Solar Energetic Particles (SEPs): A Tutorial Review and Introduction to WG3 Questions at SHINE 2004

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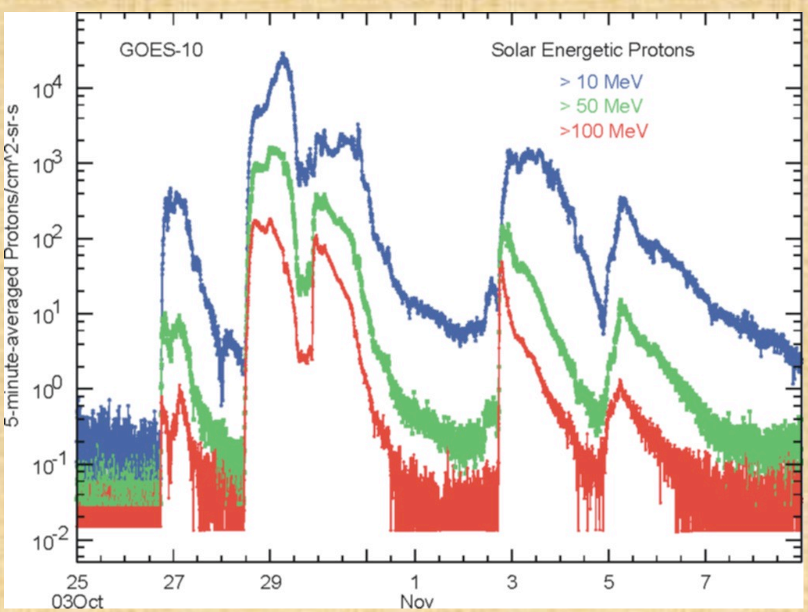
SHINE 2004 Student Day

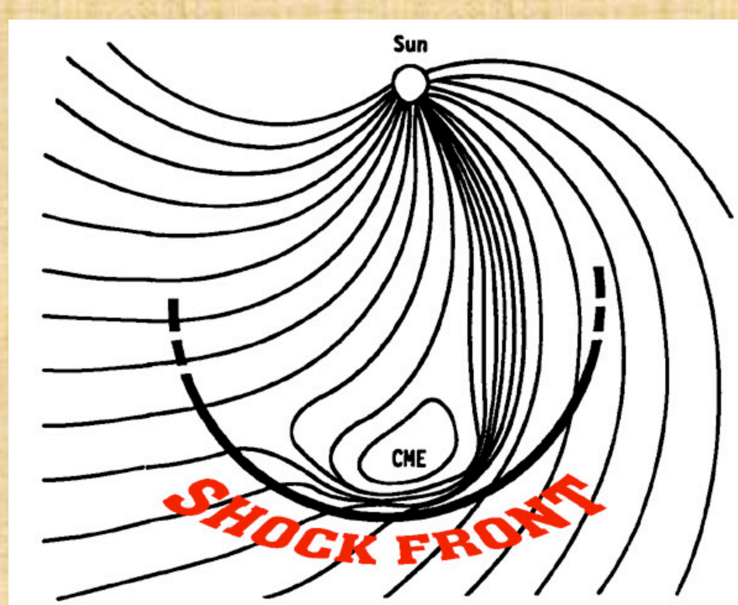
Big Sky, Montana

2004 June 27

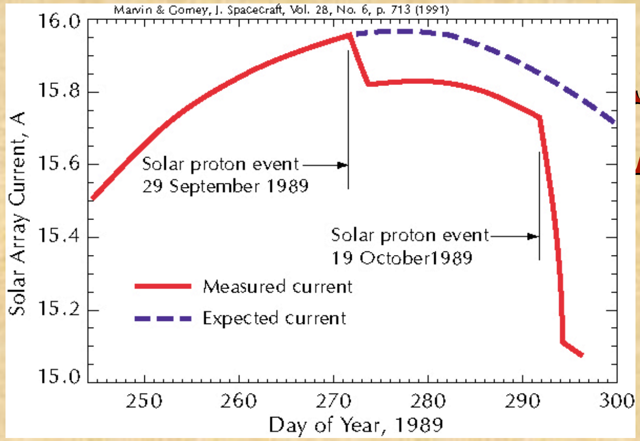
Characteristics of <u>Large</u> SEP Events

