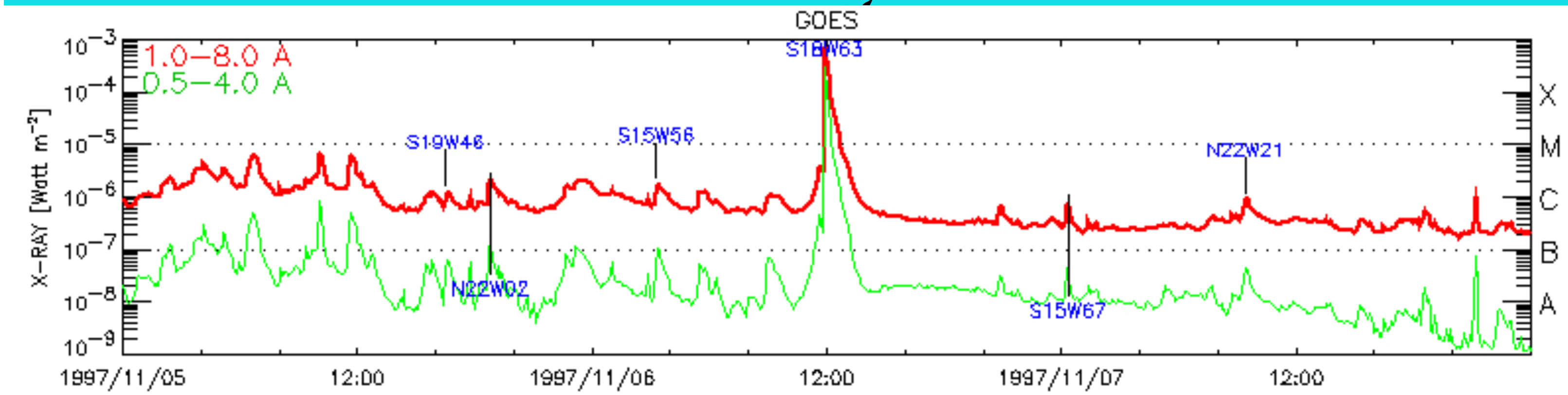


Two Groups =>	Impulsive Flare acceleration	Gradual Shock acceleration
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
Q_{Fe}	~20	~14
Duration	Hours	Days
X-rays	Impulsive	Gradual
Coronagraph	--	√CME (96%)

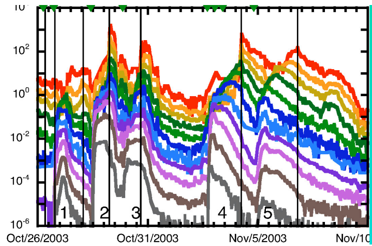


Problems with 2 Classes

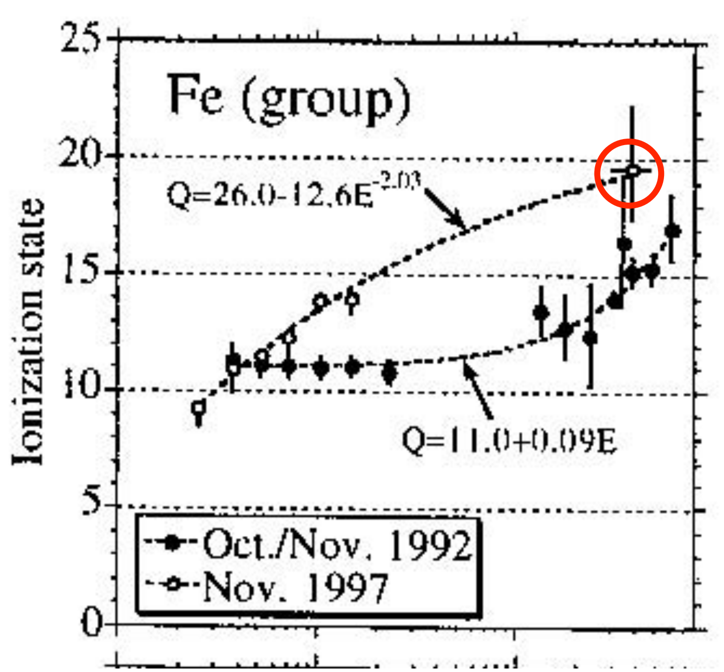
- How should we classify these events?



		Gradual Shock acceleration
		~0.0005
Fe/O	~1	~0.1
Q_{Fe}	~20	~14
Duration	Hours	Days
X-rays	Impulsive √	Gradual
Coronagraph	--	√CME (96%)

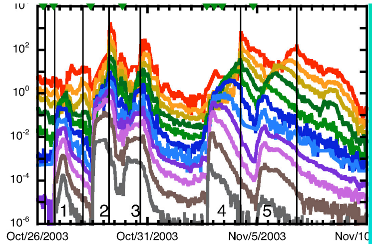


Problems with 2 Classes



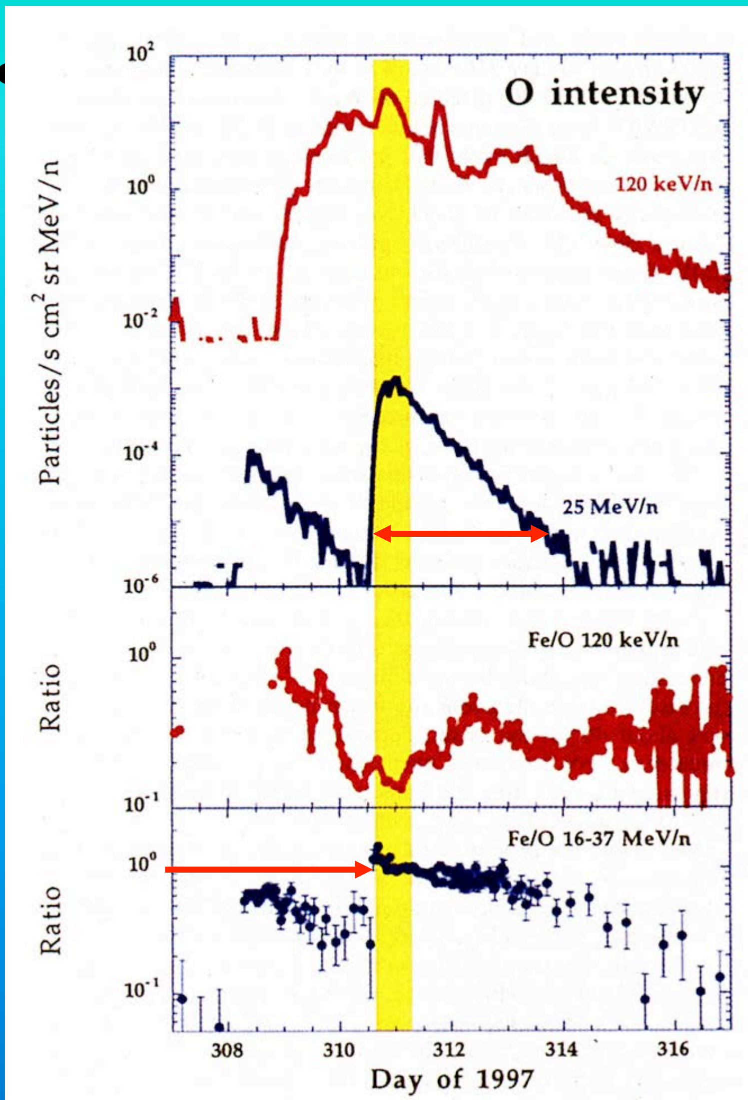
...fy these events?

Two Groups =>	Impulsive Flare acceleration	Gradual Shock acceleration
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
Q_{Fe}	√ ~20	~14
Duration	Hours	Days
X-rays	Impulsive	√ Gradual
Coronagraph	--	√CME (96%)

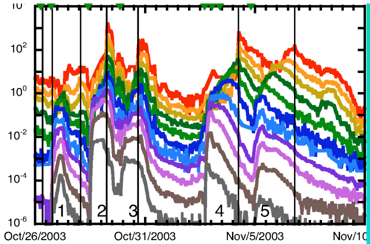


Problems with 2 Classes

• ... sify these events?

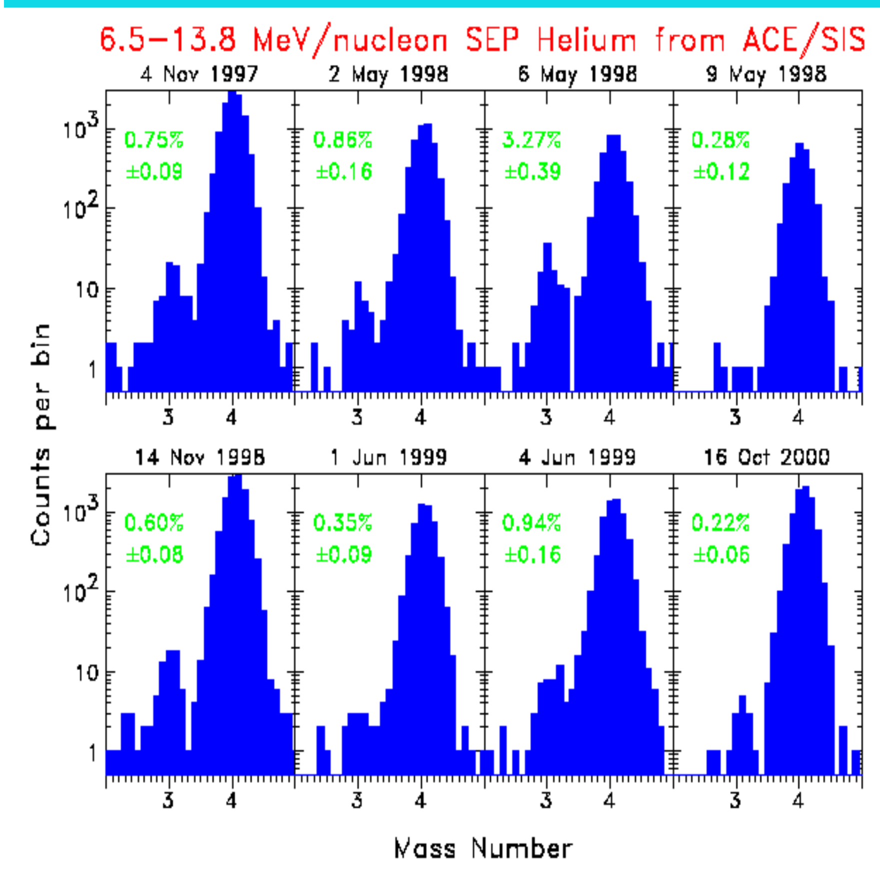


Two Groups =>	Impulsive Flare acceleration	Gradual Shock acceleration
$^3He/^4He$	~1	~0.0005
Fe/O	√ ~1	~0.1
Q_{Fe}	√ ~20	~14
Duration	Hours	√ Days
X-rays	Impulsive	√ Gradual
Coronagraph	--	√CME (96%)

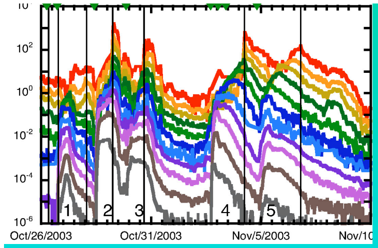


Problems with 2 Classes

- How should we classify these events?

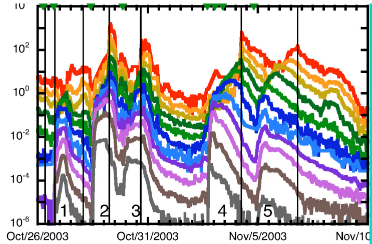


Two Groups =>	Impulsive Flare acceleration	Gradual Shock acceleration
$^3He/^4He$	~1	√ ~0.0005
Fe/O	√ ~1	~0.1
Q_{Fe}	√ ~20	~14
Duration	Hours	√ Days
X-rays	Impulsive	√ Gradual
Coronagraph	--	√CME (96%)



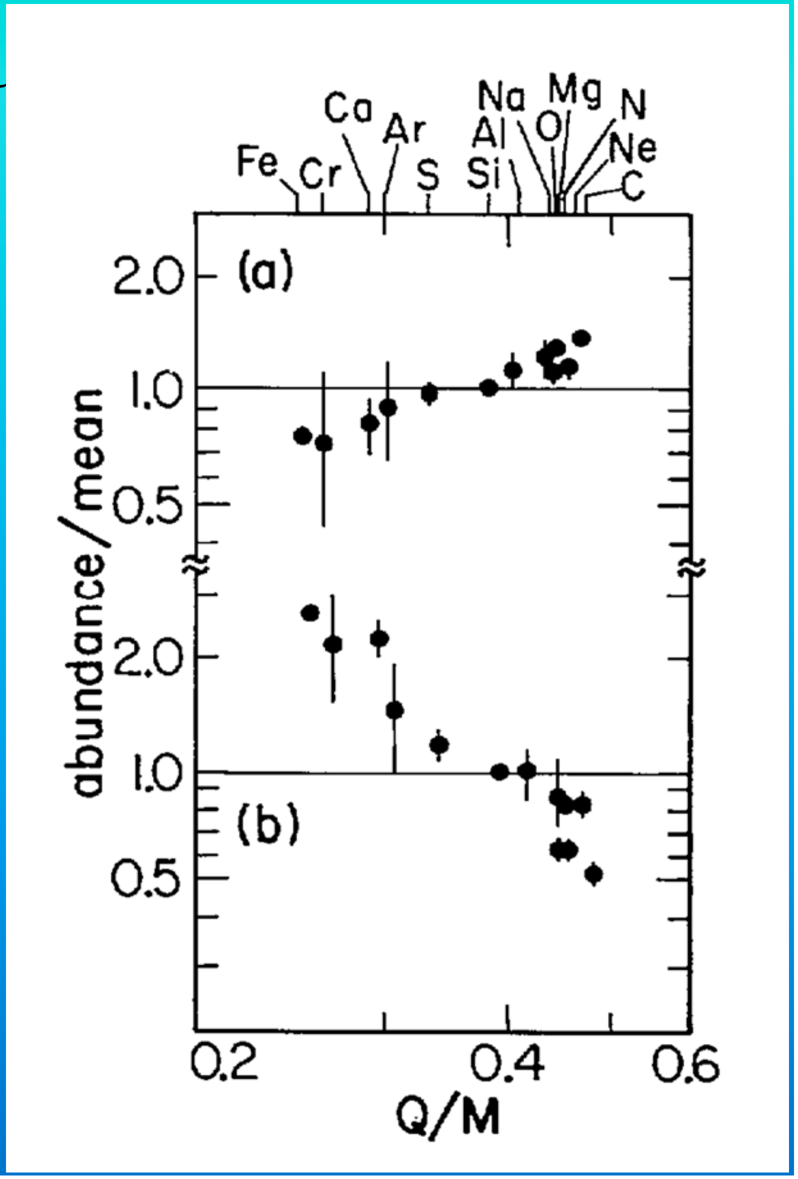
Possible Explanations

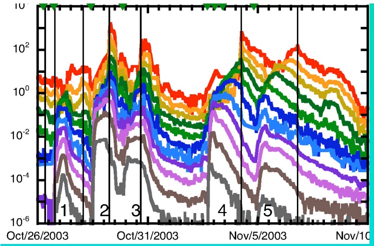
- What happens when new results challenge old beliefs?



Possible Explanations

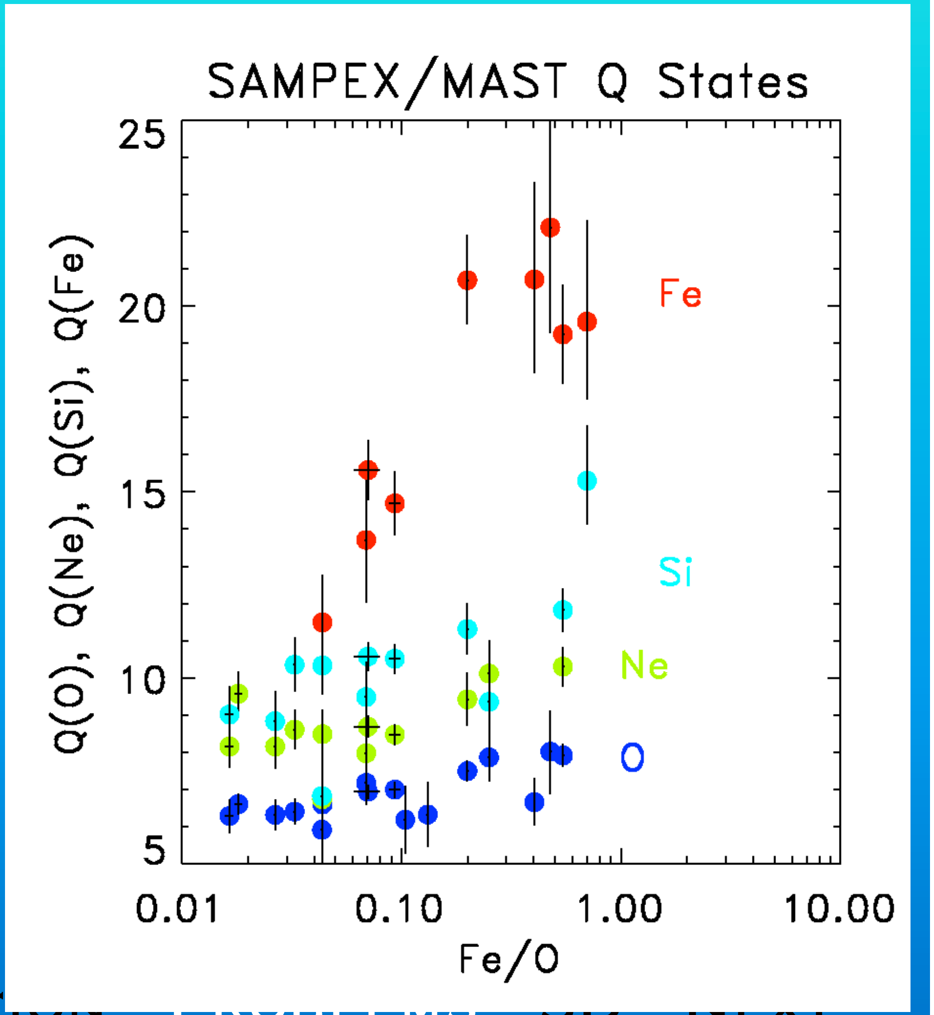
- What happens when new resu… beliefs?
  - › Q/M effect

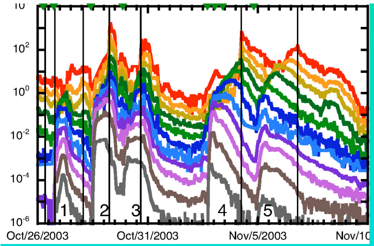




Possible Explanations

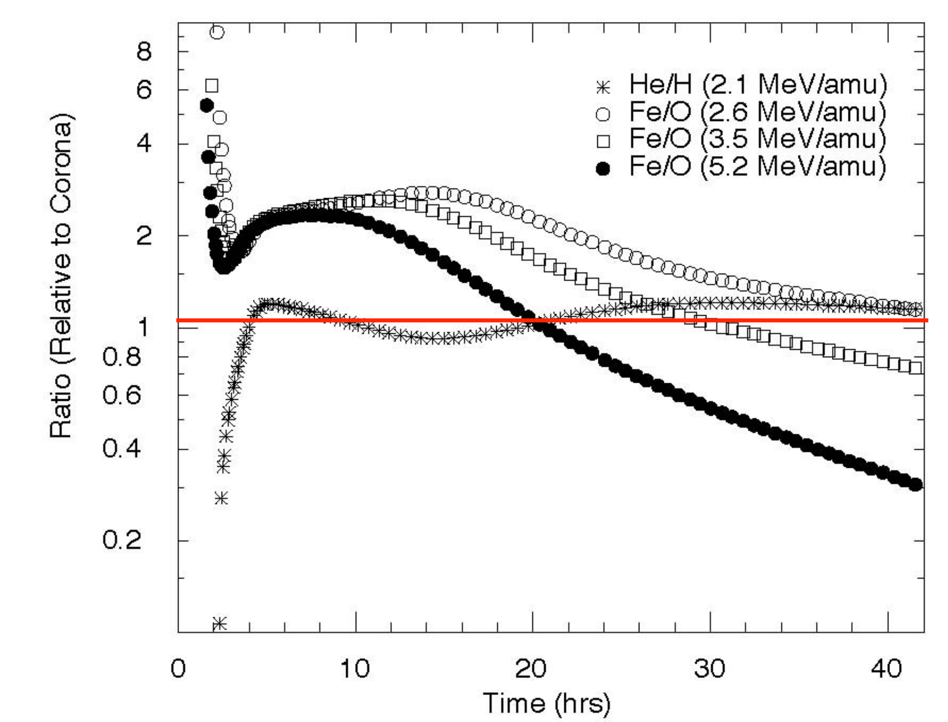
- What happens when new results challenge old beliefs?
  - ~~Q/M effect~~

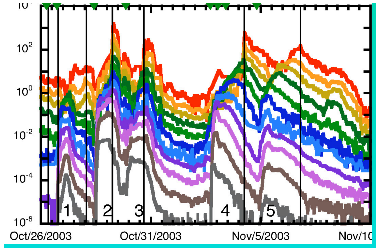




Possible Explanations

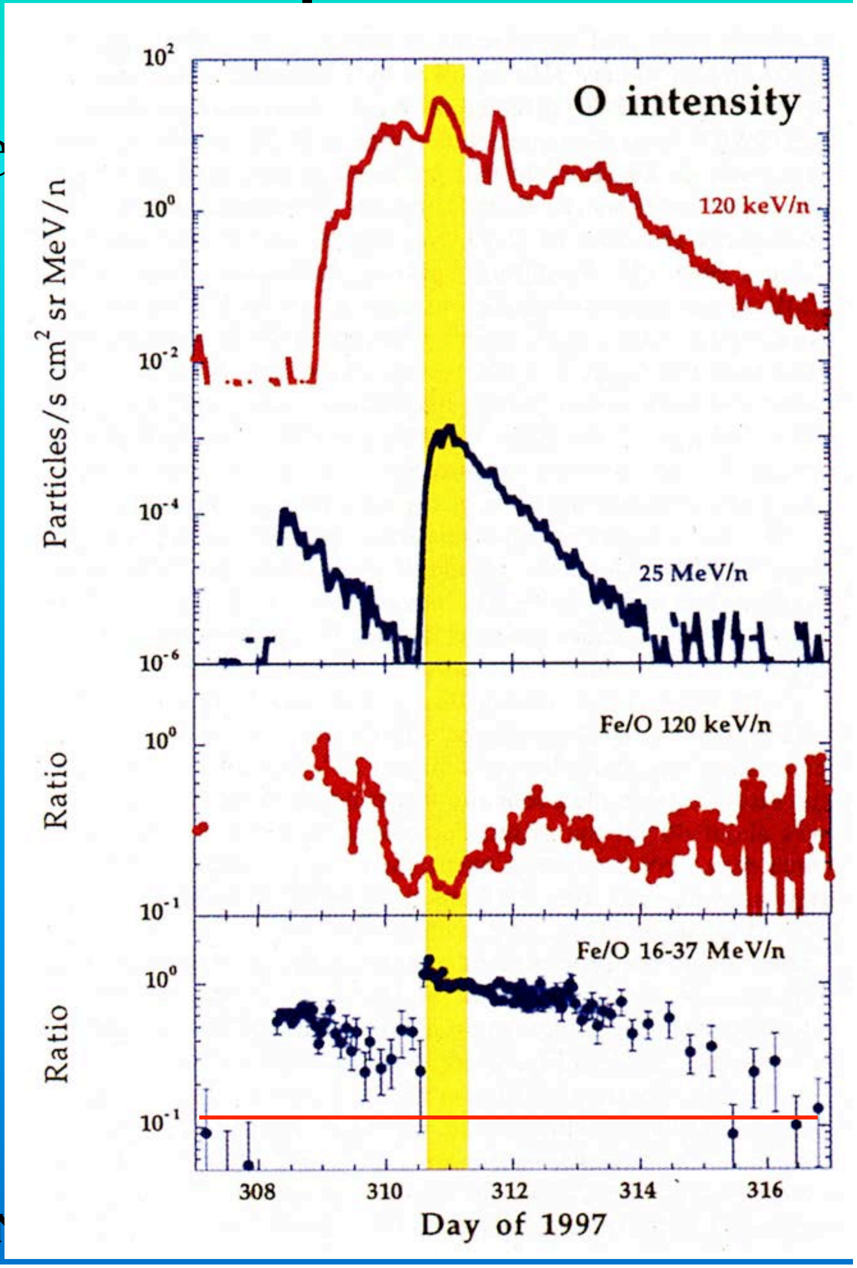
- What happens when new results challenge old beliefs?
  - ~~Q/M effect~~
  - Velocity dispersion effect