- ***High-energy (~30 keV – ~30 GeV) particle emission from the Sun***
- ***x10^2 – 10^6 increase in near-Earth radiation (depending on energy)***
- ***Increased hazard lasts for hours to days (depending on energy)***
- ***Include electrons, protons, and ions from the whole (natural) periodic table***
    - ***Minor ions (Z > 2) are powerful probes of SEP physics***
- ***Produced by shocks driven by very fast (top 1-2%) coronal mass ejections***
    - ***A productive venue for studying shock physics***
- ***~5 - 10 large events/year in solar-active years***

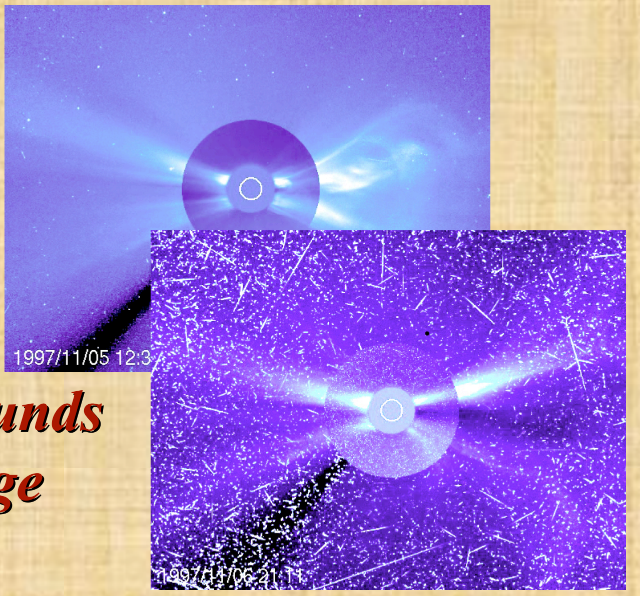




Solar Particle Effects on Space Systems



Solar Panel Degradation



Sensor Backgrounds & Damage

Single Event Effects (SEEs)