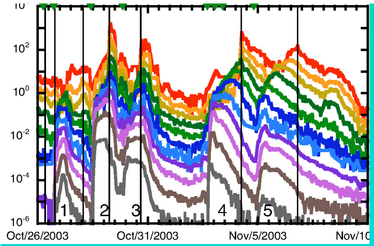




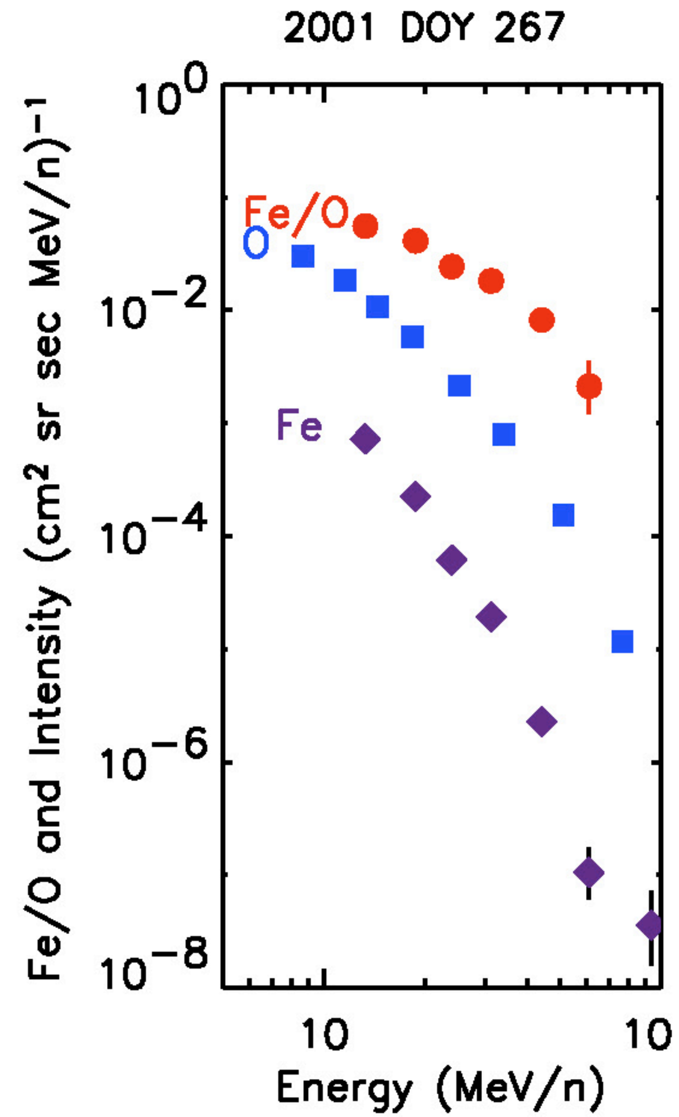
Possible Explanations

- What happens when new re
beliefs?
  - › ~~Q/M effect~~
  - › ~~Velocity dispersion effect~~

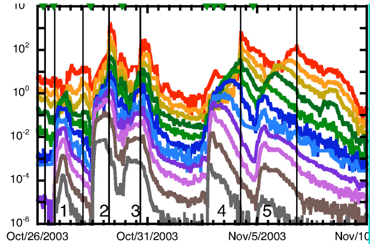




Possible Explanations

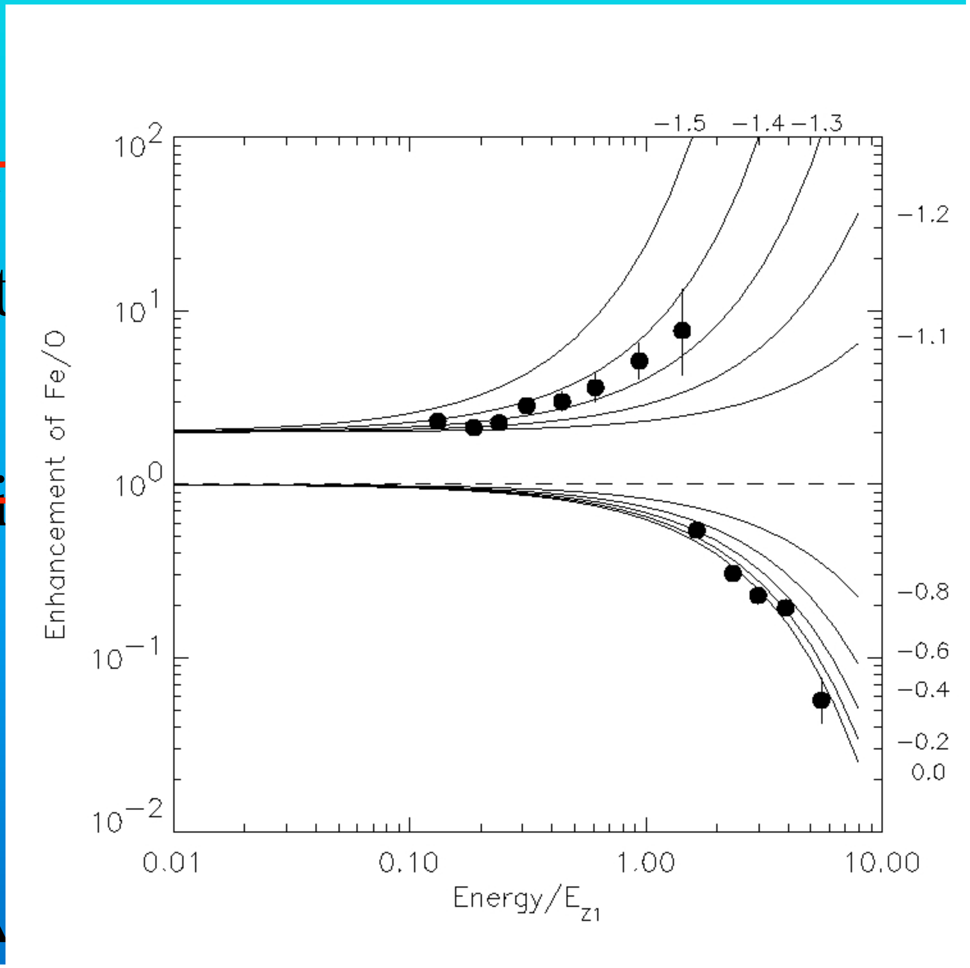


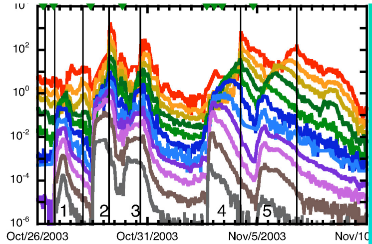
- What happens when new results beliefs?
  - ~~Q/M effect~~
  - ~~Velocity dispersion effect~~
- Grudging acceptance into existin (shock acceleration)
  - Diffusion from shock region



Possible Explanations

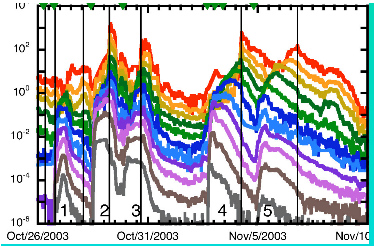
- What happens when new results challenge old beliefs?
  - ~~Q/M effect~~
  - ~~Velocity dispersion effect~~
- Grudging acceptance int (shock acceleration)
  - ~~Diffusion from shock regi~~





Possible Explanations

- What happens when new results challenge old beliefs?
  - ~~Q/M effect~~
  - ~~Velocity dispersion effect~~
- Grudging acceptance into existing framework (shock acceleration)
  - ~~Diffusion from shock region~~
  - Suprathermal flare material (small amounts from *preceding* flares)



Possible Explanations

- What happens when new results challenge old beliefs?
  - ~~Q/M~~
  - ~~Veloc~~
- Grudgi
  (shock
  - ~~Diffu~~
  - Supra
    preced

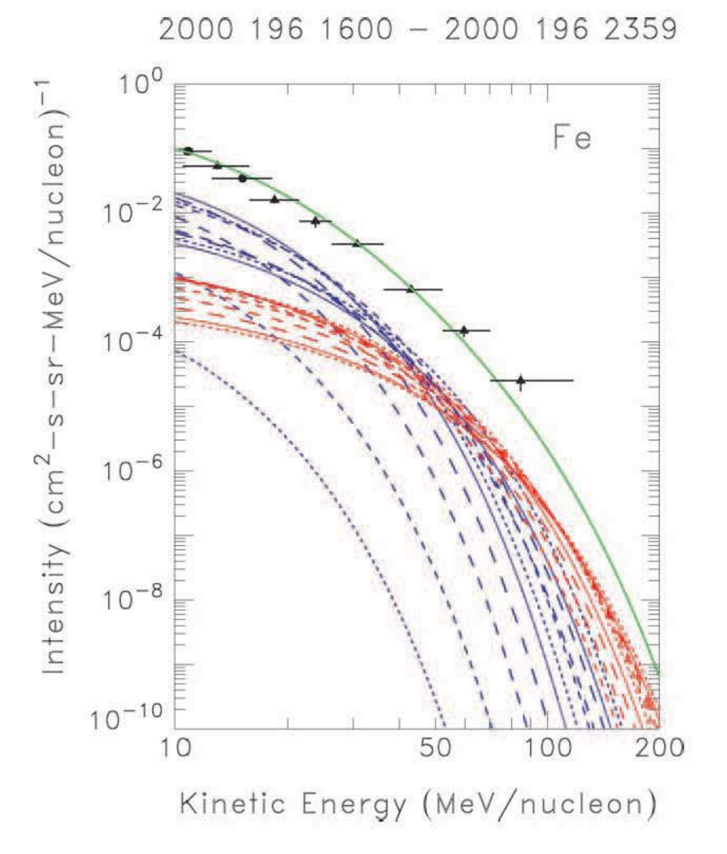
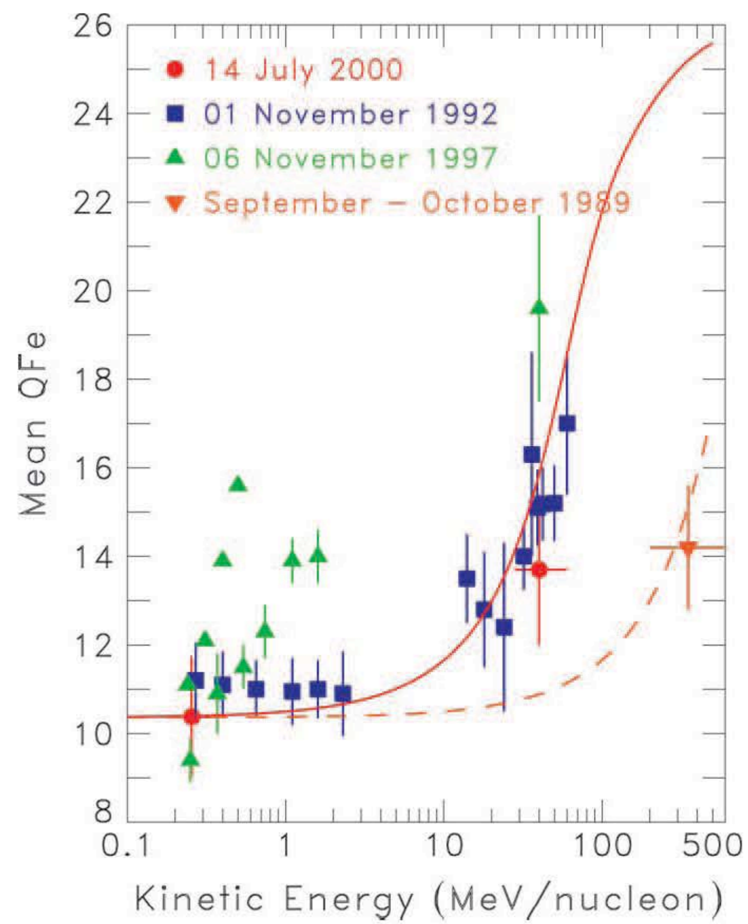
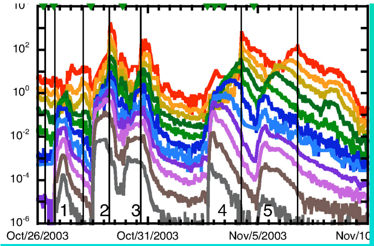


FIG. 2.—Contributions of various ionic charge states to the Fe spectrum. Blue curves are Q_{Fe} = 6–16, which arise primarily from the solar wind; red curves are $Q_{Fe} > 16$ from the remnant flare suprathermal component. The green curve is the sum.

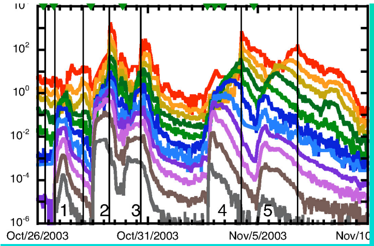


WHAT



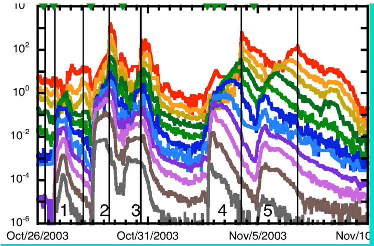
Possible Explanations

- What happens when new results challenge old beliefs?
  - ~~Q/M effect~~
  - ~~Velocity dispersion effect~~
- Grudging acceptance into existing framework (shock acceleration)
  - ~~Diffusion from shock region~~
  - Suprathermal flare material (small amounts from *preceding* flares) Not always



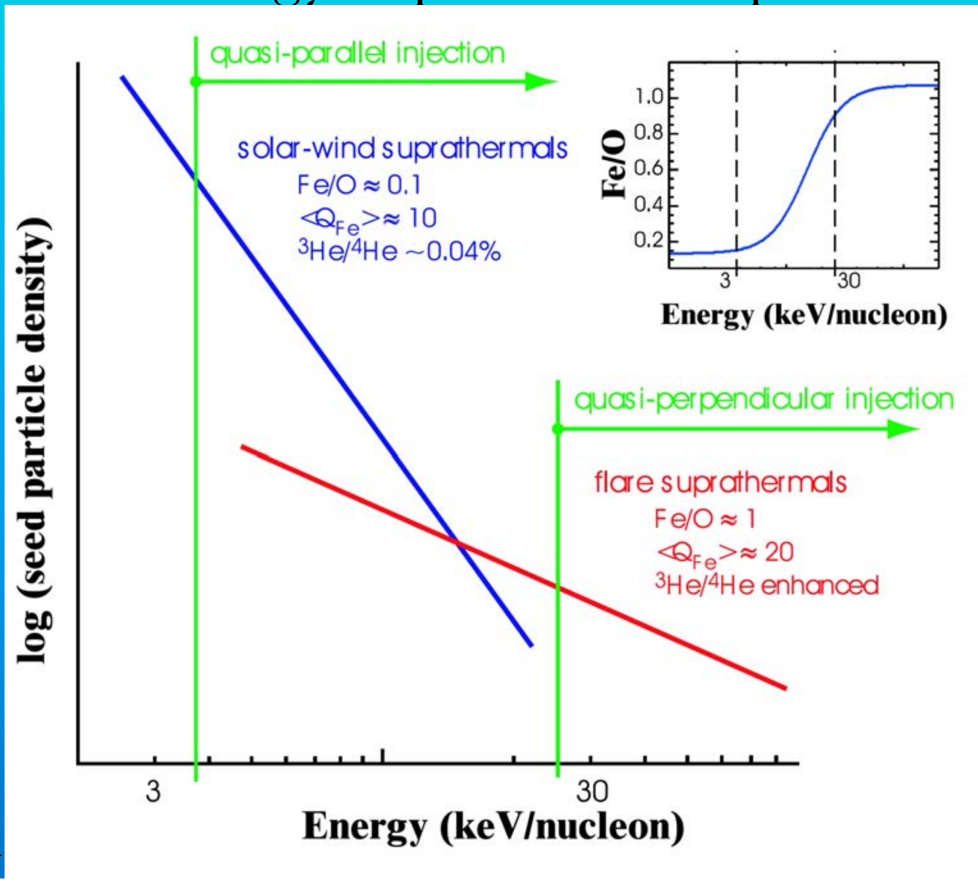
Possible Explanations

- Two competing theories
  - › Shock orientation
    - flare suprathermals present → energy-dependent composition of the seed population
    - perpendicular vs parallel shock difference

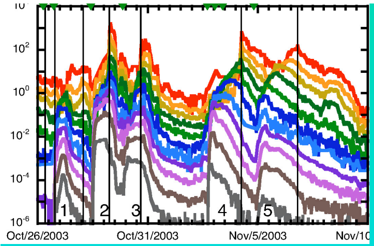


Possible Explanations

- Two competing theories
  - › Shock orientation
    - flare suprathermals present → energy-dependent composition of the seed population
    - perpendicular vs parallel

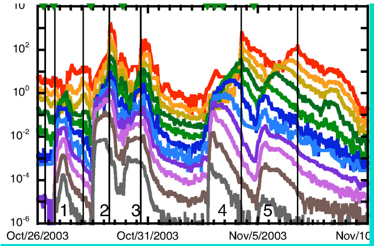


Tylka et al. 2005



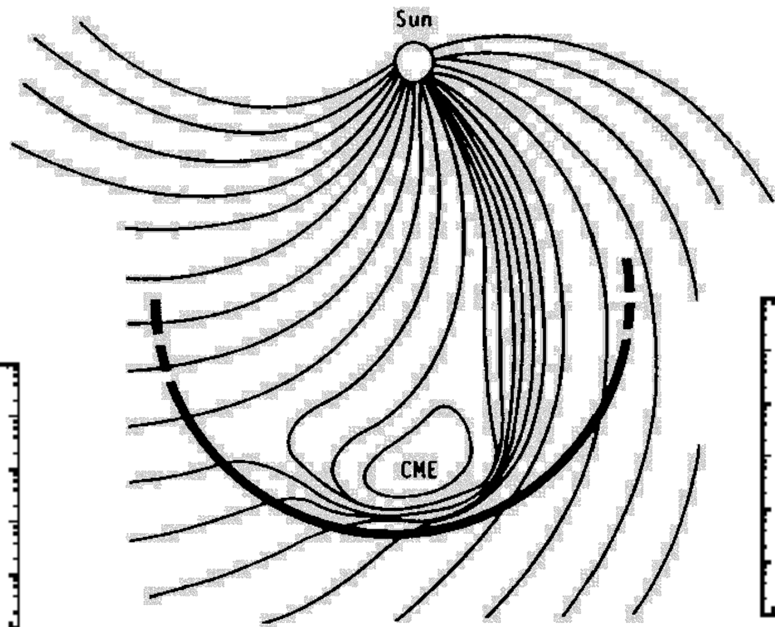
Possible Explanations

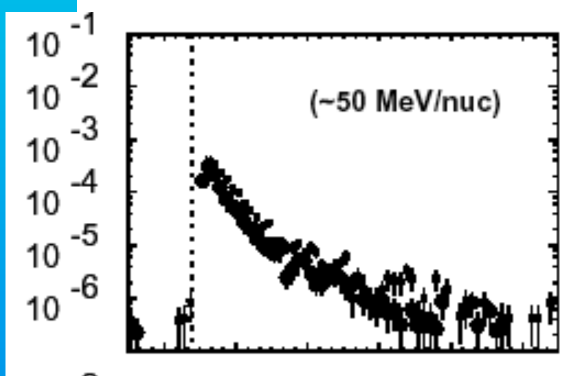
- Two competing theories
  - › Shock orientation
    - flare suprathermals present → energy-dependent composition of the seed population
    - perpendicular vs parallel shock difference
  - › Direct flare contribution
    - flare particles can escape
    - observation depends on
      - » connection to flare
      - » strength of shock
      - » size of flare

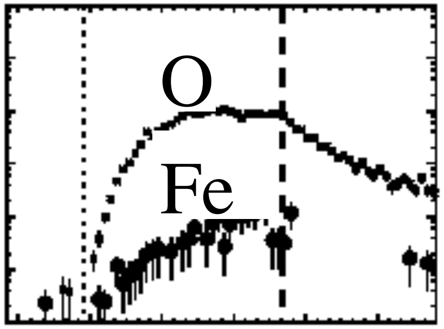


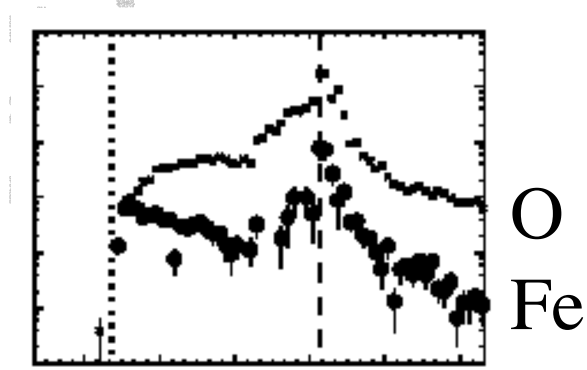
Possible Explanations

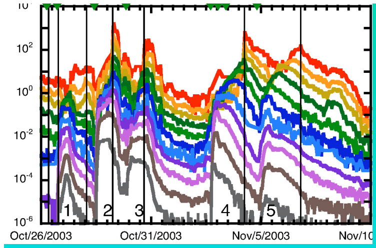
- Two competing theories





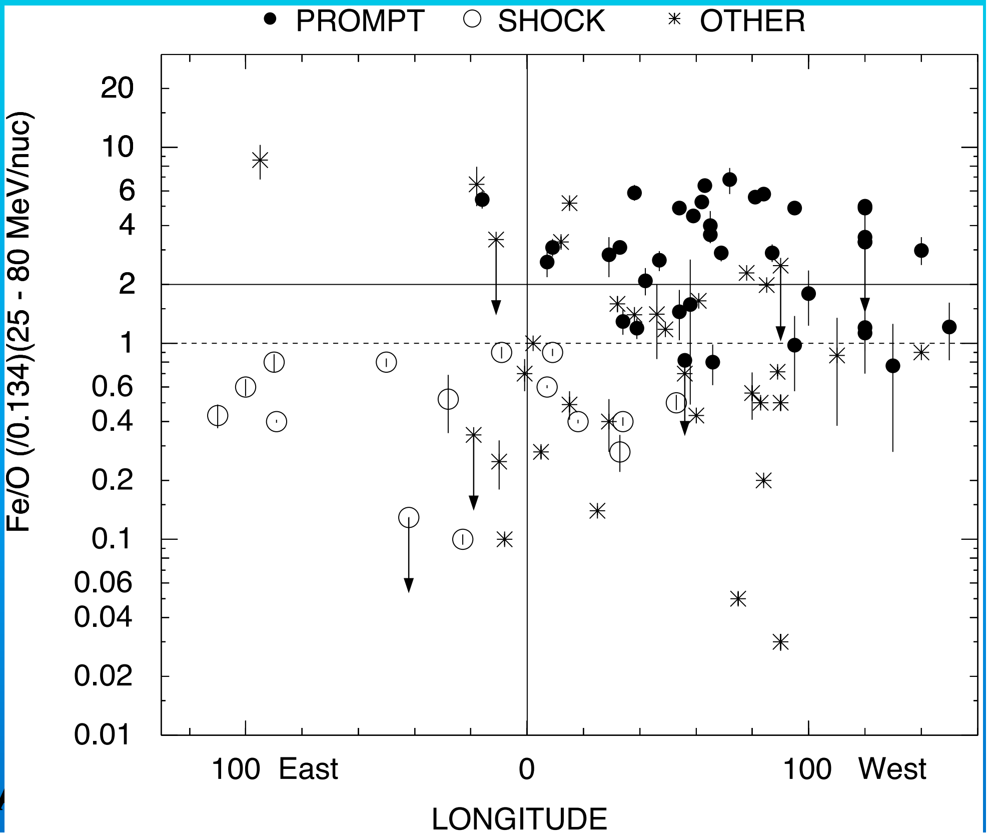


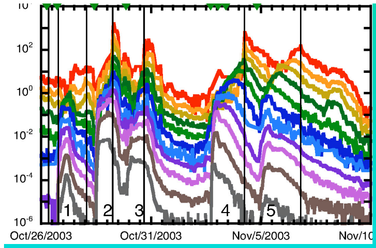




Points of View

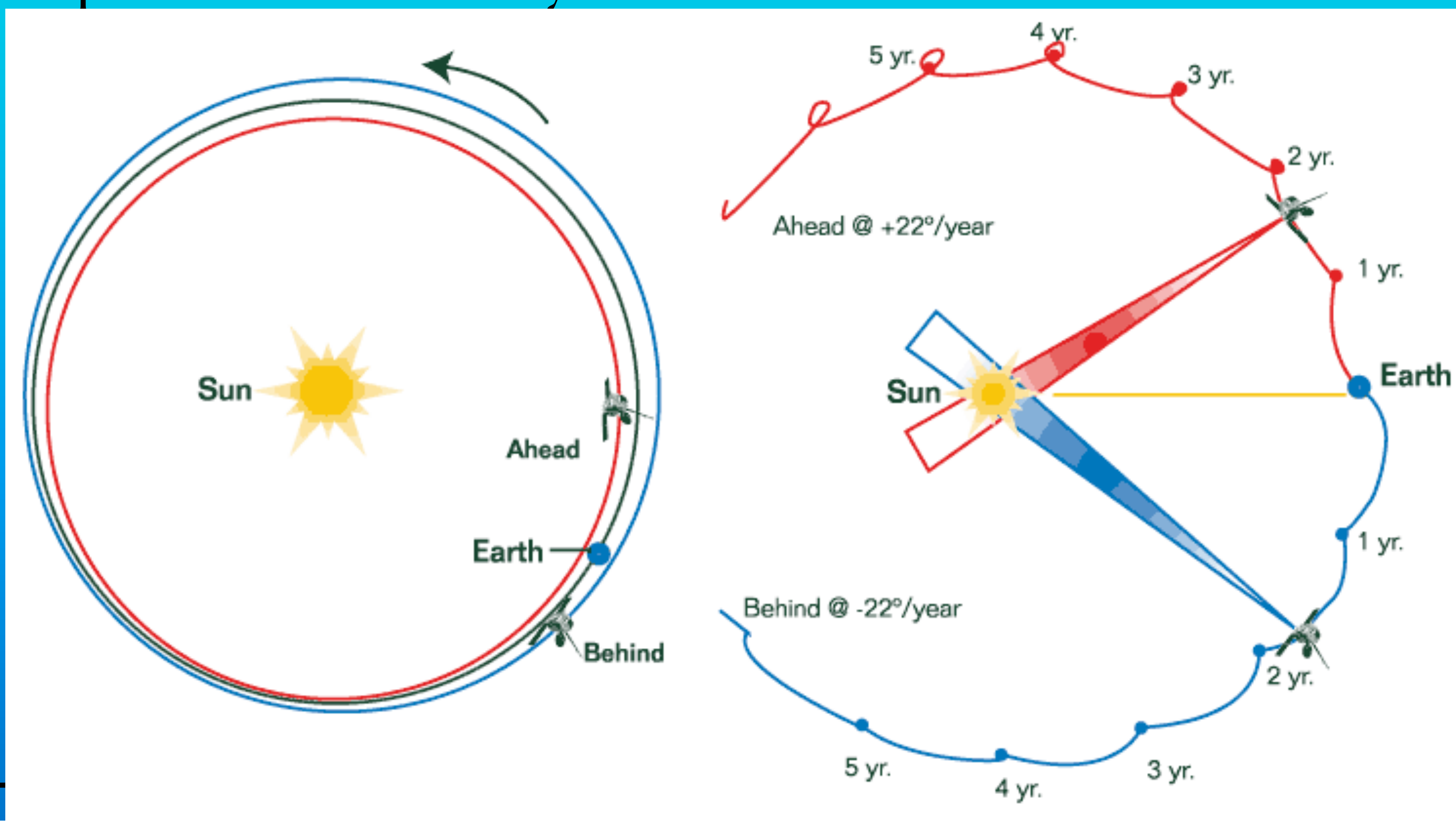
- Limitations of a single point of view
  - SEP observations mostly from along the Sun-Earth line
  - Can only determine where the solar source region is (often front side)
  - Longitude dependence?
  - Really need multiple points of view

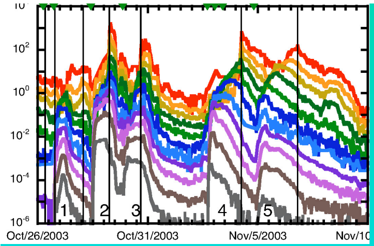




STEREO and 3D

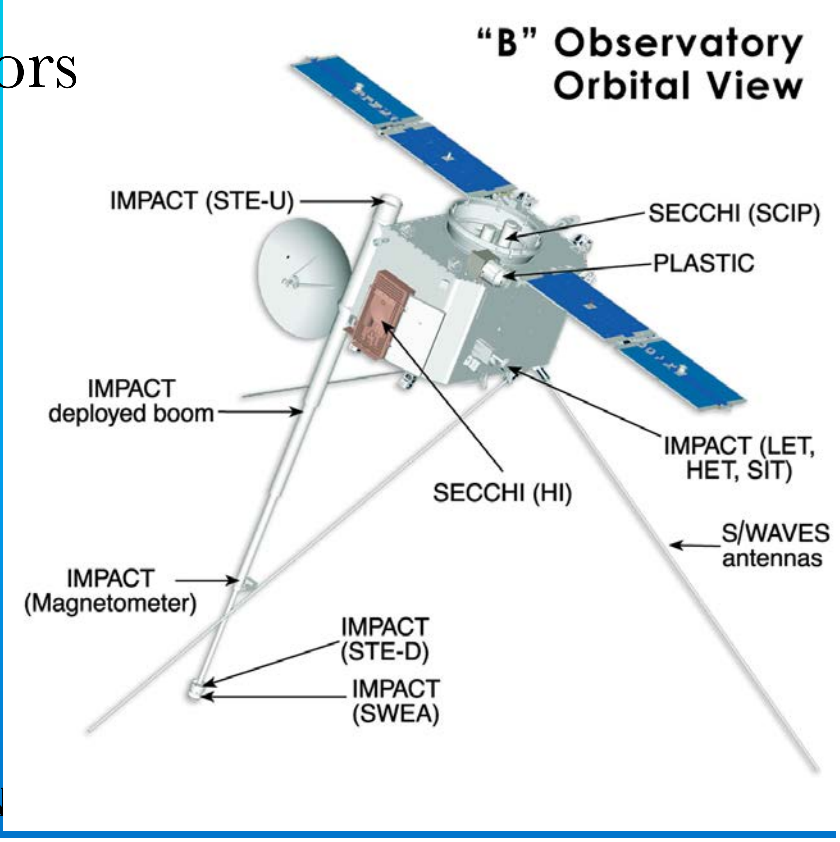
- Launches 25 October 2006
- Twin spacecraft
  - › Separate at 22.5°/year from Sun-Earth line

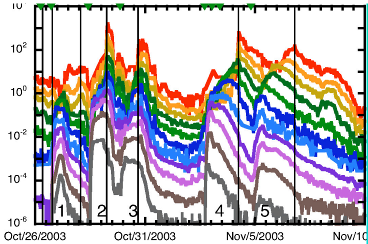




STEREO and 3D

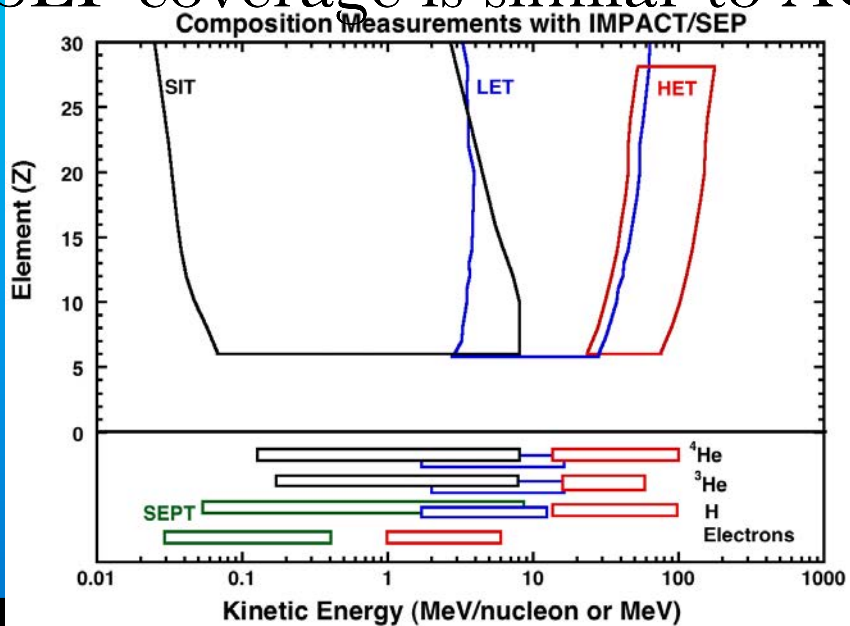
- Launches 25 October 2006
- Twin spacecraft
  - › Separate at 22.5°/year from Sun-Earth line
  - › Imaging, Particle, Fields sensors

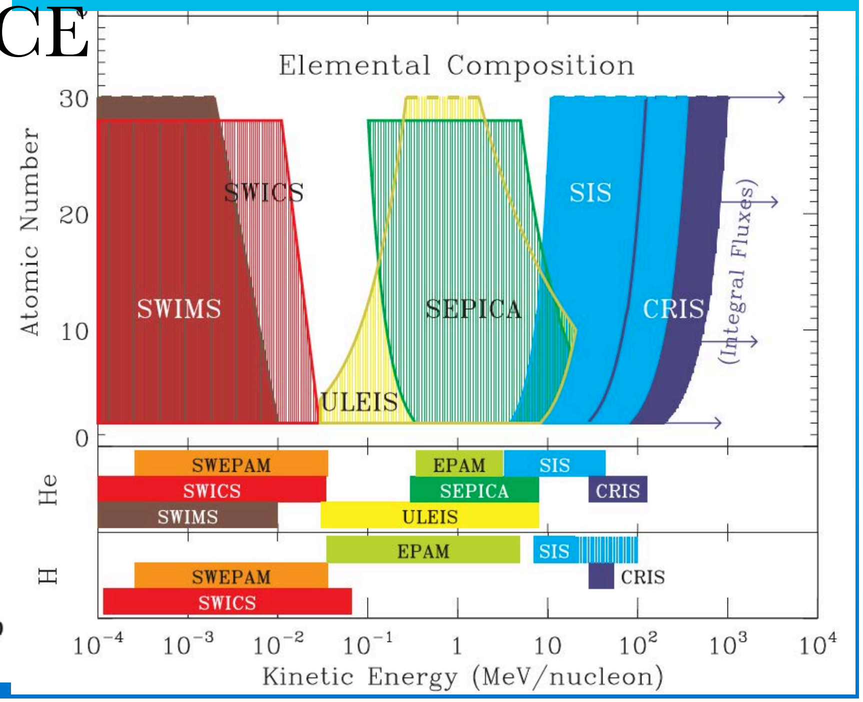


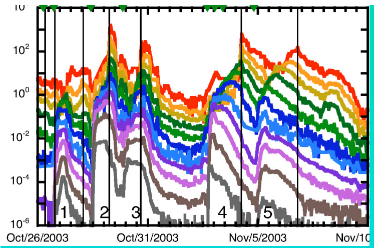


STEREO and 3D

- Launches 25 October 2006
- Twin spacecraft
  - Separate at 22.5°/year from Sun-Earth line
  - Imaging, Particle, Fields sensors
  - SEP coverage is similar to ACE

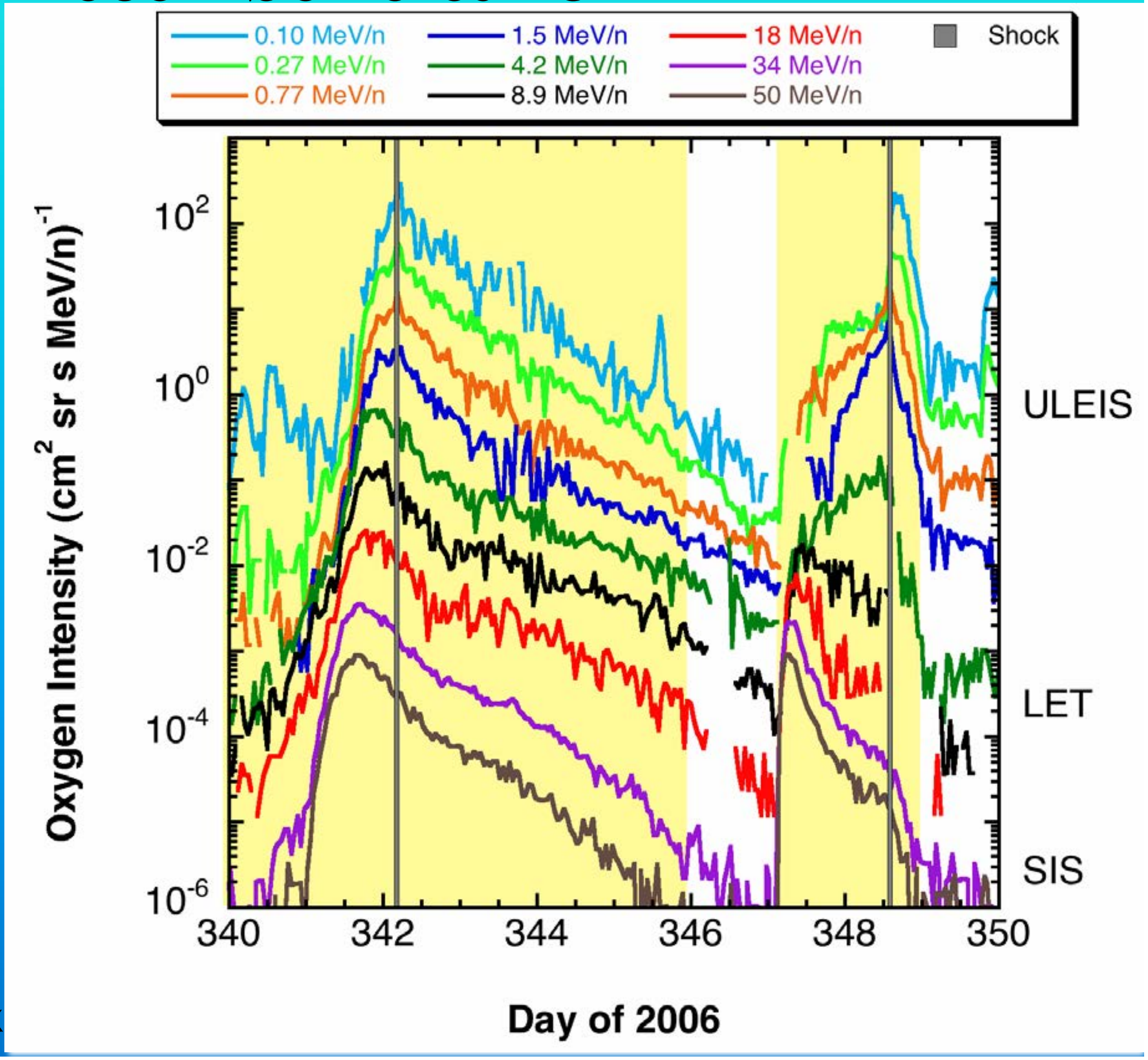




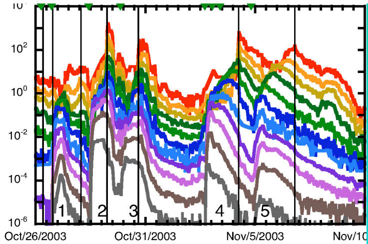


STEREO and 3D

- Large SEP events December 6 & 13

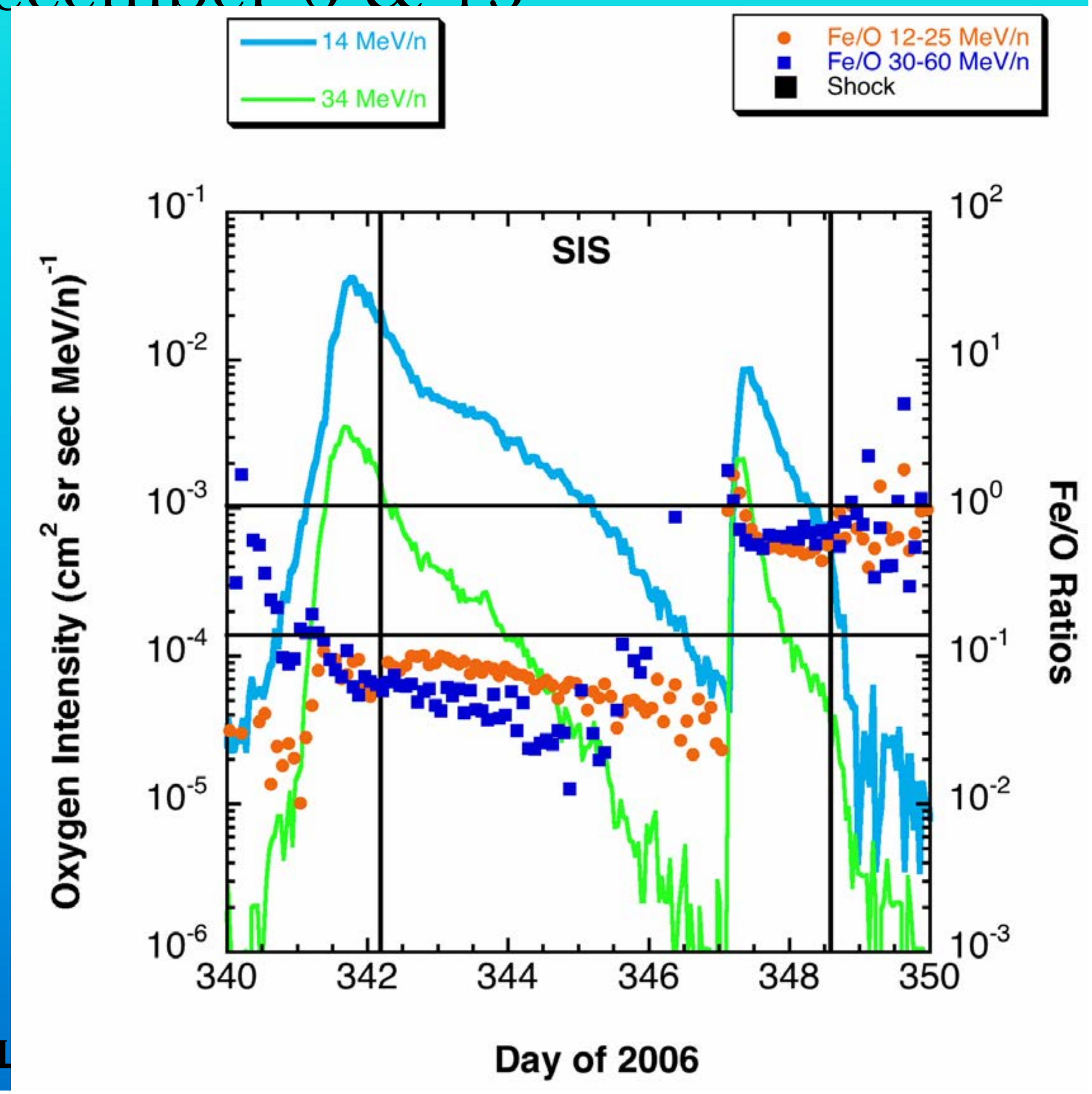


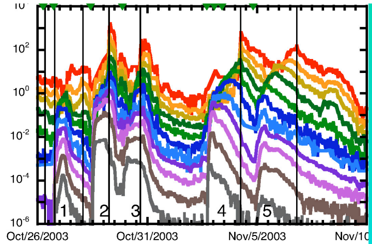
WHAT HISTORY AC



STEREO and 3D

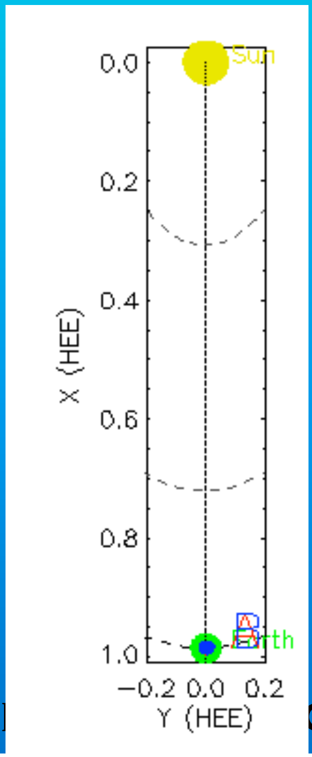
- Large SEP events December 6 & 13
  - › Second is Fe-rich

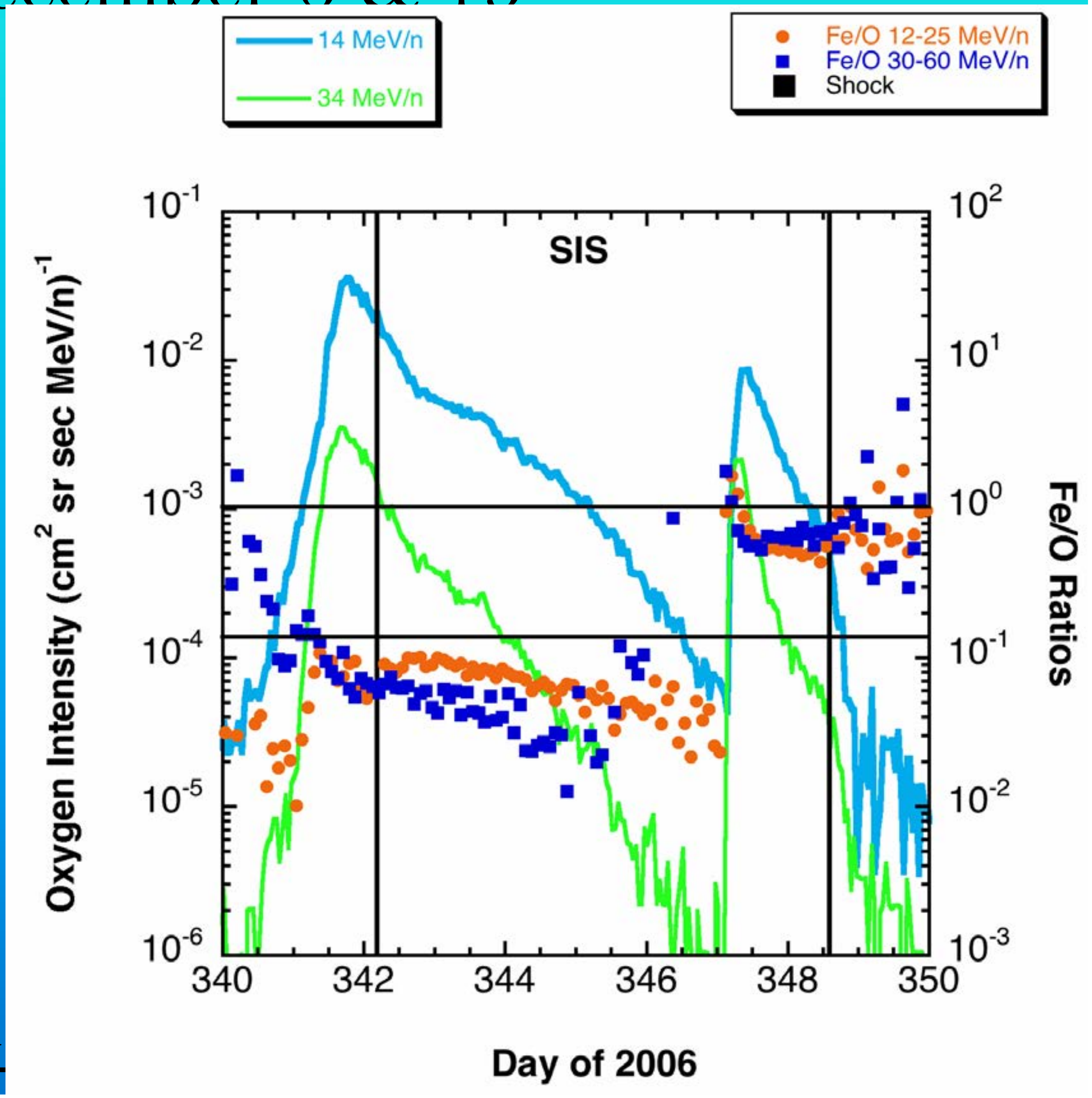


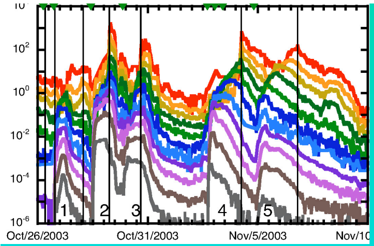


STEREO and 3D

- Large SEP events December 6 & 13
  - Second is Fe-rich
  - But no longitude separation yet