-- soft upsets

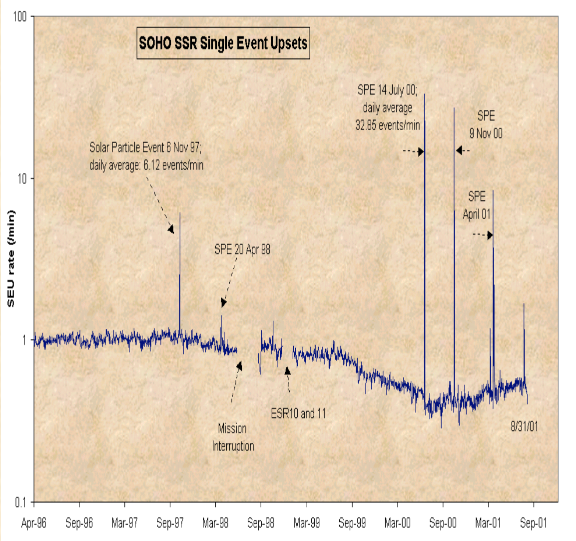
-- latch-ups

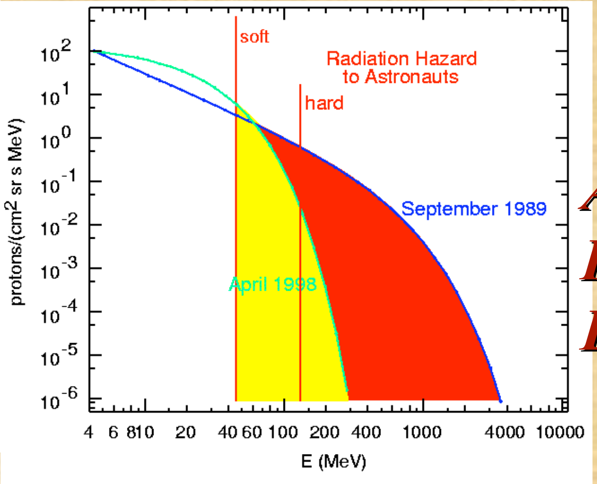
-- burnouts

-- gate rupture

-- functional interrupt

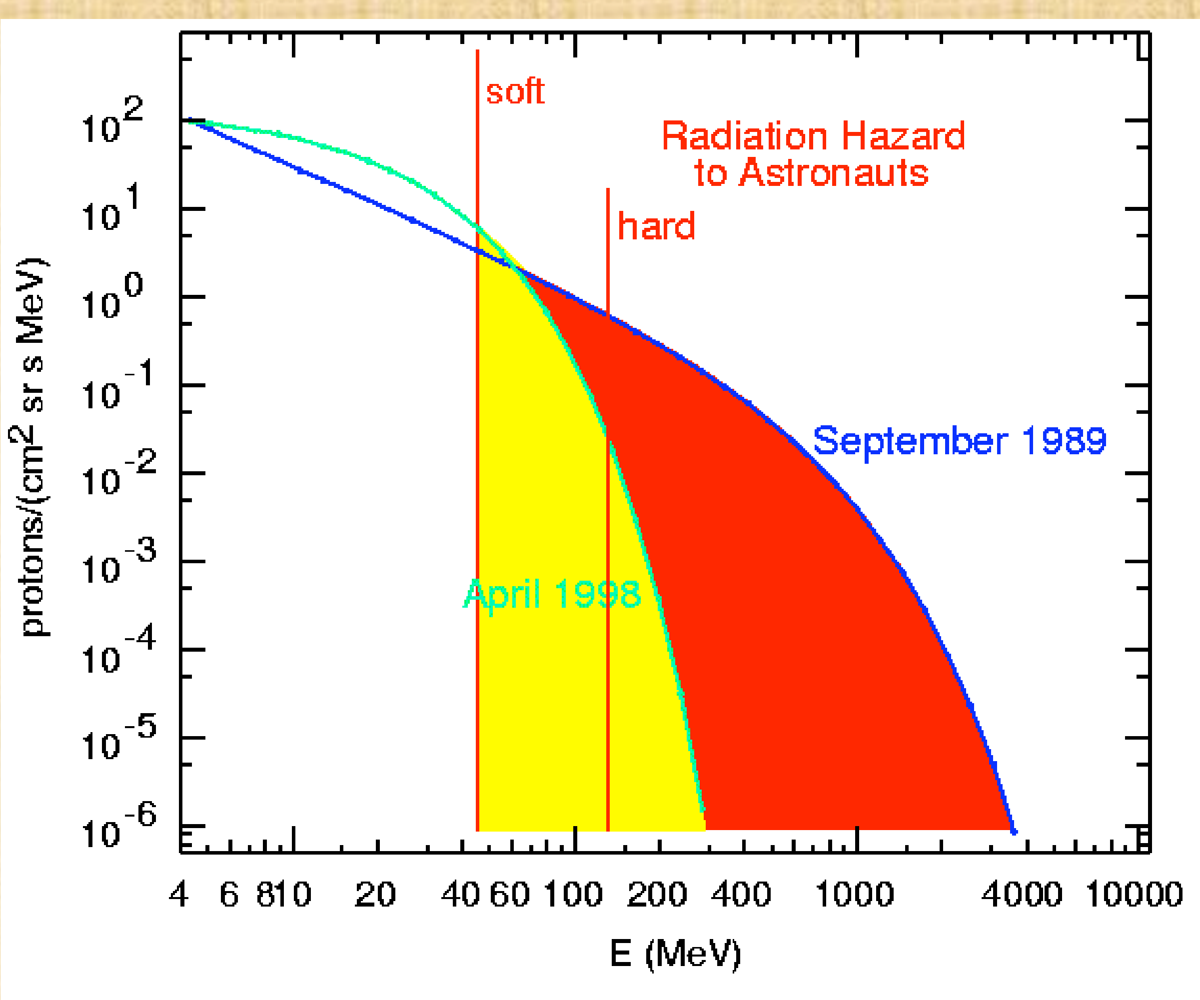
-- …





Astronaut Radiation Exposure

Solar Particles & Astronaut Radiation Exposure



Proton spectra from 2 events, both produced by ~2000 km/s CMEs on the west limb.

Behind 10 g/cm^2 aluminum, these spectra produce:

*50 mrem/hour**

*4 rem/hour**

For comparison:

Average Person:

360 mrem/year

Radiation Worker Limit:

5 rem/year

Astronaut Limit:

50 rem/year

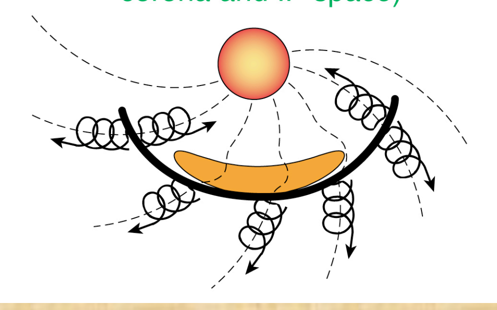
****These dose calculations are for interplanetary space, without the shielding effect of Earth's magnetosphere. Also, the dose calculations do not include secondary neutrons produced in the shielding material. (Aluminum would not be a good choice for the shielding material in a solar "storm shelter".)***

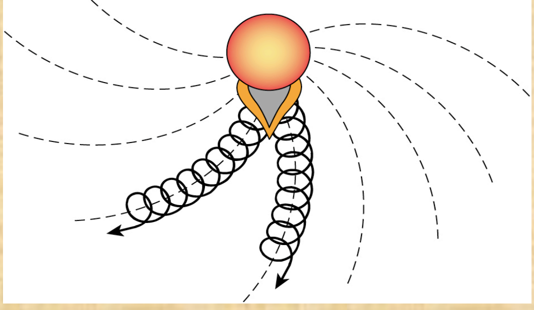
Outline

1. ***Backtrack: Two Kinds of SEP Events***
2. ***Impulsive ("Flare-Accelerated") SEPs***
   - ***Trans-Fe Ions (WG3 Session #2, Tues PM)***
   - ***Timing Studies***
3. ***Gradual ("Shock-Accelerated") SEPs***
   - ***Timing Studies***
   - ***Seed Populations***
   - ***Transport***
   - ***Spectral Characteristics***
   - ***Variability at High Energies (WG3 Session #1, Tues AM)***
4. ***Other WG3 Sessions***

The "Standard Model": Two Kinds of SEP Events (Reames 1995)

These names are unfortunate historical baggage…





Event Size	*"Big"*	*"Small"*
Duration at ~1 MeV/nuc	*~days*	*~hours*
Frequency at Solar Max	*~10 / year*	*~1000 / year over the whole Sun*
Source Location	*Over the whole Sun*	*Restricted to magnetically-connected longitudes, ~W30-W80*
Composition at ~1 MeV/nuc		
Event-Integrated Fe/O	*~0.1*	*~1.0*
**Trans-Fe (30 ≤ Z ≤ 82)*	*Nominal coronal values*	*100x – 1000x enhancements*
Fe Charge States	*~10-14*	*~16-20*
3He/4He	*Small: Solar Wind ~0.04% ??*	*>10% ?*
Acceleration Mechanism	*Shock, driven by fast CME*	*Resonant wave-particle interactions ? at Flare/Reconnection Site*
Significance	*Extend to high energies; important for Space Weather*	*Energies too low for space-weather impact. But very interesting physics!*