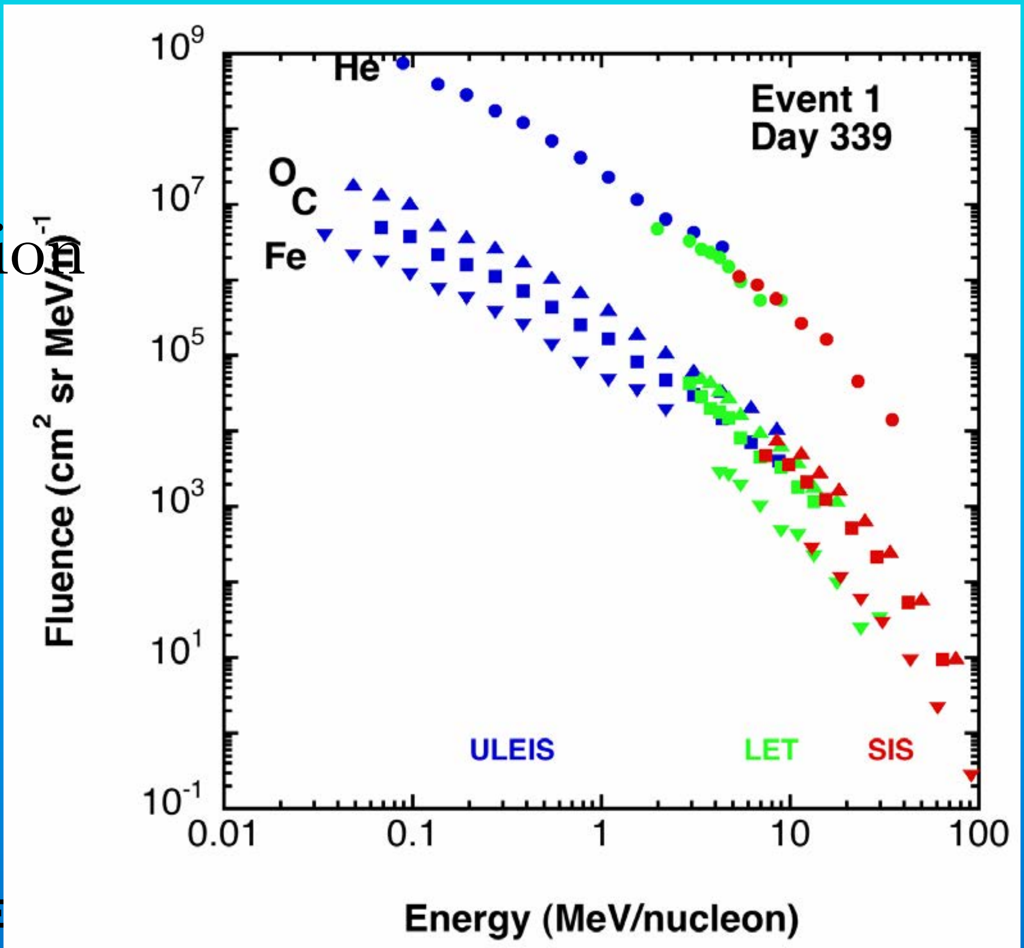


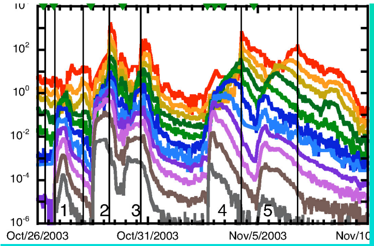




STEREO and 3D

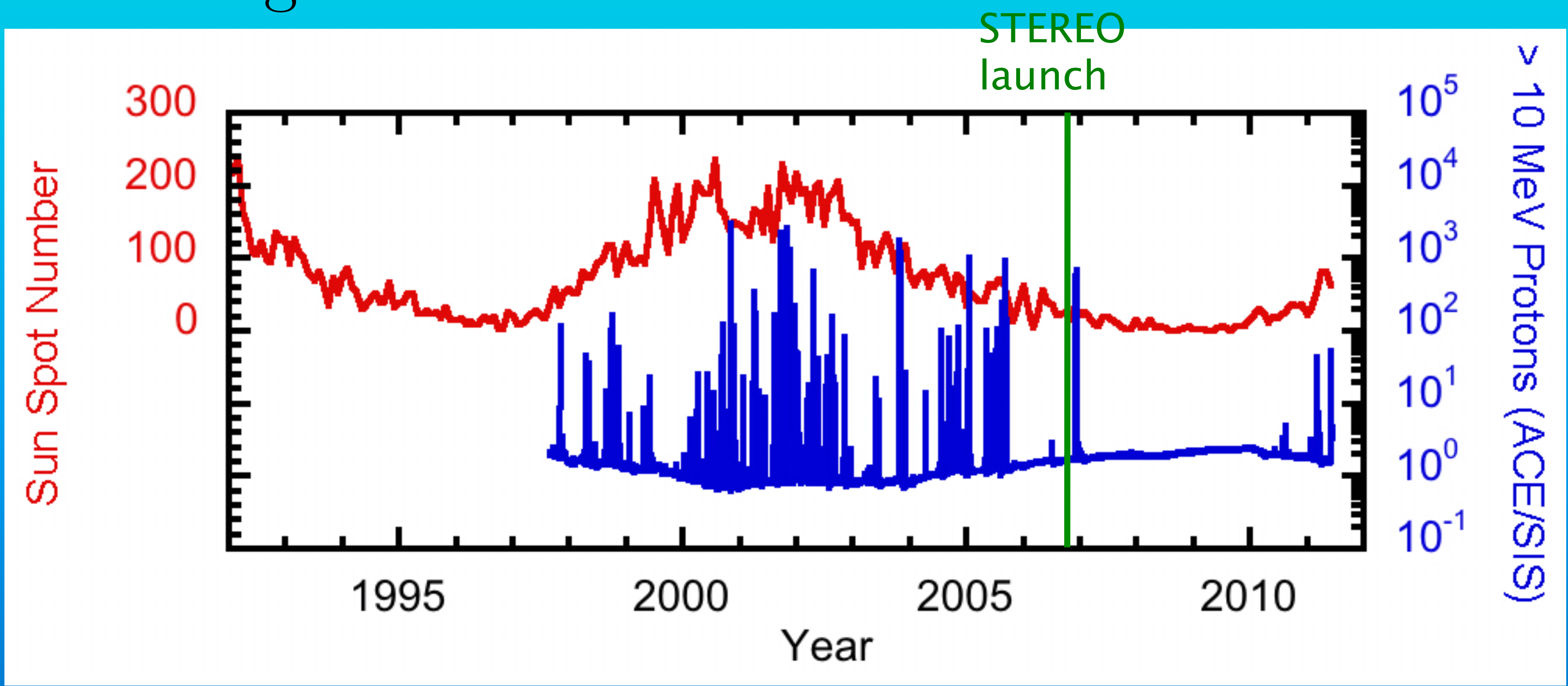
- Large SEP events December 6 & 13
  - › Second is Fe-rich
  - › But no longitude separation yet
  - › Allowed cross-calibration

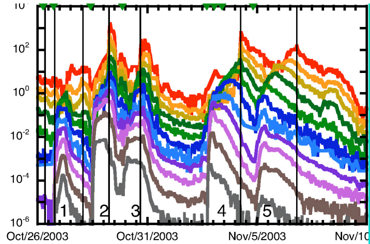




Solar Vacation

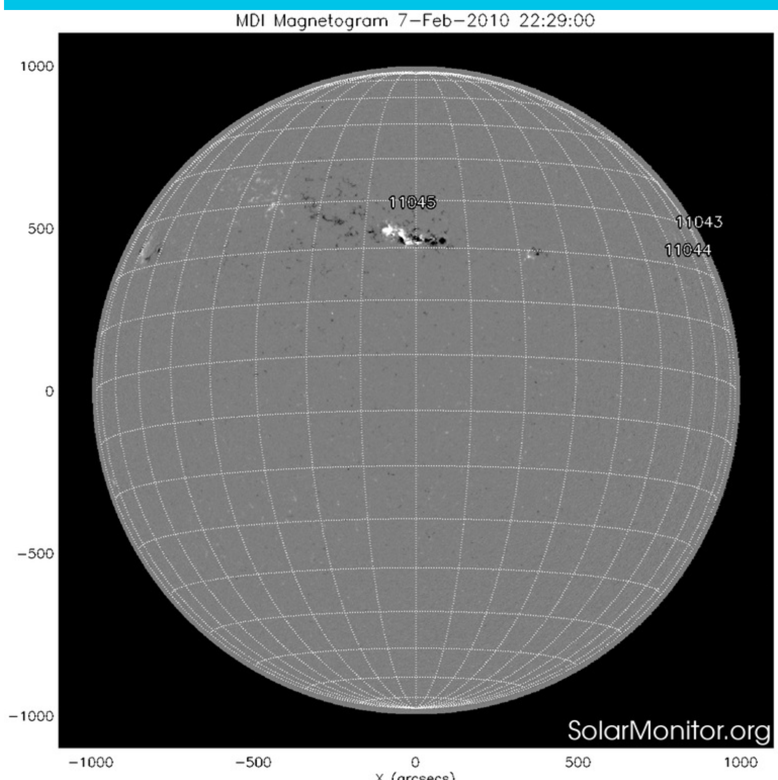
- December events are last large SEP events for years…
- Testing of Fe-rich scenarios will have to wait

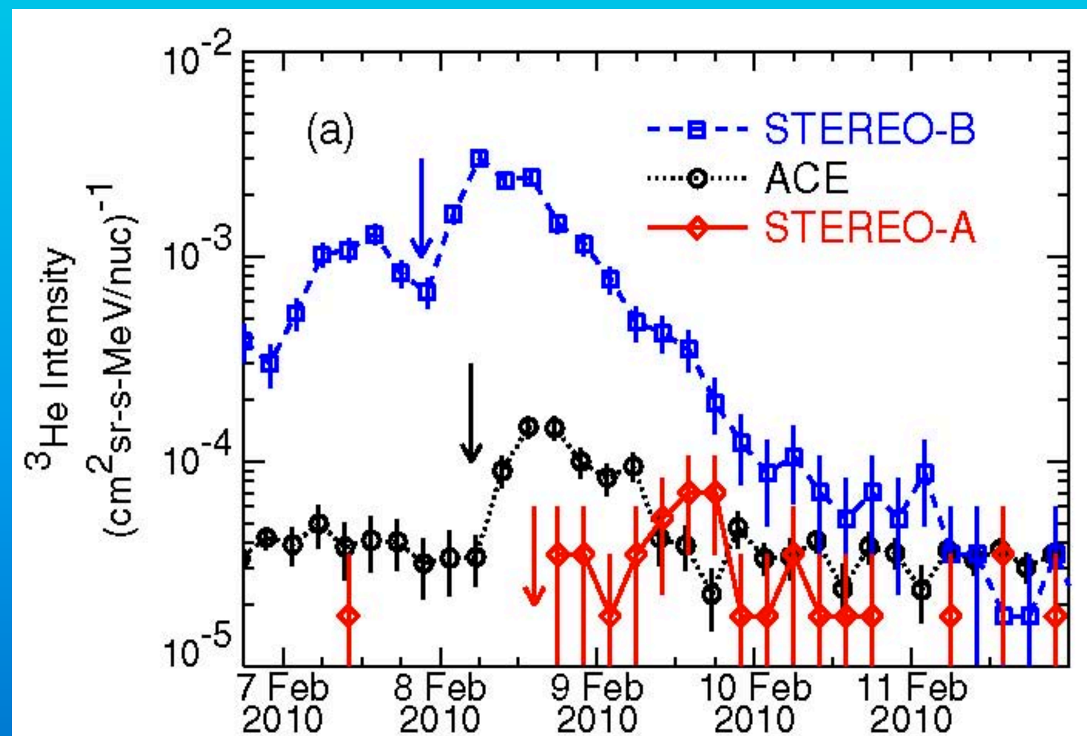


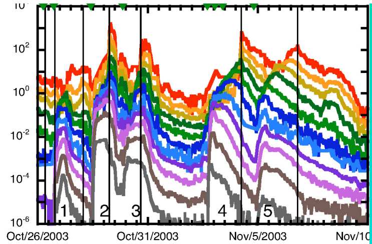


^{3}He-rich Events

- Some advantages to quiet conditions
  - Source regions easy to identify
  - ^{3}He-rich (impulsive) events seen by multiple s/c



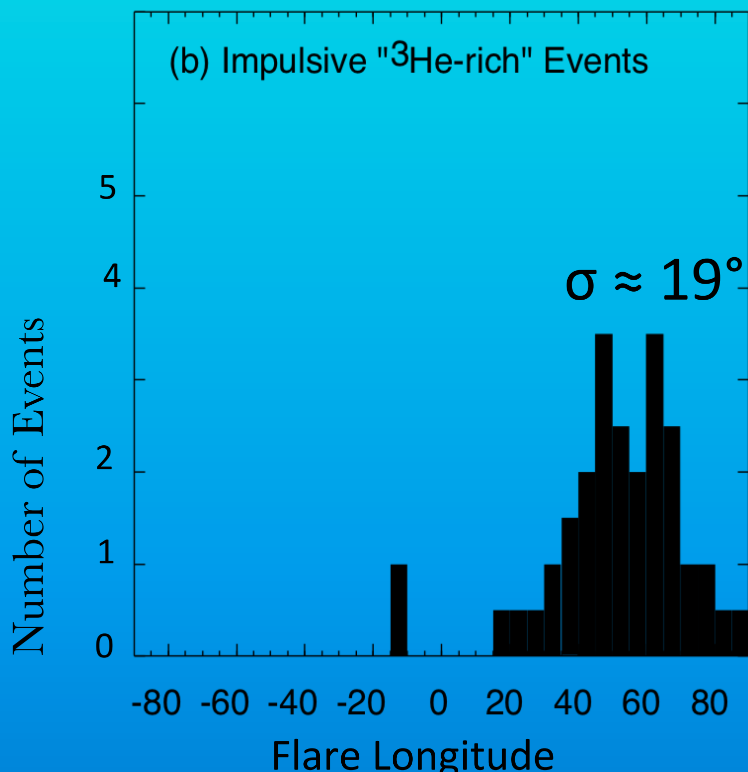




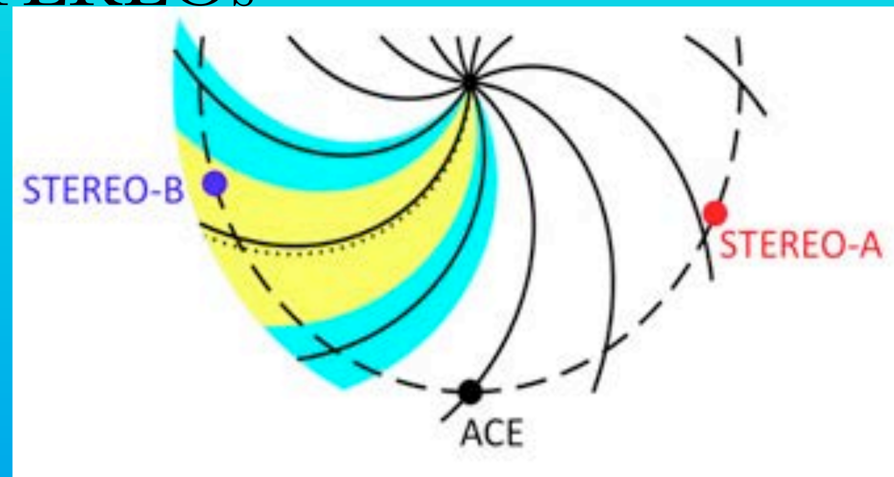
^{3}He-rich Events

- 7 February 2010 event
  - Seen by ACE and both STEREOs

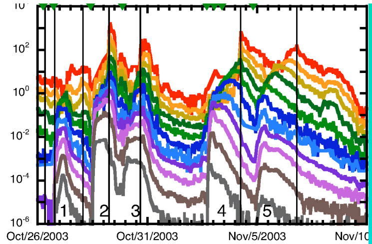
ISEE-3



Reames 1999

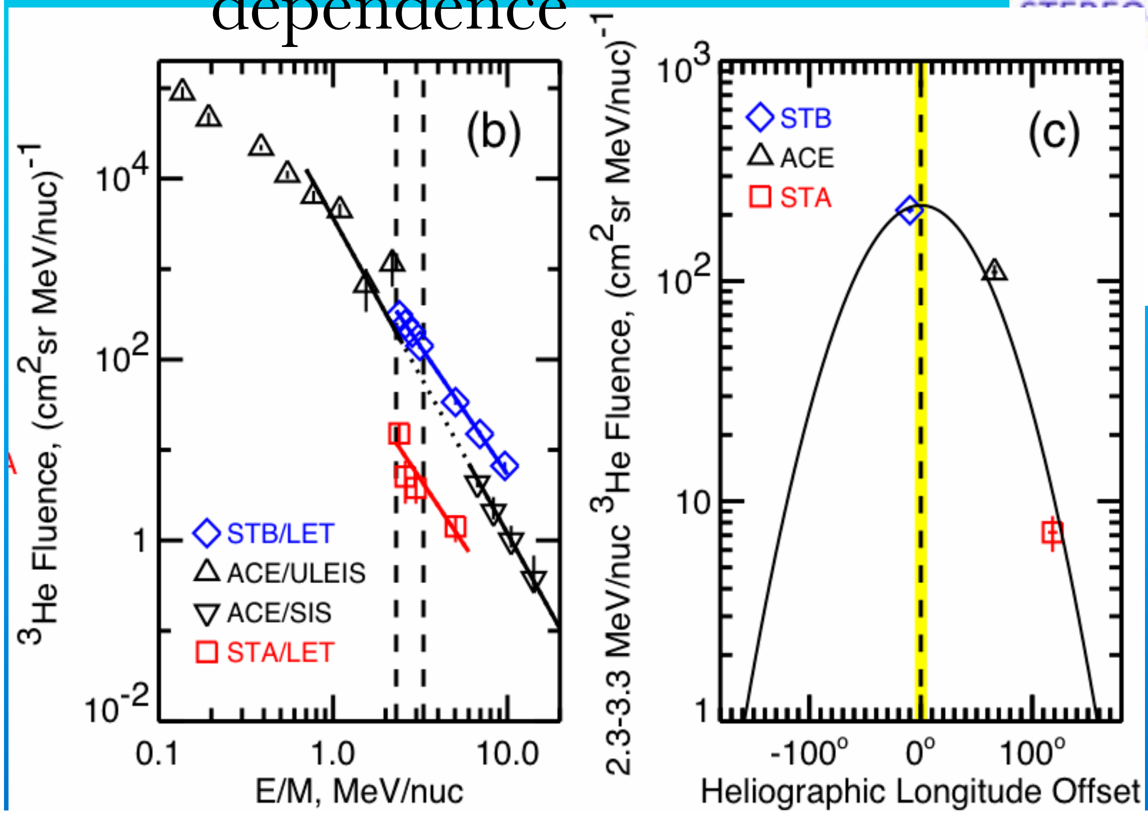


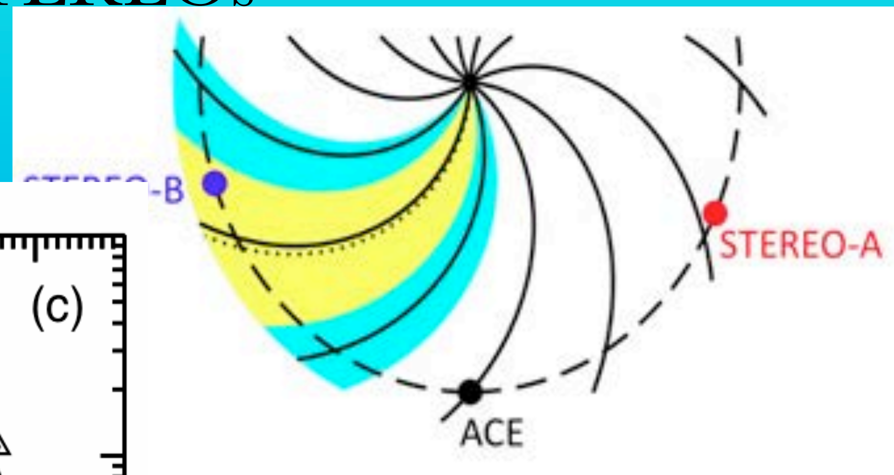
Spacecraft were 136˚ apart!



^{3}He-rich Events

- 7 February 2010 event
  - Seen by ACE and both STEREOs
  - Can examine longitude dependence

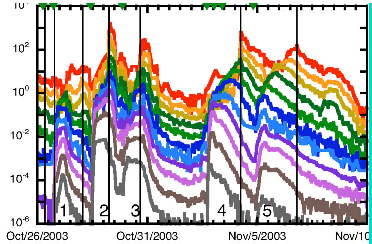




Spacecraft were 136˚ apart!

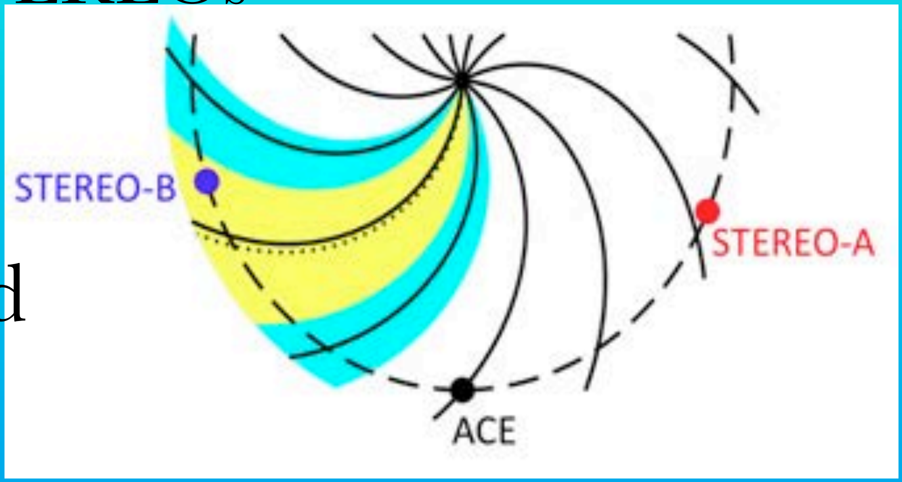
σ ≈ 48°

Problems 3D Next

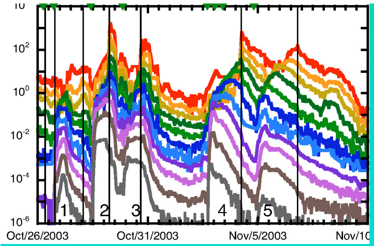


^{3}He-rich Events

- 7 February 2010 event
  - › Seen by ACE and both STEREOs
  - › Can examine longitude dependence
- Unexpectedly wide spread
  - › Possible impact on Fe-rich event explanations
  - › How/when does this happen?

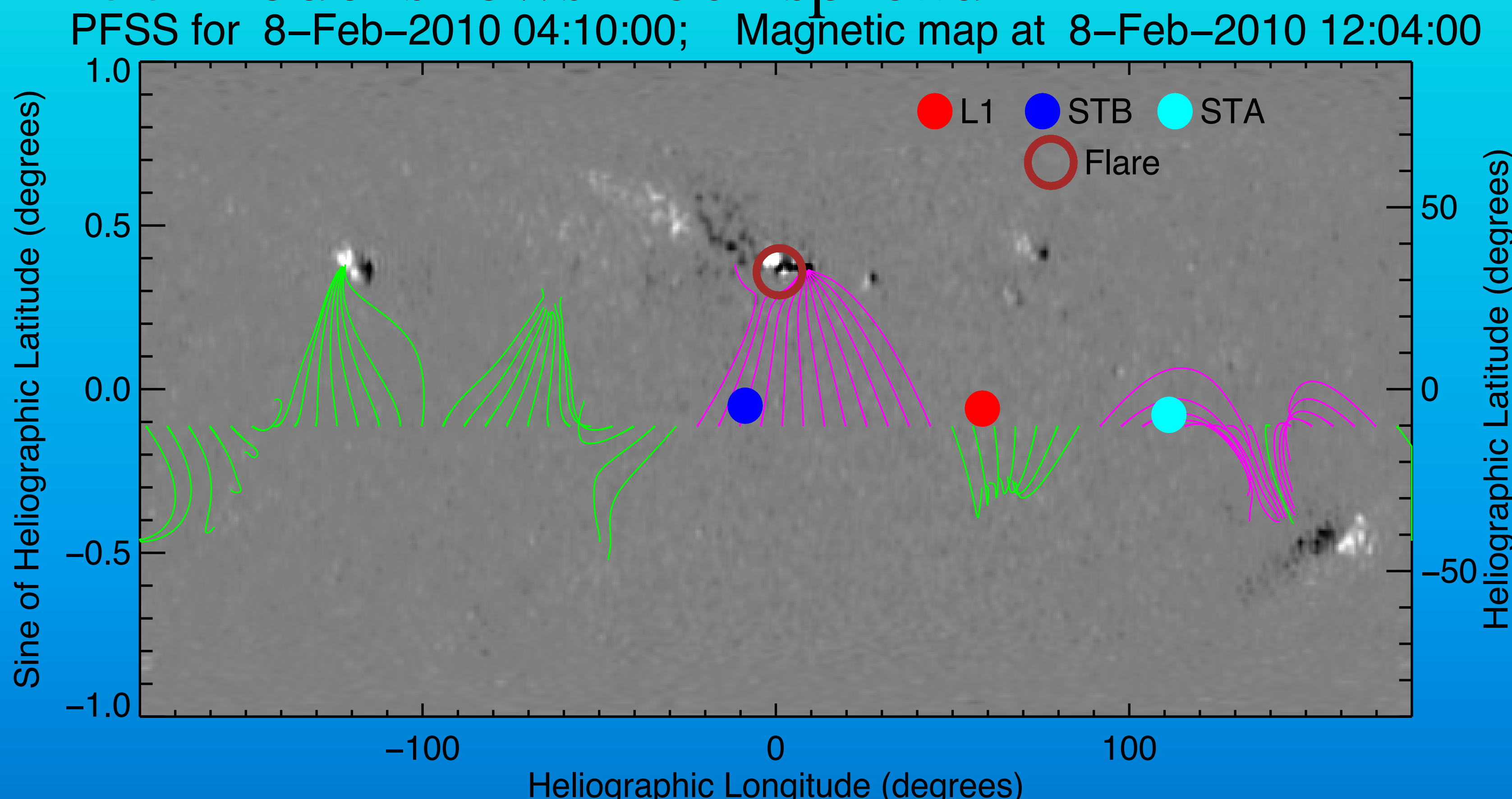


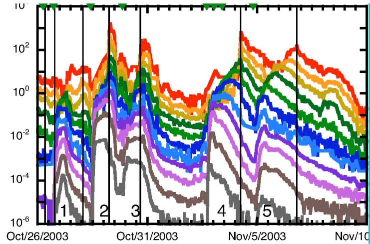
Spacecraft were 136˚ apart!



^{3}He-rich Events

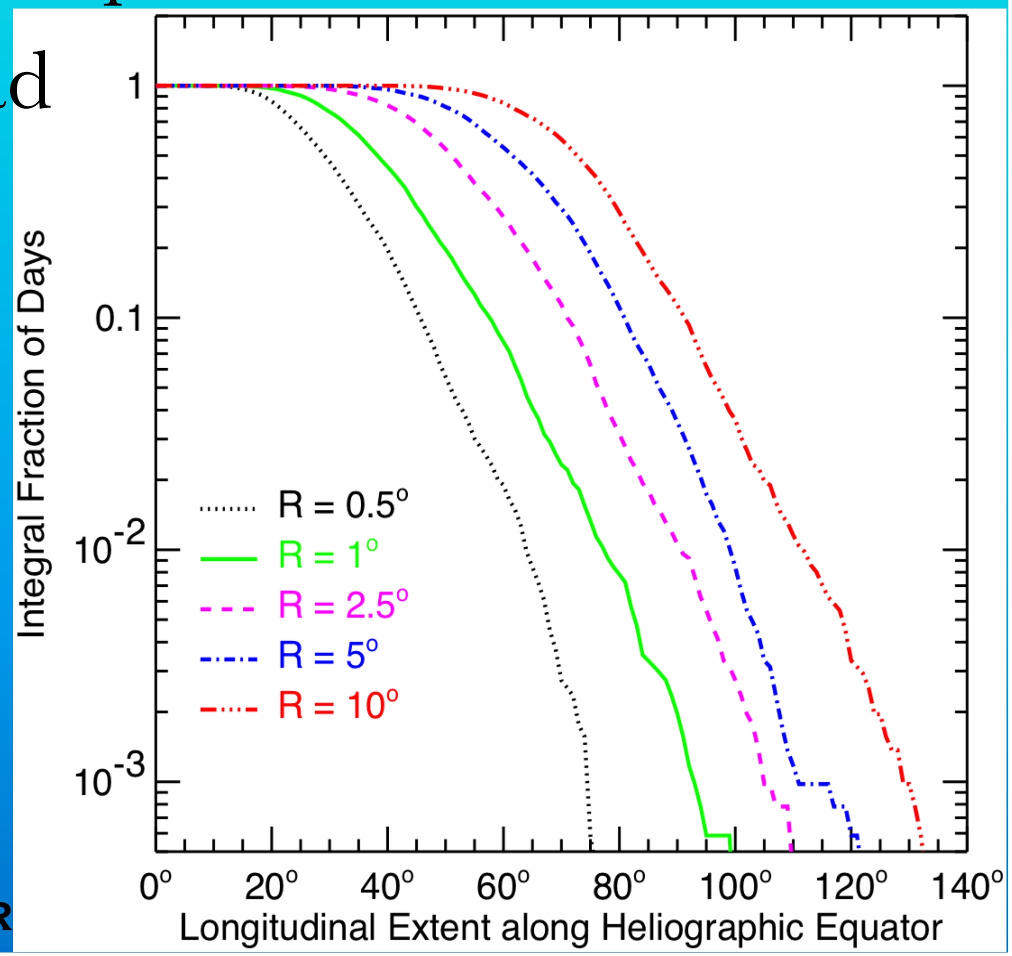
- Field line spreading at the Sun?
- PFSS model shows ~60° spread

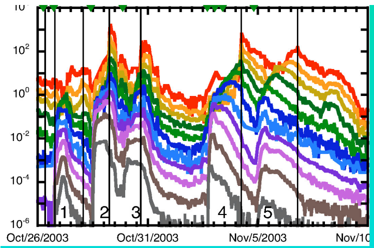




^{3}He-rich Events

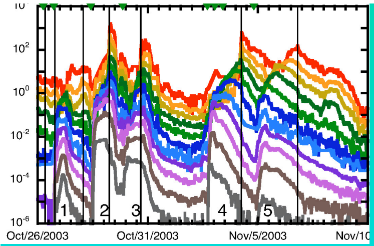
- Field line spreading at the Sun?
- PFSS model shows ~60° spread
- Rarely get >120° spread





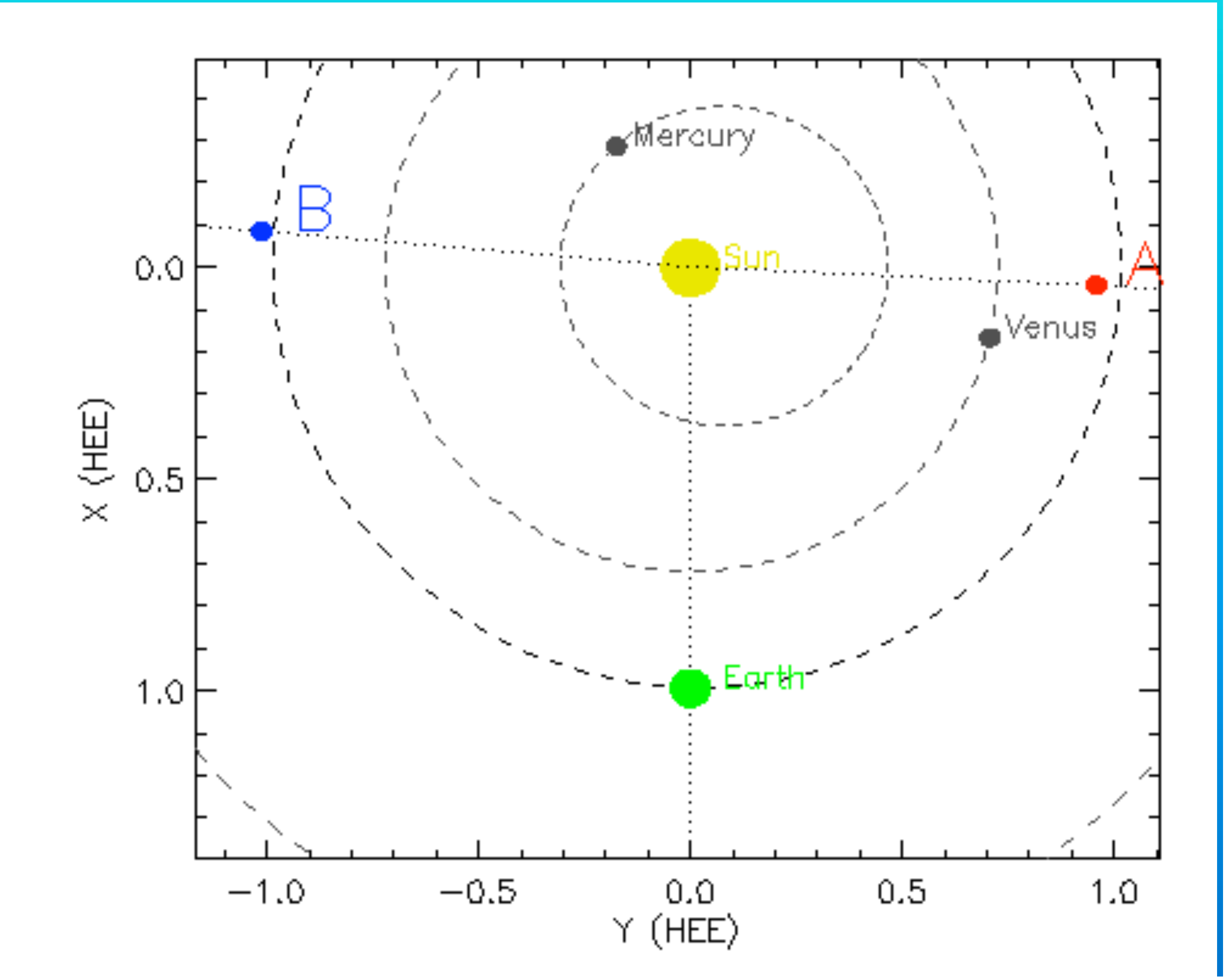
Possible Explanations

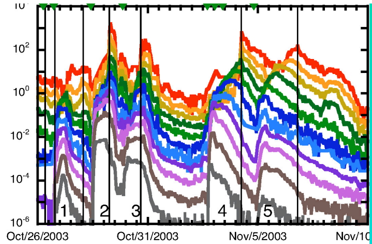
- Solar
  - › Sympathetic flaring/multiple sources
  - › Coronal transport
  - › Field line spreading via complex reconnection
- Interplanetary
  - › Field line meandering
  - › Co-rotation
  - › CME disruption of Parker spiral



Backside Events

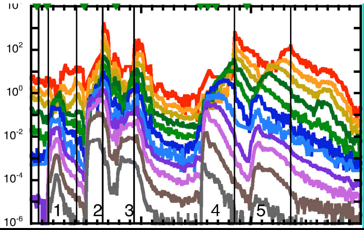
- After early 2011 STEREO provides full view of the Sun



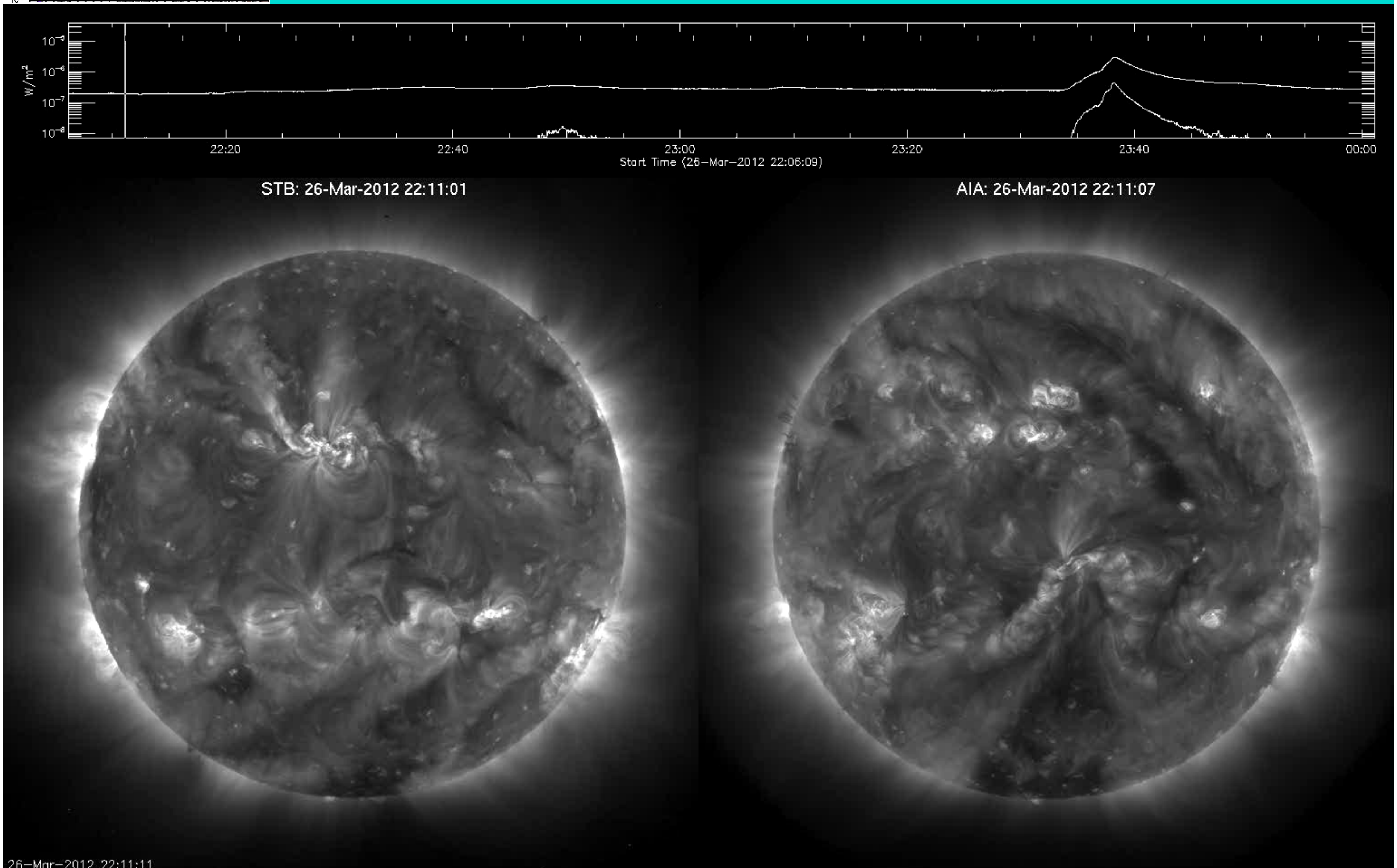


Backside Events

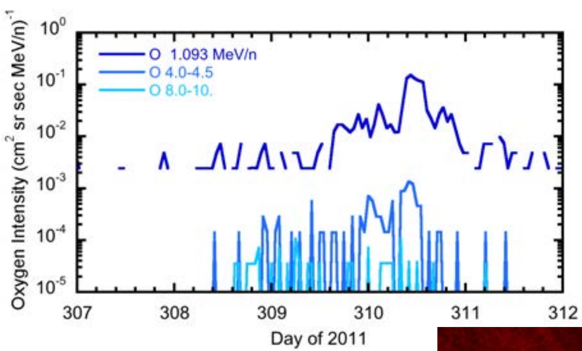
- After early 2011 STEREO provides full view of the Sun
- Allows source region to always be found

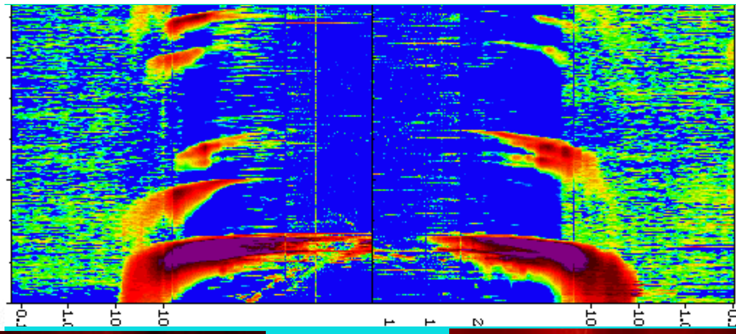


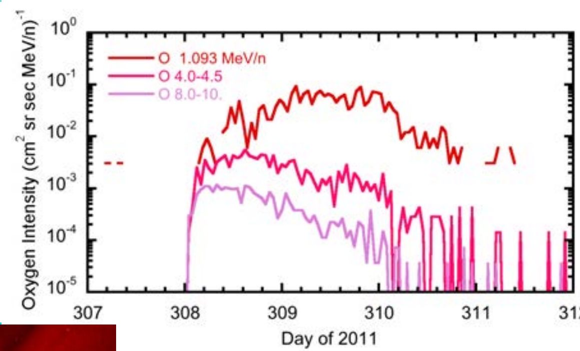
Backside Events

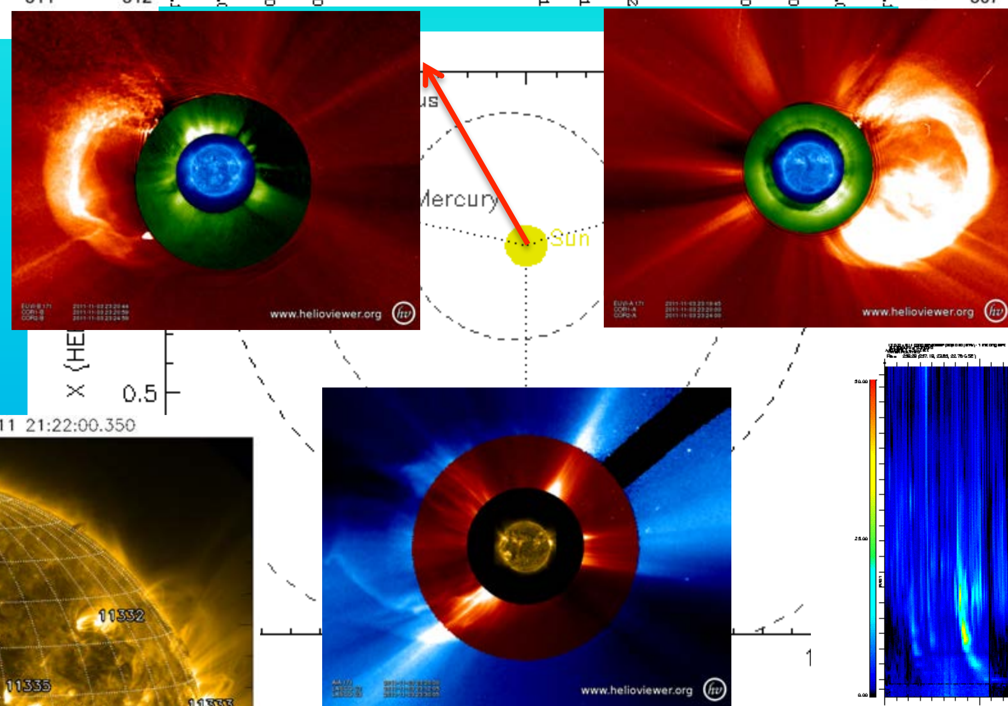


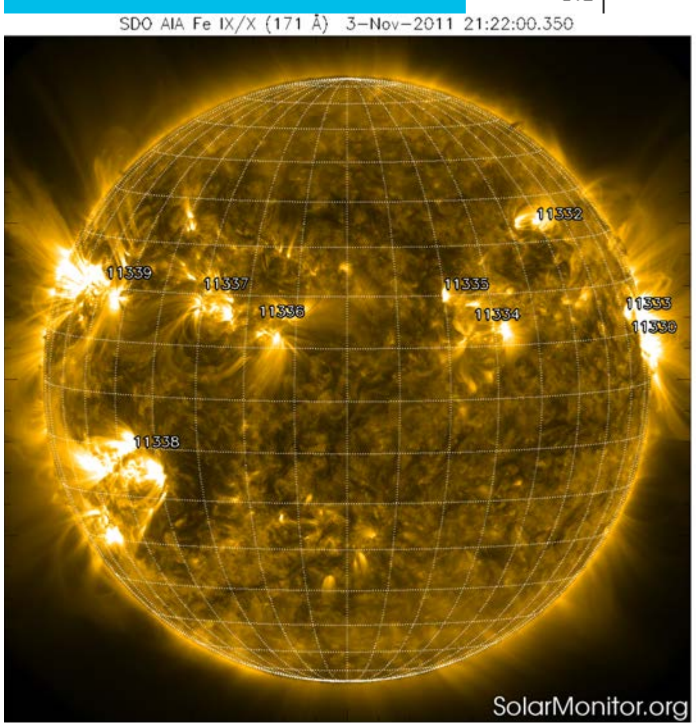
4 NOV 2011

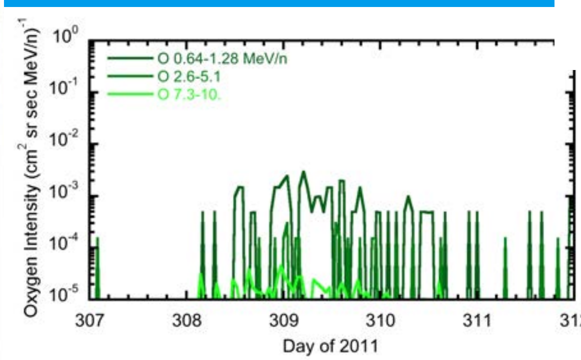

Oxygen Intensity (cm^2 sr sec MeV/n)$^{-1}$
O 1.093 MeV/n
O 4.0-4.5
O 8.0-10.
Day of 2011

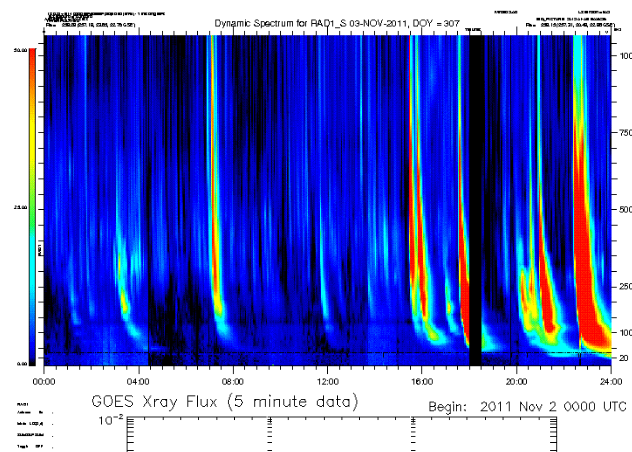


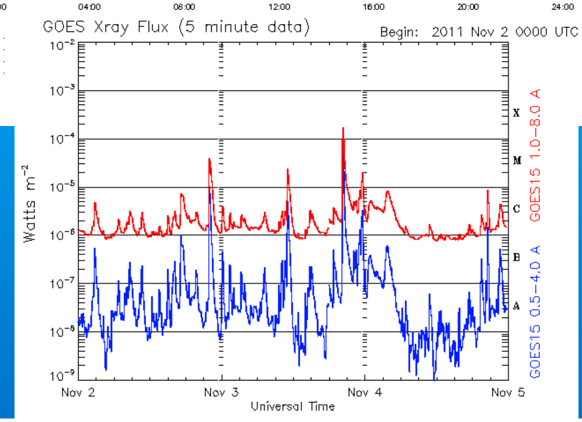

Oxygen Intensity (cm^2 sr sec MeV/n)$^{-1}$
O 1.093 MeV/n
O 4.0-4.5
O 8.0-10.
Day of 2011


Mercury
Sun
www.helioviewer.org

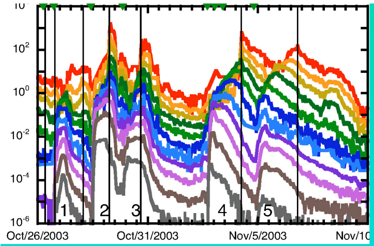

SDO AIA Fe IX/X (171 Å) 3-Nov-2011 21:22:00.350
11332
11339
11337
11335
11336
11334
11333
11330
11338
SolarMonitor.org


Oxygen Intensity (cm^2 sr sec MeV/n)$^{-1}$
O 0.64-1.28 MeV/n
O 2.6-5.1
O 7.3-10.
Day of 2011

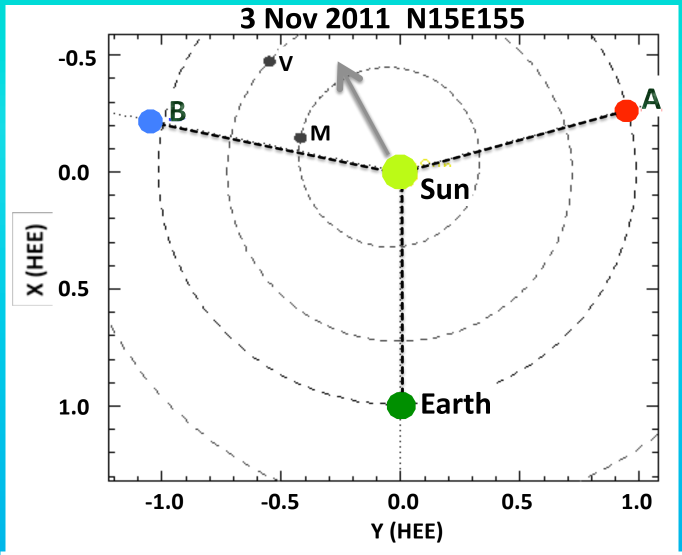

Dynamic Spectrum for RAD1_S 03-NOV-2011, DOY = 307

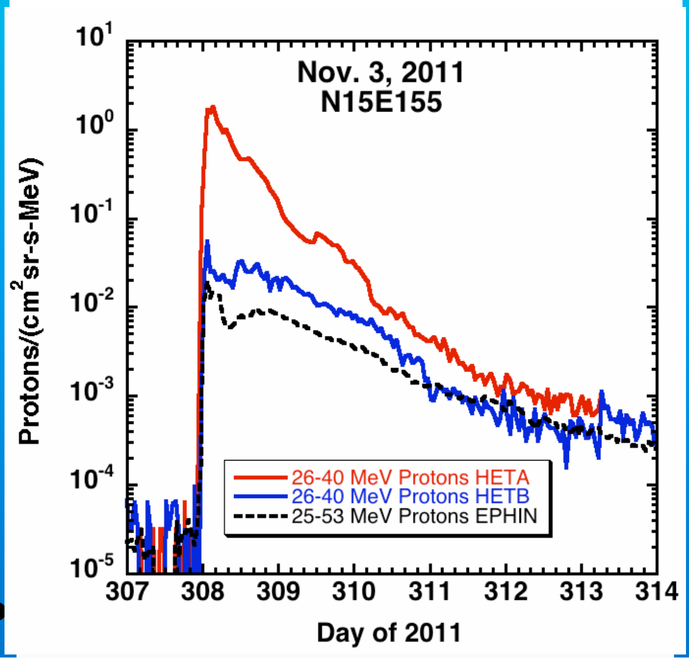

GOES Xray Flux (5 minute data)
Begin: 2011 Nov 2 0000 UTC
Watts m^{-2}
GOES15 1.0–8.0 A
GOES15 0.5–4.0 A
Nov 2
Nov 3
Nov 4
Nov 5
Universal Time

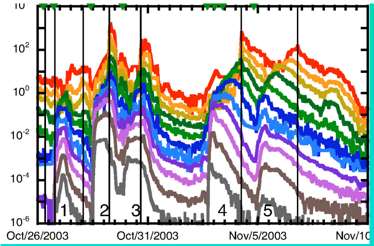
Backside Events



- After early 2011 STEREO provides full view of the Sun
- Allows source region to always be found
- Even far removed source regions can yield fast rise times