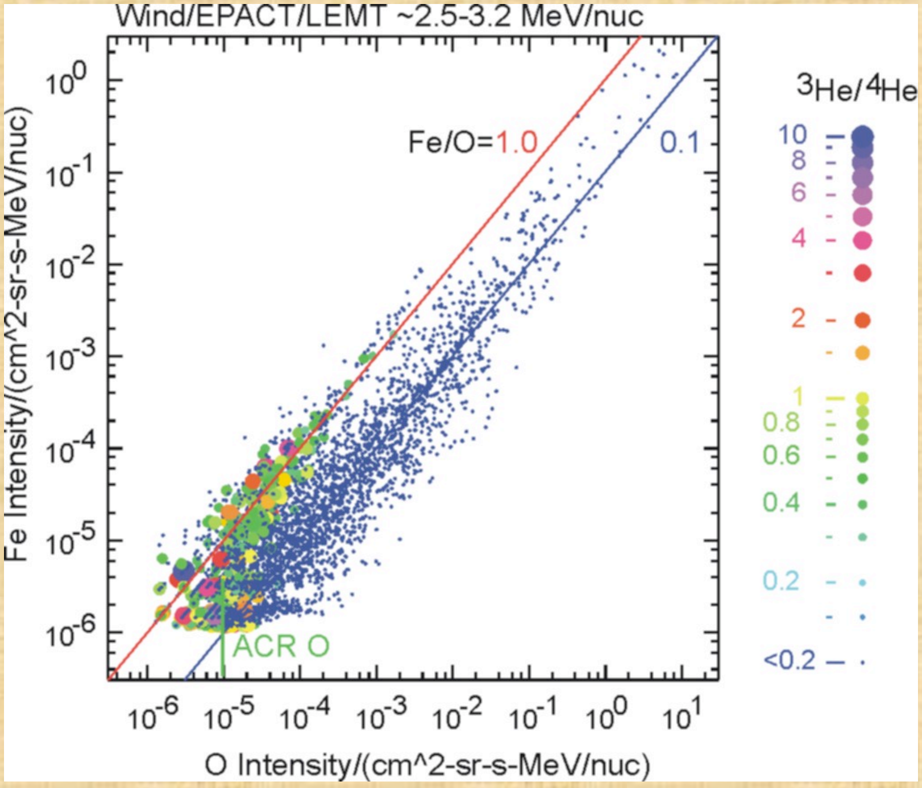
* *New in Cycle 23*

"Impulsive" (Flare) & "Gradual" (CME-Shock) SEP Events

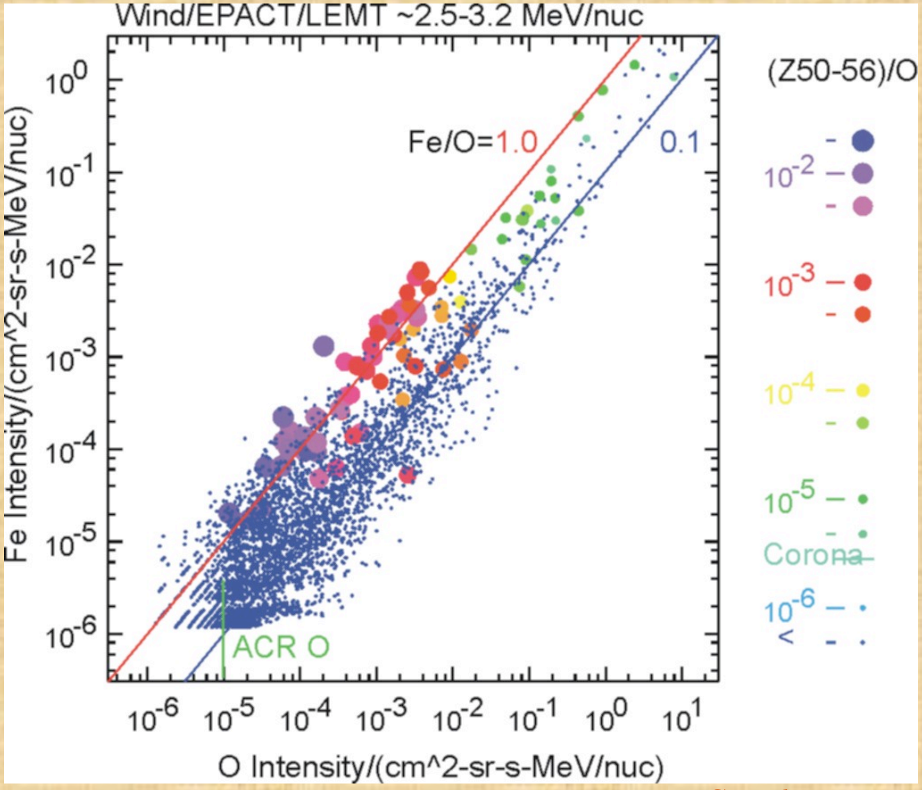
Fe & O intensities at ~3 MeV/nuc
8-hour averages from Wind 1994-2003

Reames & Ng, Ap J (2004), in press

Symbol color shows $^3He/^4He$



Symbol color shows (50 ≤ Z ≤ 56)/O



See also:
Reames (2000);
Tylka et al. (2002)
Mason et al. (2004)

- ✓ *Two loci of points: Fe/O ~1 (impulsive) and Fe/O ~ 0.1 (gradual)*
- ✓ *Strong $^3He/^4He$ and trans-Fe enhancements seen in impulsive events.*