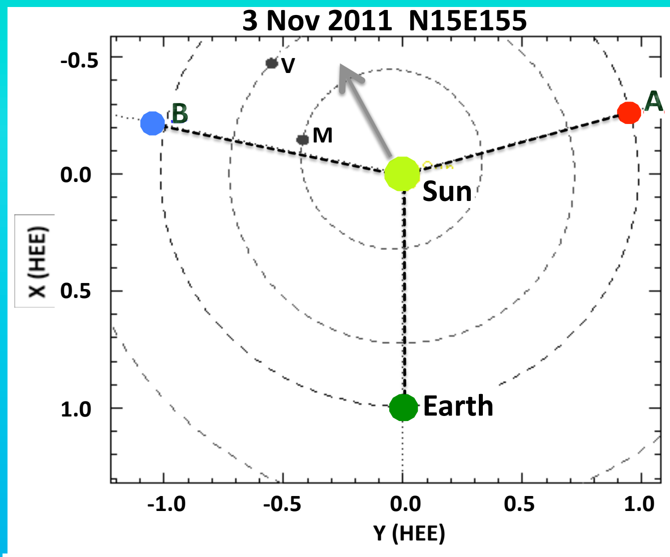


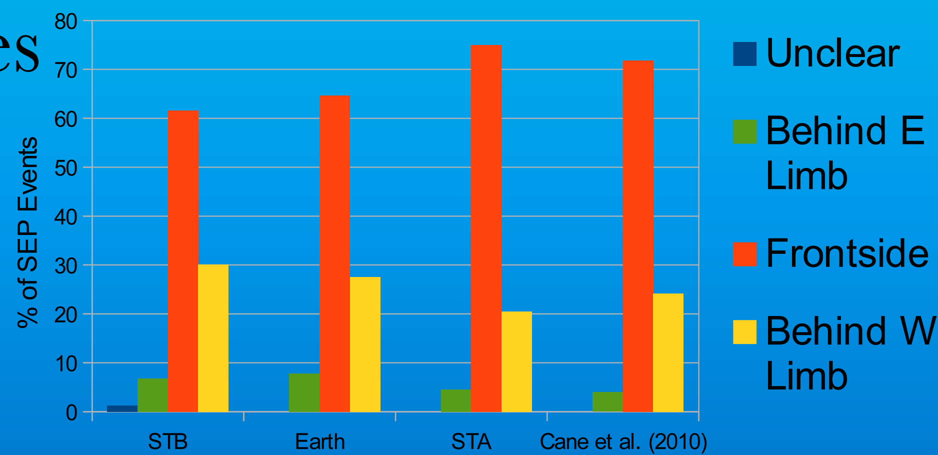


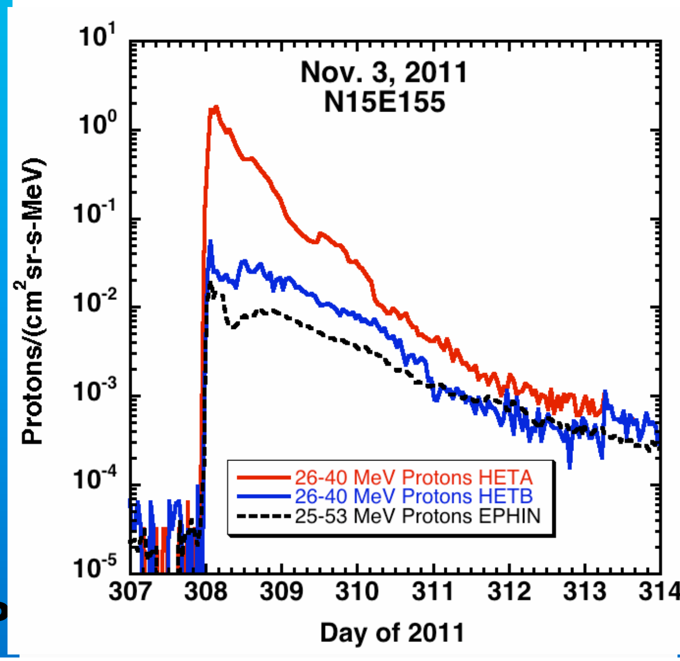


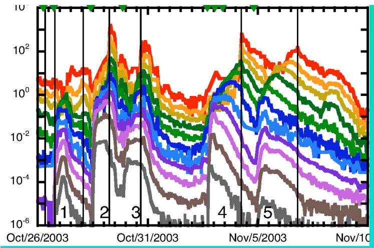
Backside Events

- After early 2011 STEREO provides full view of the Sun
- Allows source region to always be found
- Even far removed source regions can yield fast rise times



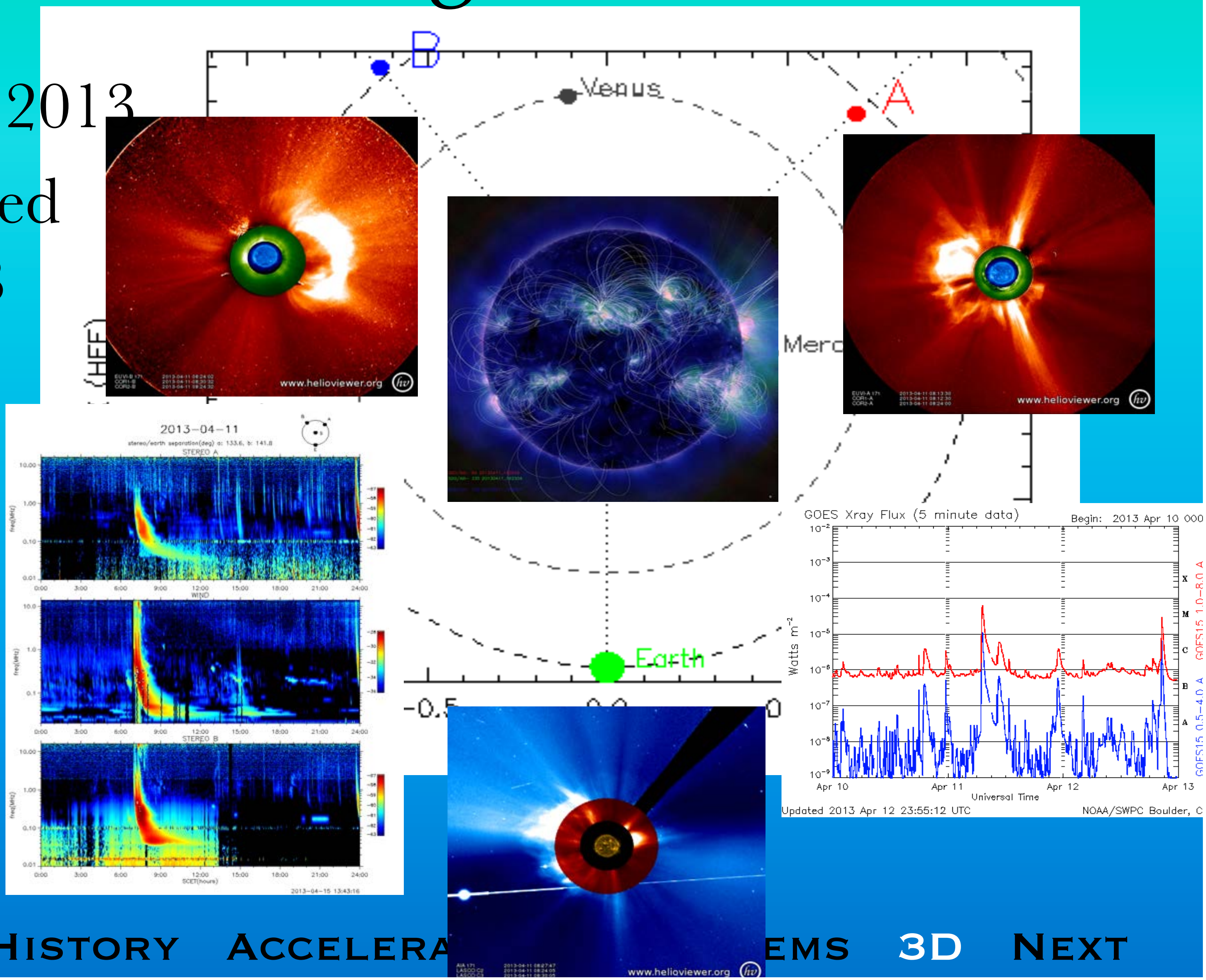


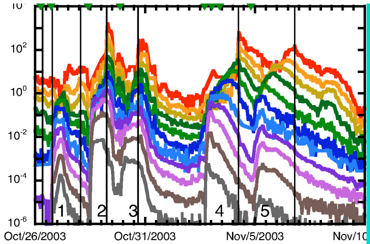




Testing Fe-rich Scenarios

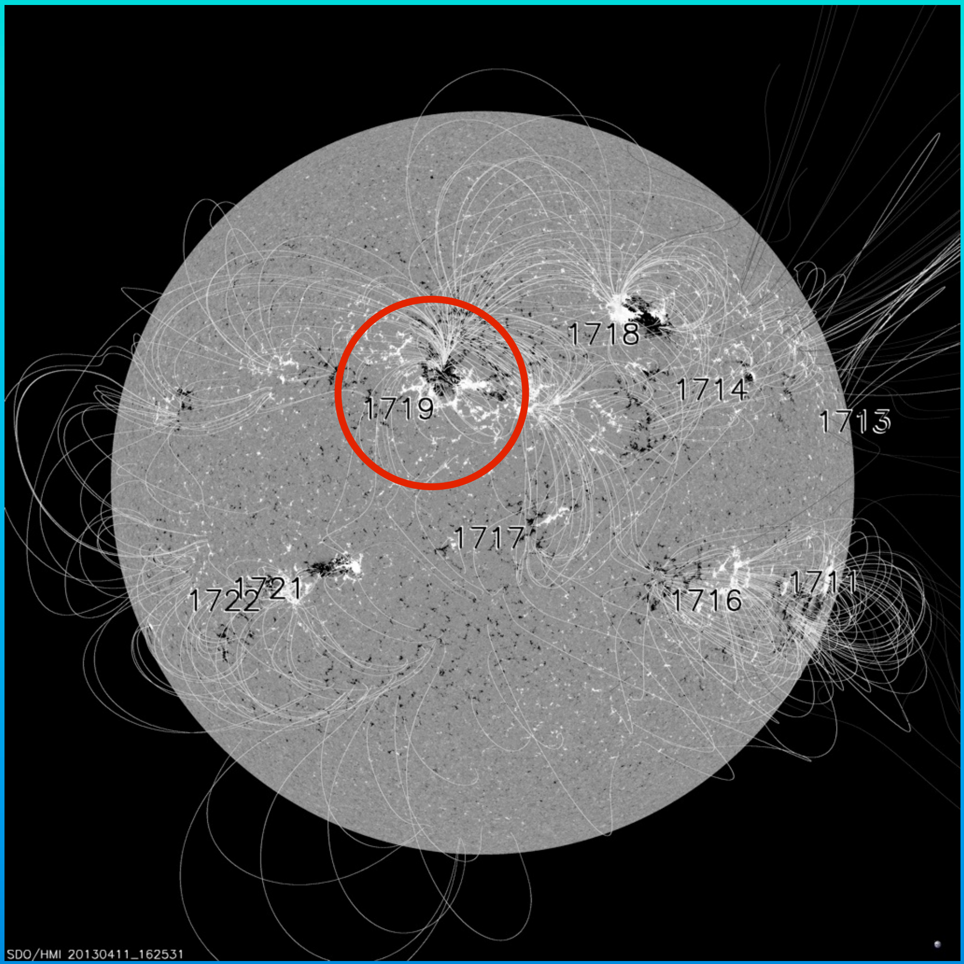
- 11 Apr 2013
- Observed by STB & ACE

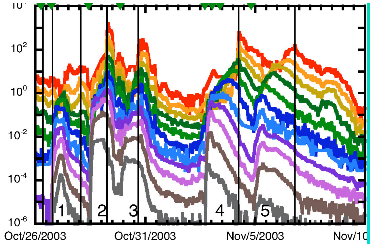




Testing Fe-rich Scenarios

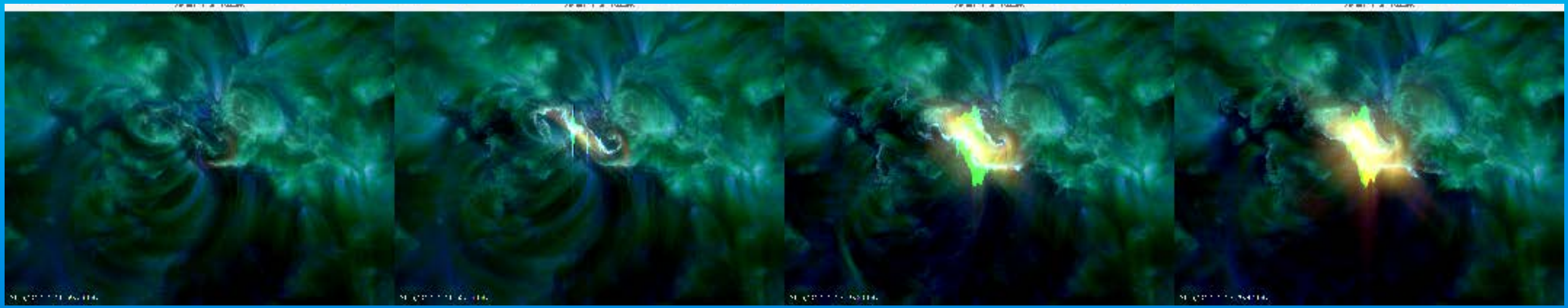
- Active Region 11719
  - › N07E13

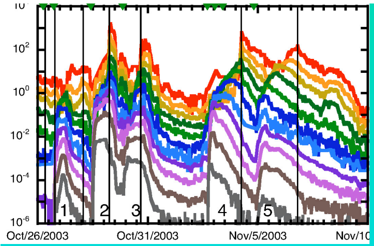




Testing Fe-rich Scenarios

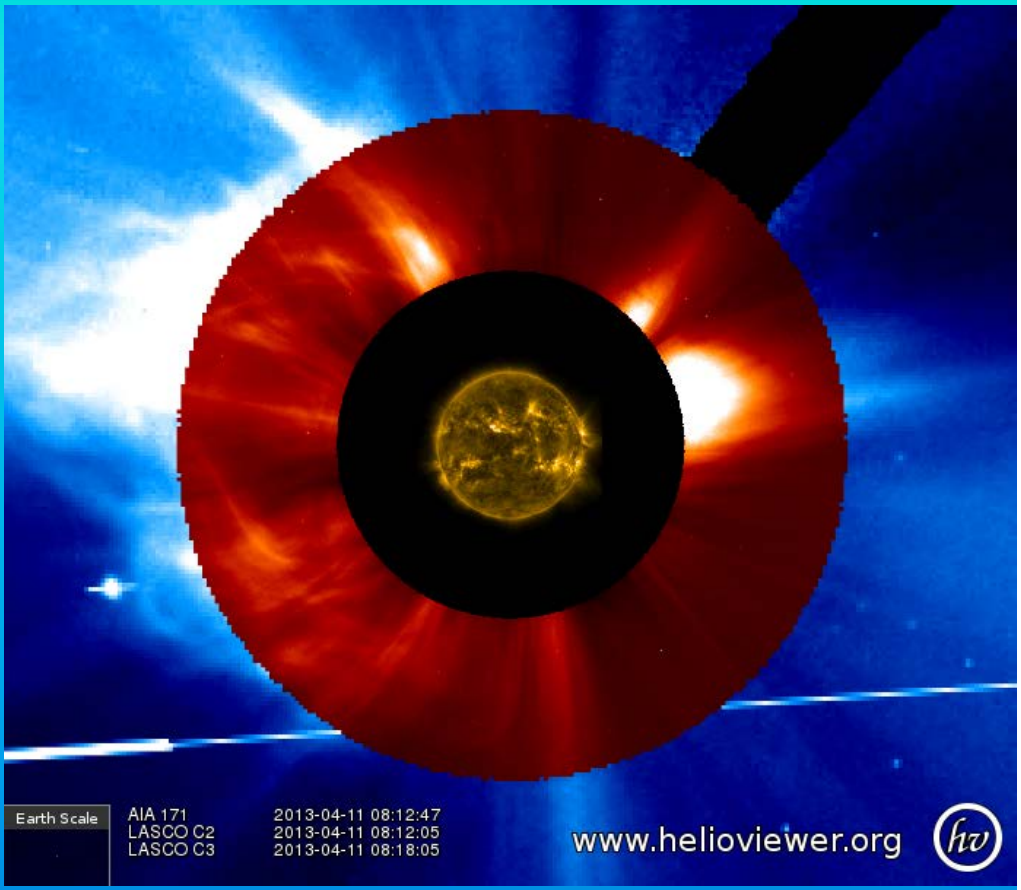
- Active Region 11719
  - N07E13
- Flare
  - M6.5
  - 0713 (11 April 2013)

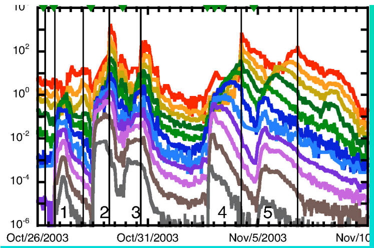




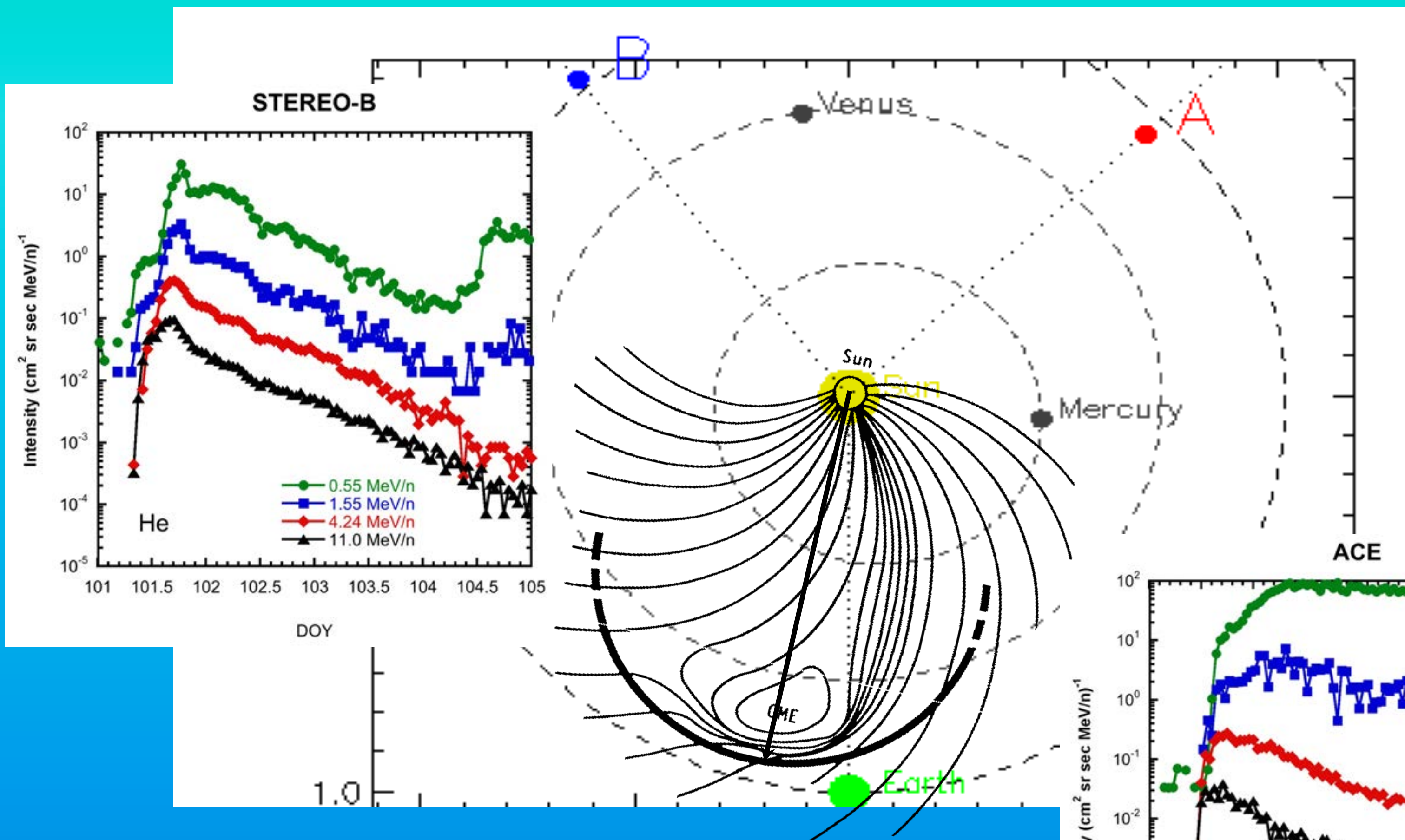
Testing Fe-rich Scenarios

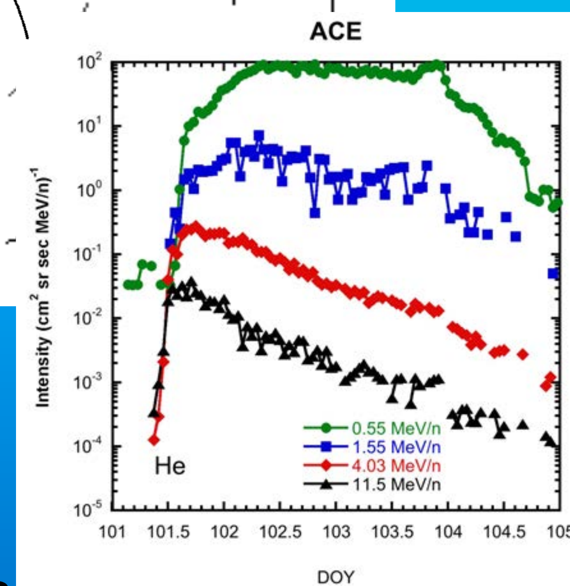
- Active Region 11719
  - › N07E13
- Flare
  - › M6.5
  - › 0713 (11 April 2013)
- CME
  - › ~900 km/s
  - › ~160°



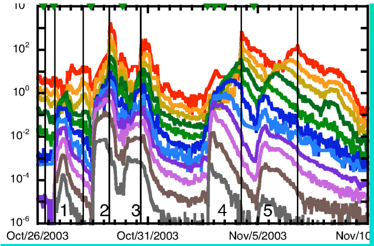


Testing Fe-rich Scenarios



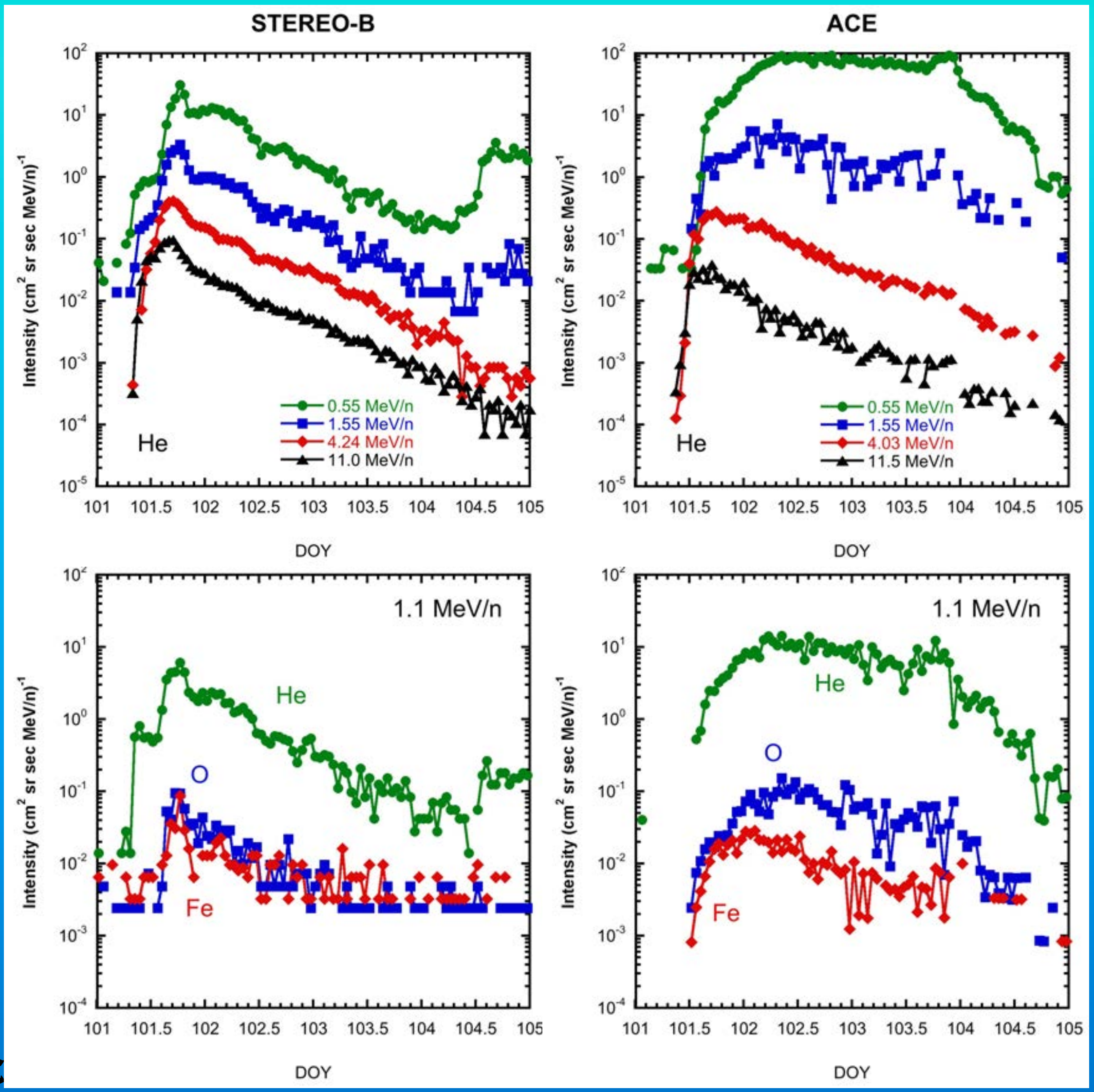


- 142° separation between ACE & STB

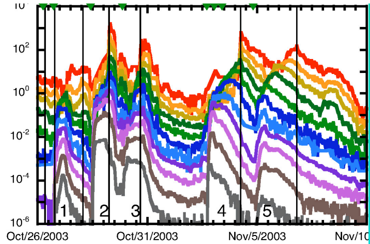


Testing Fe-rich Scenarios

- Observed by ACE and STB in heavies
  - › region was over the west limb for STB
  - › fast rise at both spacecraft
- Different O and Fe profiles/ composition

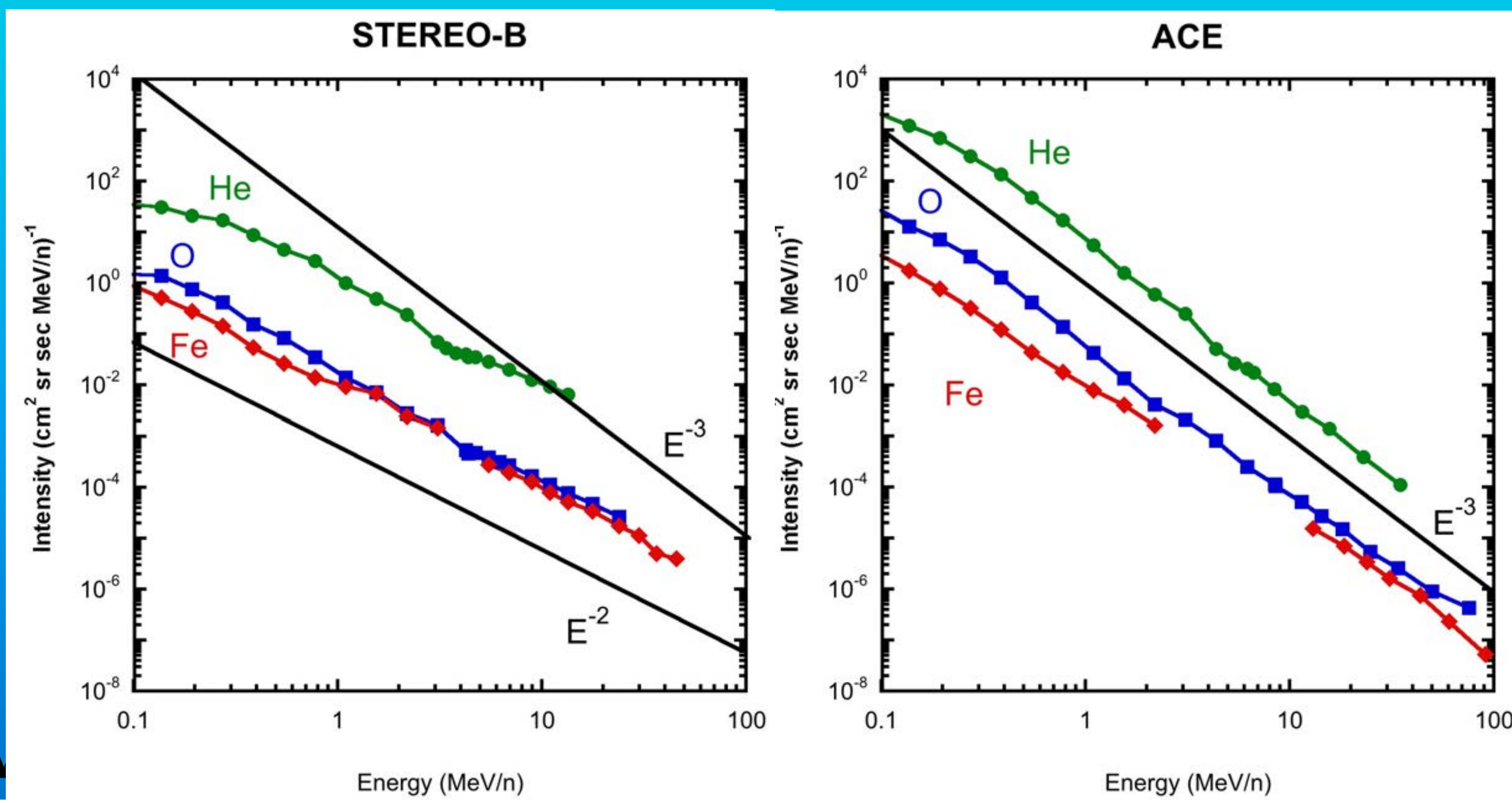


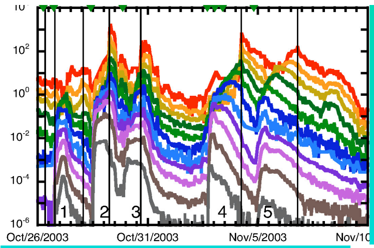
WHAT HISTORY ACC



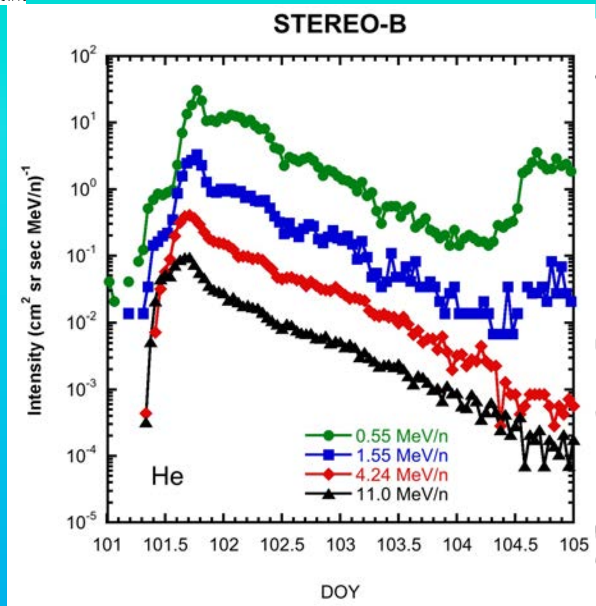
Testing Fe-rich Scenarios

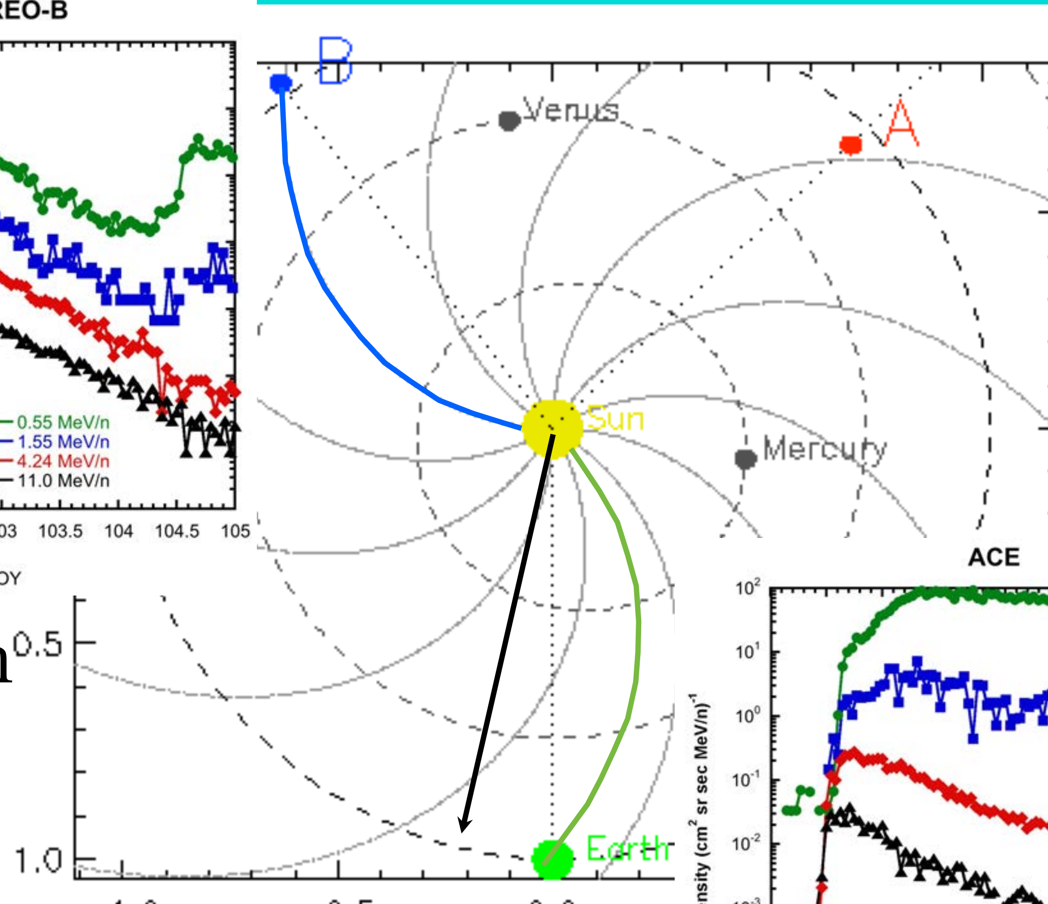
- Event integrated spectra show differences
  - › STB has harder spectra, ~E^{-2} and more Fe-rich
  - › ACE has spectra closer to E^{-3} but still Fe-enhanced

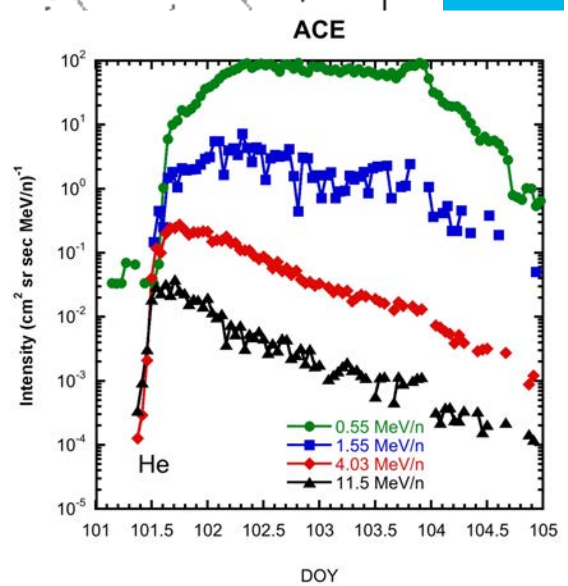




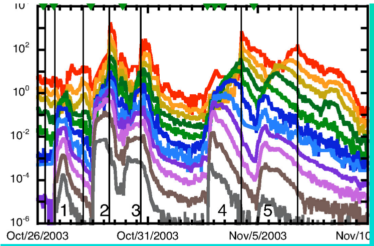
Testing Fe-rich Scenarios





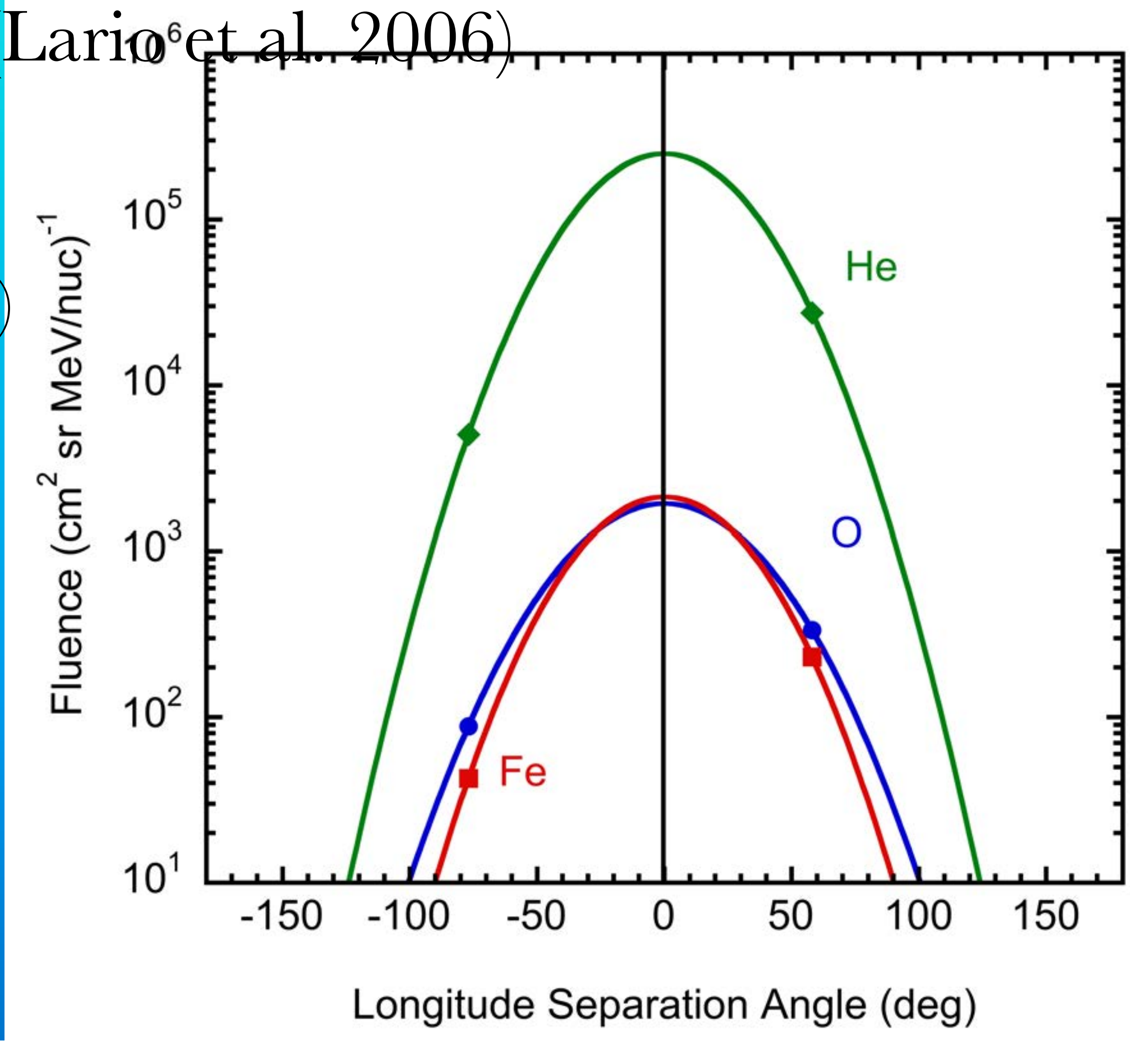


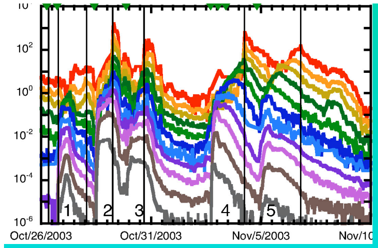
- Footpoints are on either side (E13)
  - E77° vs W58°
  - Neither is directly connected to flare



Testing Fe-rich Scenarios

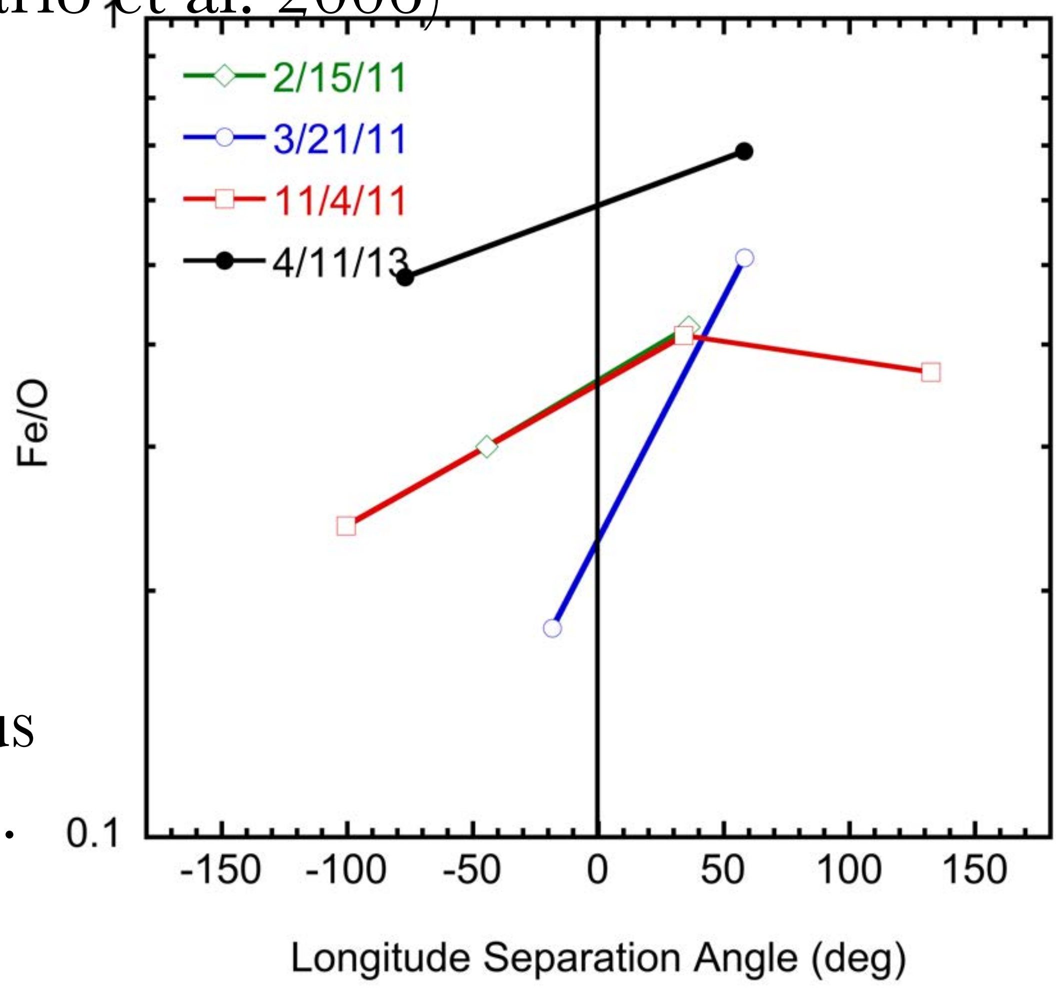
- Longitude dependence
  - › Fitting a Gaussian (Lario et al. 2006)
    - σ = 27°, 31°, 28°
    - Narrower than typical (σ = 45-50°)
    - Suggests Fe/O~1 at flare connection

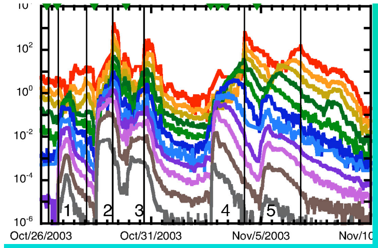




Testing Fe-rich Scenarios

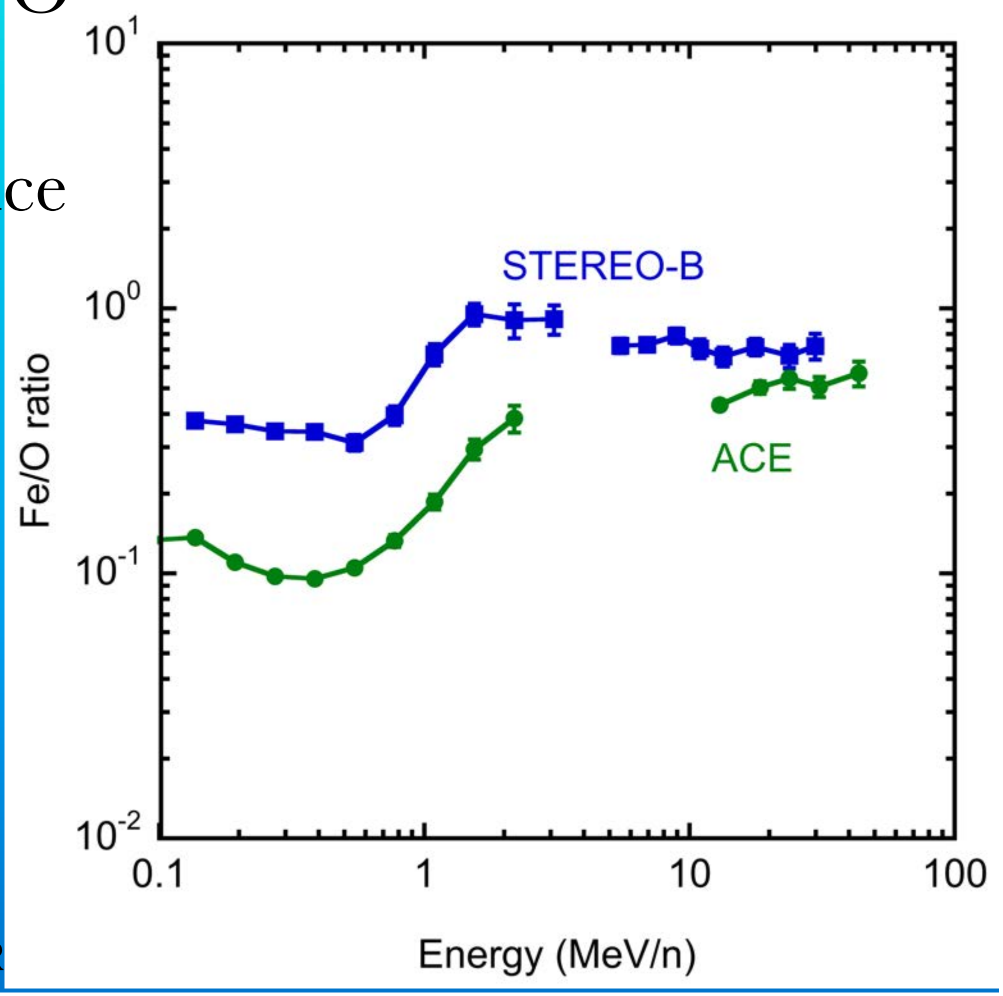
- Longitude dependence
  - Fitting a Gaussian (Lario et al. 2006)
    - σ = 27°, 31°, 28°
    - Narrower than typical (σ = 45-50°)
    - Suggests Fe/O~1 at flare connection
  - Compared to other ~Fe-rich events
  - Not a strong consensus on direct flare contrib.