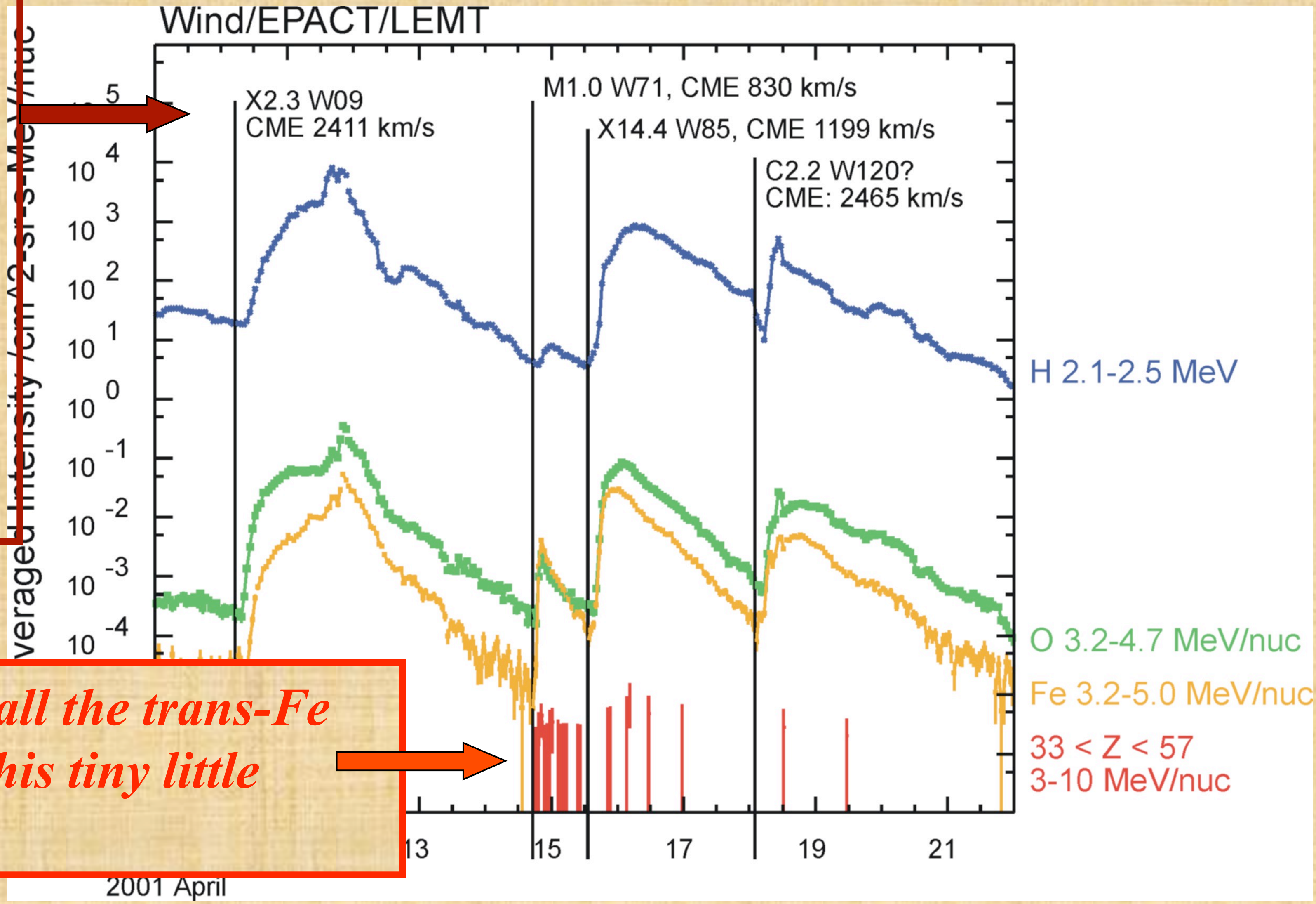
Impulsive Solar Particle Events

particles accelerated by processes associated with flares

1. ***Trans-Fe Enhancements***
2. ***Timing Studies***

The SEP Events of April 2001

Hourly-Averaged Particle Intensity vs. Time



Note: All of these events have <u>both</u> fast CMEs <u>and</u> big flares.