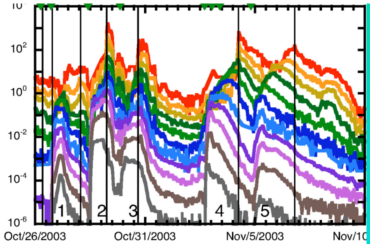




Testing Fe-rich Scenarios

- Fe/O increasing with energy? Yes
  - STB reaches higher Fe/O values but starts higher
  - ACE+STB E dependence is very similar



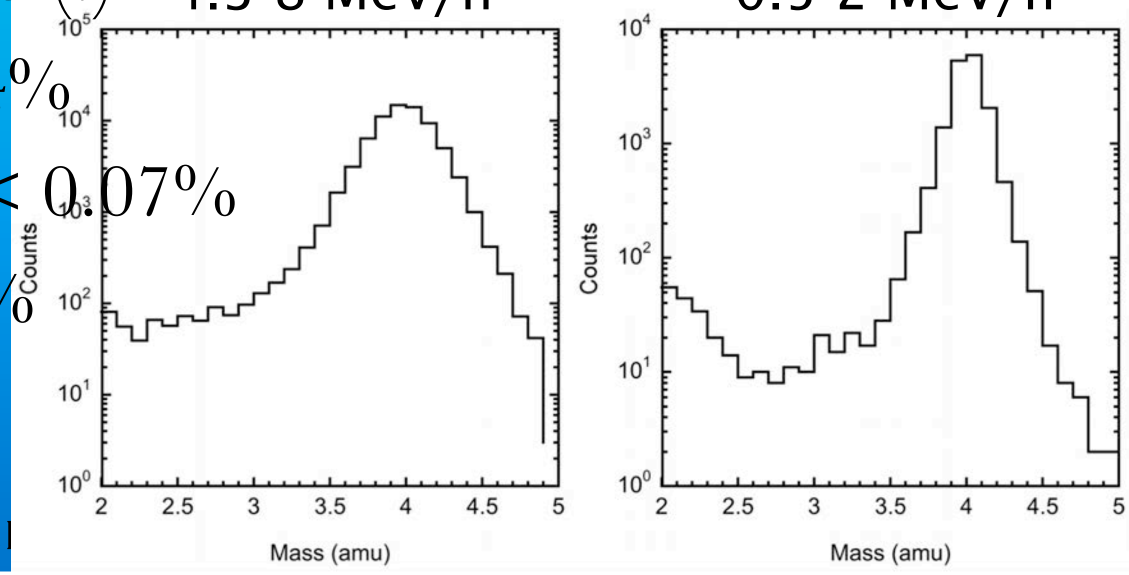


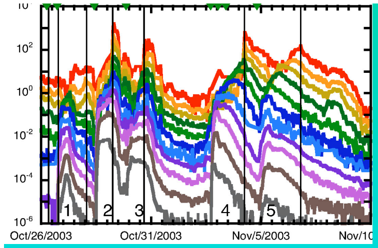
Testing Fe-rich Scenarios

- Fe/O increasing with energy? Yes
  - STB reaches higher Fe/O values but starts higher
  - ACE+STB E dependence is very similar
- Enhanced ^{3}He? No (!)
  - LET: $^3He/^4He < 4\%$
  - ULEIS: $^3He/^4He < 0.07\%$
  - SIS: $^3He/^4He < 1\%$

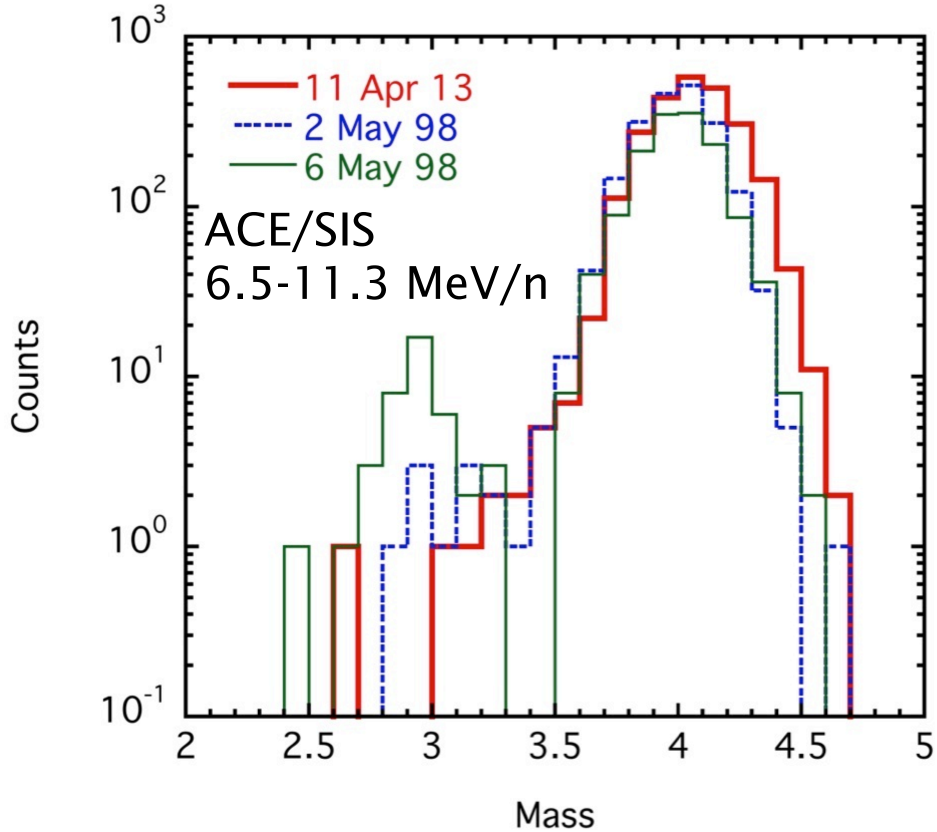
STEREO-B
4.3-8 MeV/n

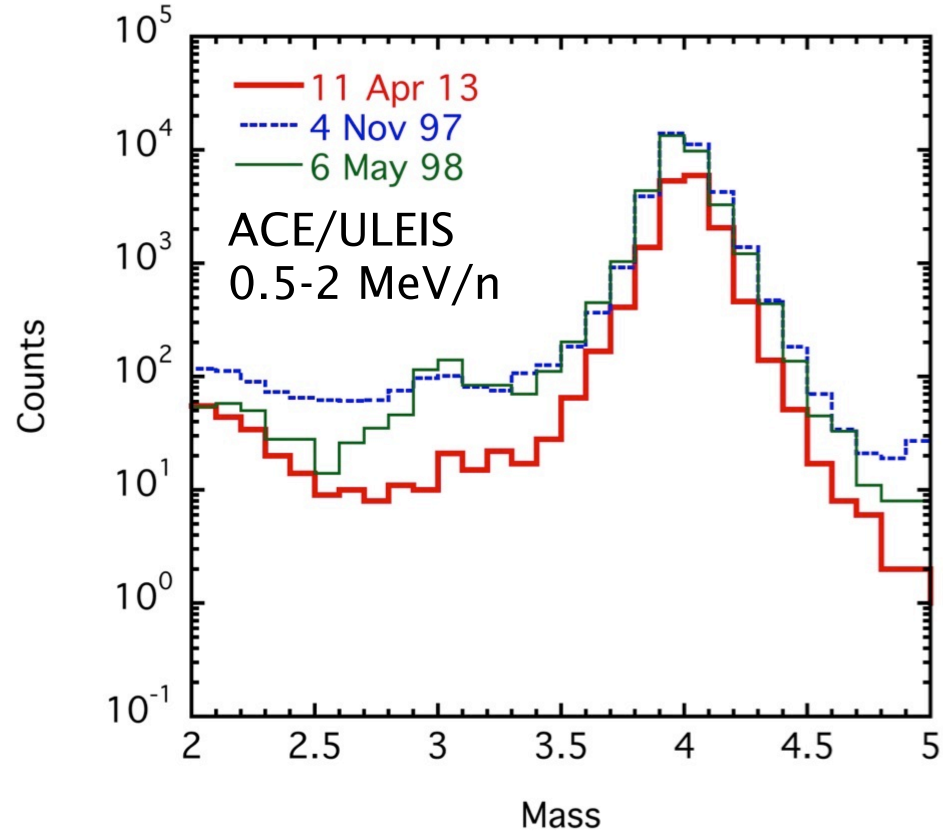
ACE
0.5-2 MeV/n



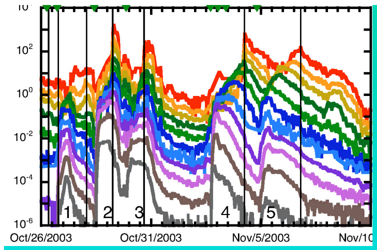


Testing Fe-rich Scenarios



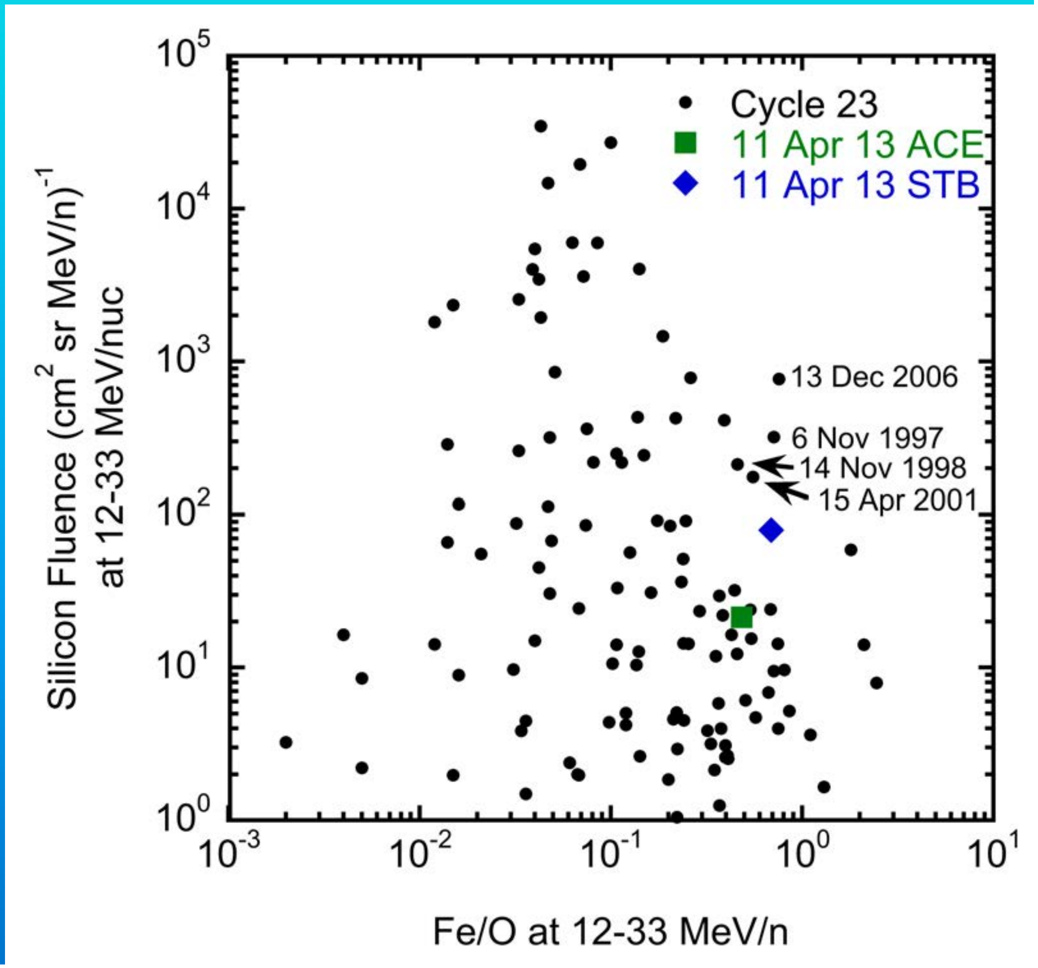


- Much less ^{3}He compared to cycle 23 events
  - 6 May 98: 4% and 0.534%
  - 2 May 98: <0.2% 4 Nov 97: 0.165%

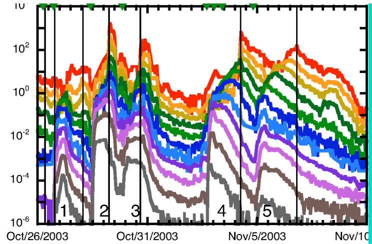


Testing Fe-rich Scenarios

- Fe-rich compared to cycle 23 events?
  - › Similar to 13 Dec 2006 and 6 Nov 1997

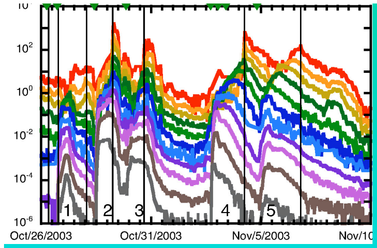


WHAT HISTORY ACCELE



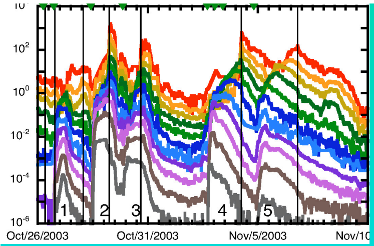
Testing Fe-rich Scenarios

- Fe-rich compared to cycle 23 events?
  - Similar to 13 Dec 2006 and 6 Nov 1997
  - But less ^{3}He (although 13 Dec 2006 had little ^{3}He)
- Direct flare contribution scenario
  - Most closely connected spacecraft has higher Fe/O
  - No ^{3}He - problem
- Suprathermals + Shock Orientation
  - Requires different shock orientation or suprathermals at ACE & STB
  - No ^{3}He – problem



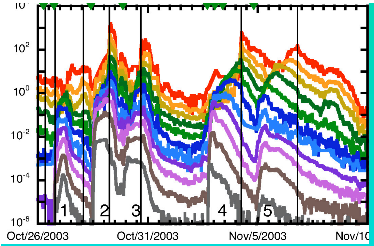
3D Questions

- ^{3}He is not always confined to a narrow range
  - › Potential issue for Fe-rich scenarios
  - › *Q: What governs when ^{3}He spreads widely?*
  - › *Q: How is ^{3}He spread widely?*
- Many events are from backside
  - › Space weather prediction issue
  - › *Q: How are SEPs transported so quickly to far longitudes?*
  - › *Q: Is this a 'near-Sun' or interplanetary effect?*
- Tests of Fe-rich scenario inconclusive
  - › *Q: Does ^{3}He need to go with Fe-rich?*
  - › *Q: Why are there so few Fe-rich events this cycle?*



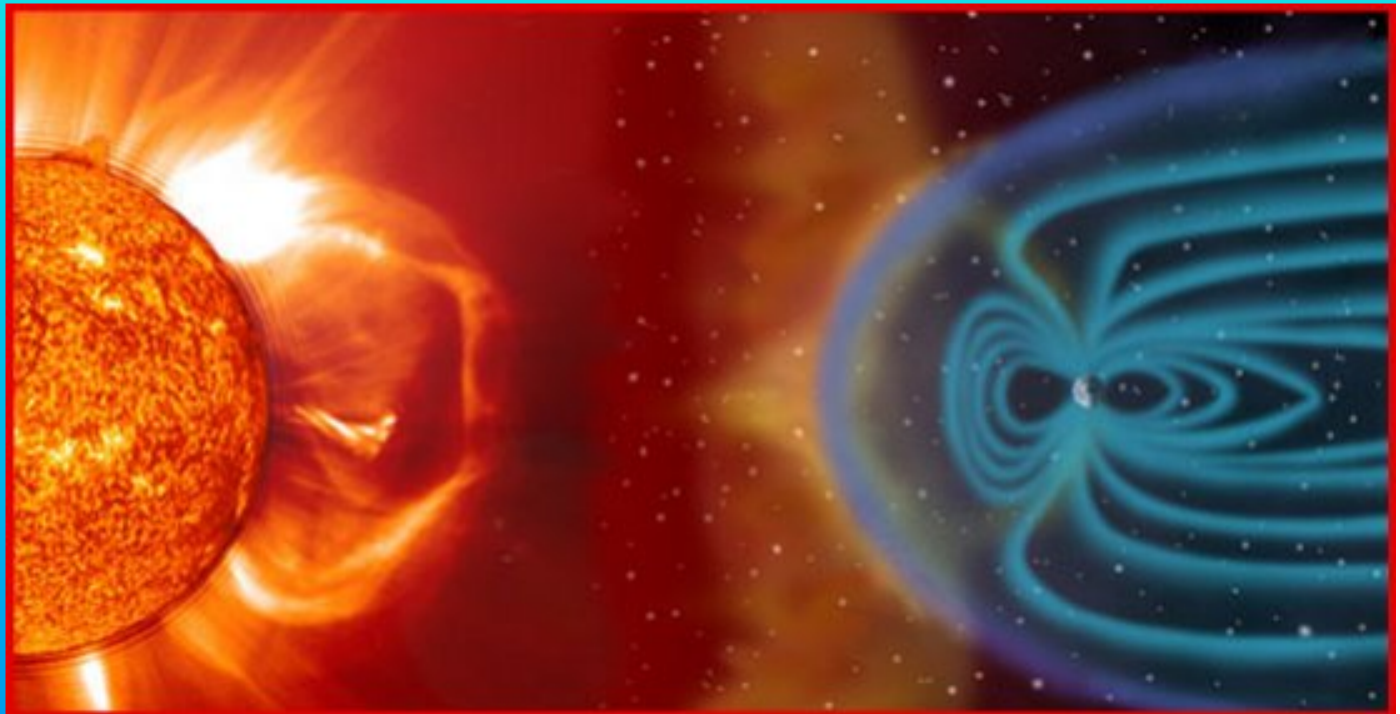
Where we stand

- Difficulty is that much of the action is closer to the Sun

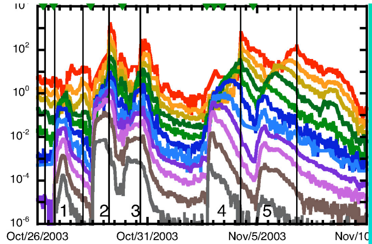


Where we stand

- Difficulty is that much of the action is closer to the Sun



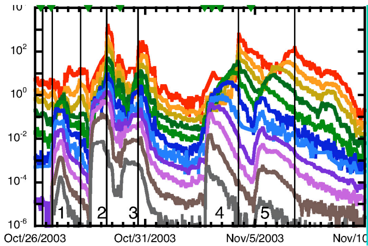
WHAT HISTORY ACCELERATION PROBLEMS 3D NEXT



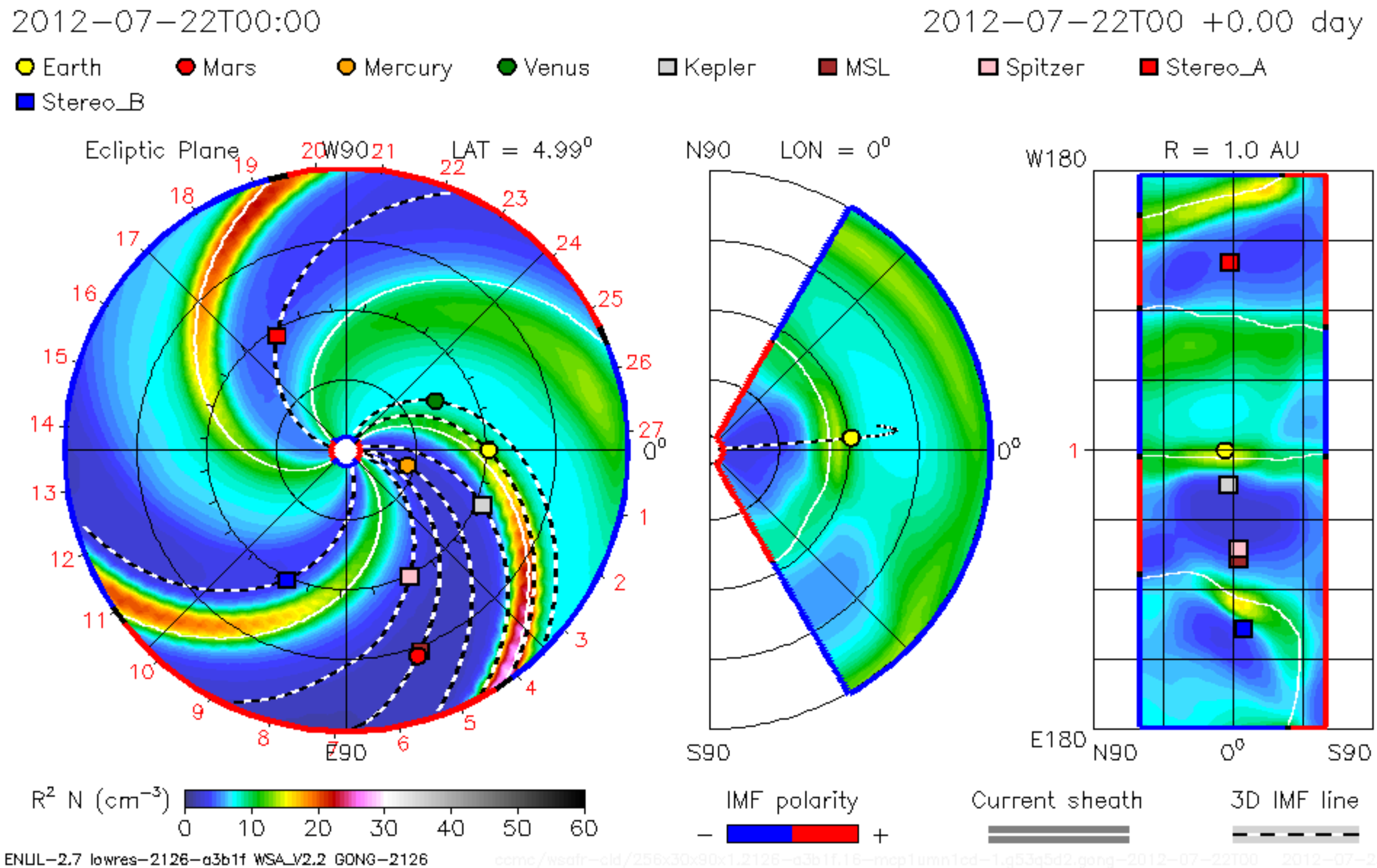
Where we stand

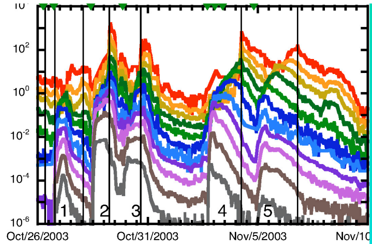
- Difficulty is that much of the action is closer to the Sun
- There's a lot of space in space

- We don't have many measurements inside 1 AU
  - › MESSENGER at Mercury makes some limited measurements



Where we stand

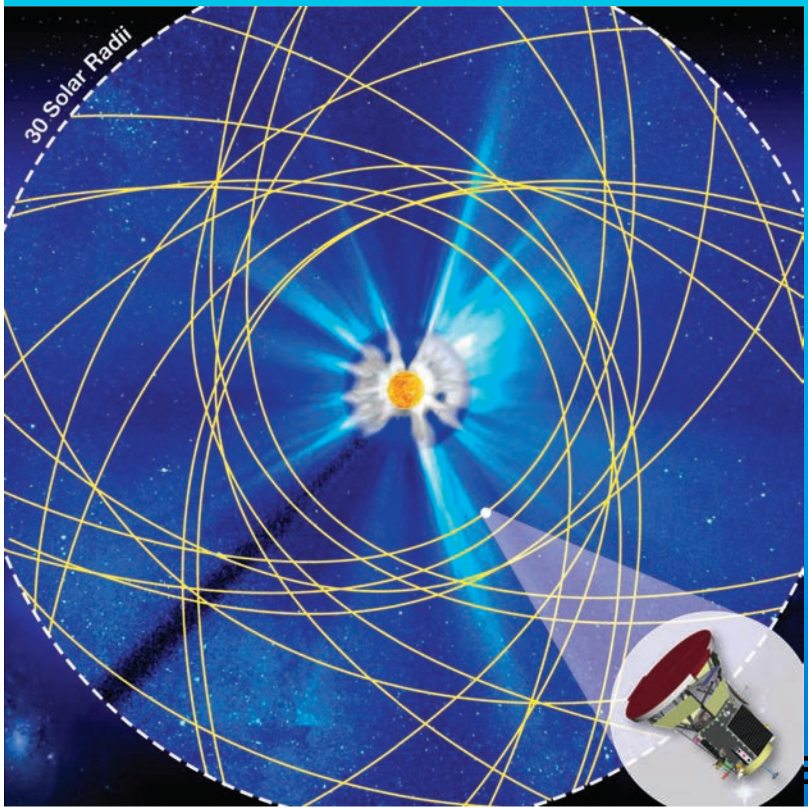


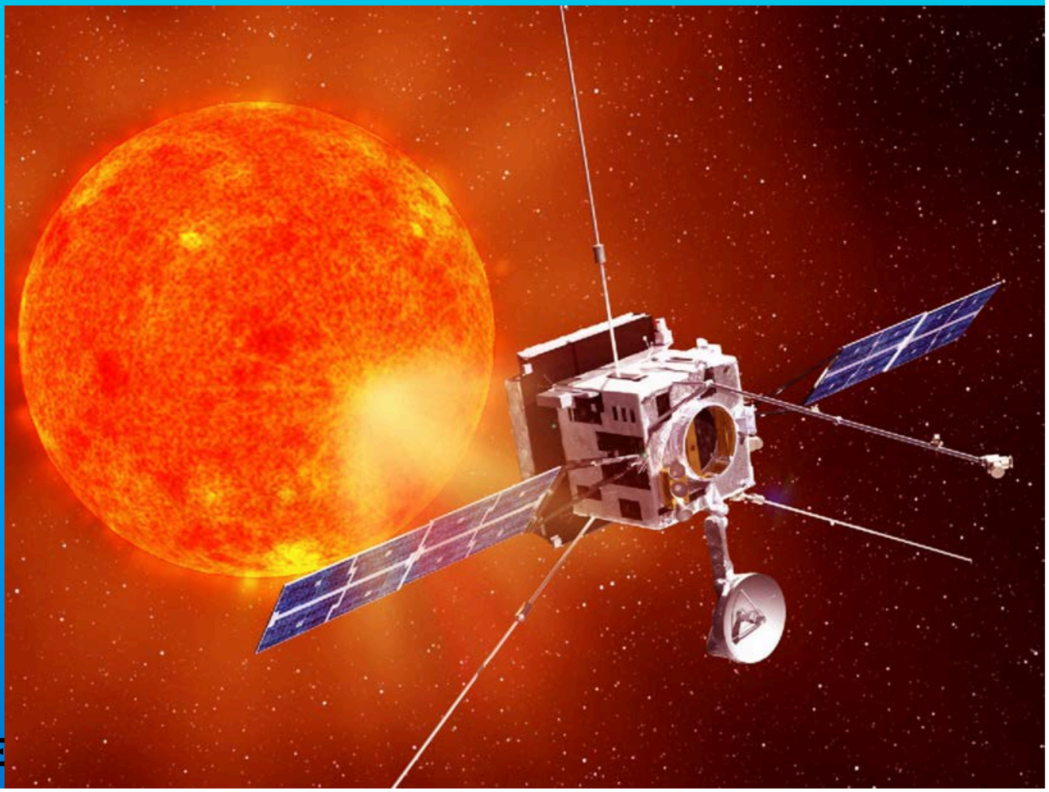


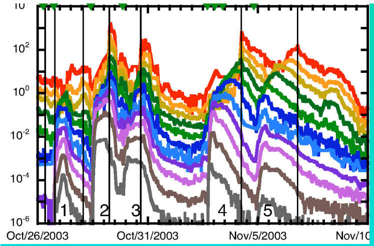
Next Frontier

- So let's go to the Sun…
- Solar Probe Plus (NASA) – 10Rs
- Solar Orbiter (ESA) – 30 Rs

Launch 2018







10²
10⁰
10⁻²
10⁻⁴
10⁻⁶
1
2
3
4
5
Oct/26/2003
Oct/31/2003
Nov/5/2003
Nov/10