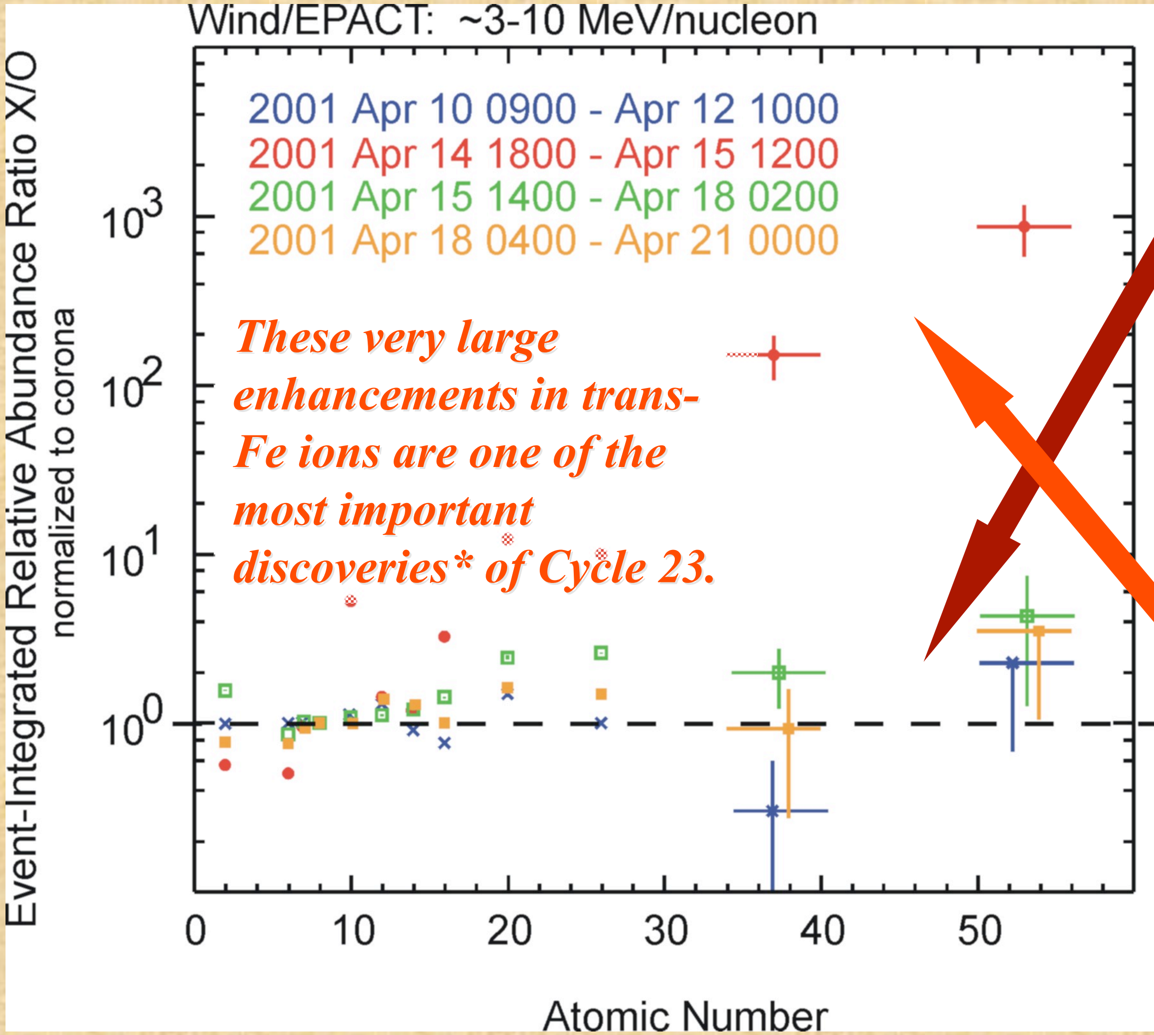
How do we know what caused what?

Look at all the trans-Fe ions in this tiny little event!

Trans-Fe Ions in Impulsive (“Flare”) SEP Events

Reames (2000), Mason et al. (2004), Reames & Ng (2004)

Event-Integrated X/O vs. Atomic Number



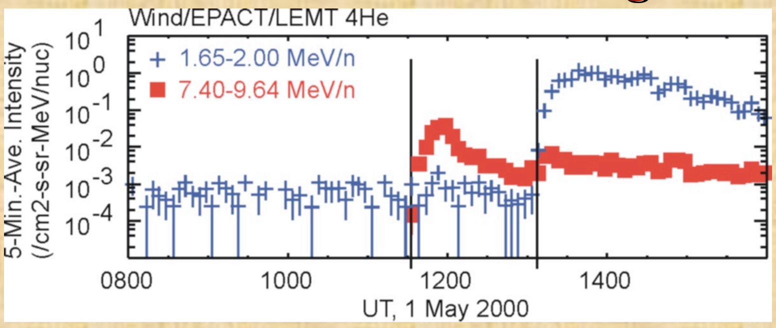
The big events have close-to-nominal coronal composition across the whole periodic table, at least at these energies.

But the little event shows strong enhancements in heavy ions, including 100x – 1000x enhancements above Fe.

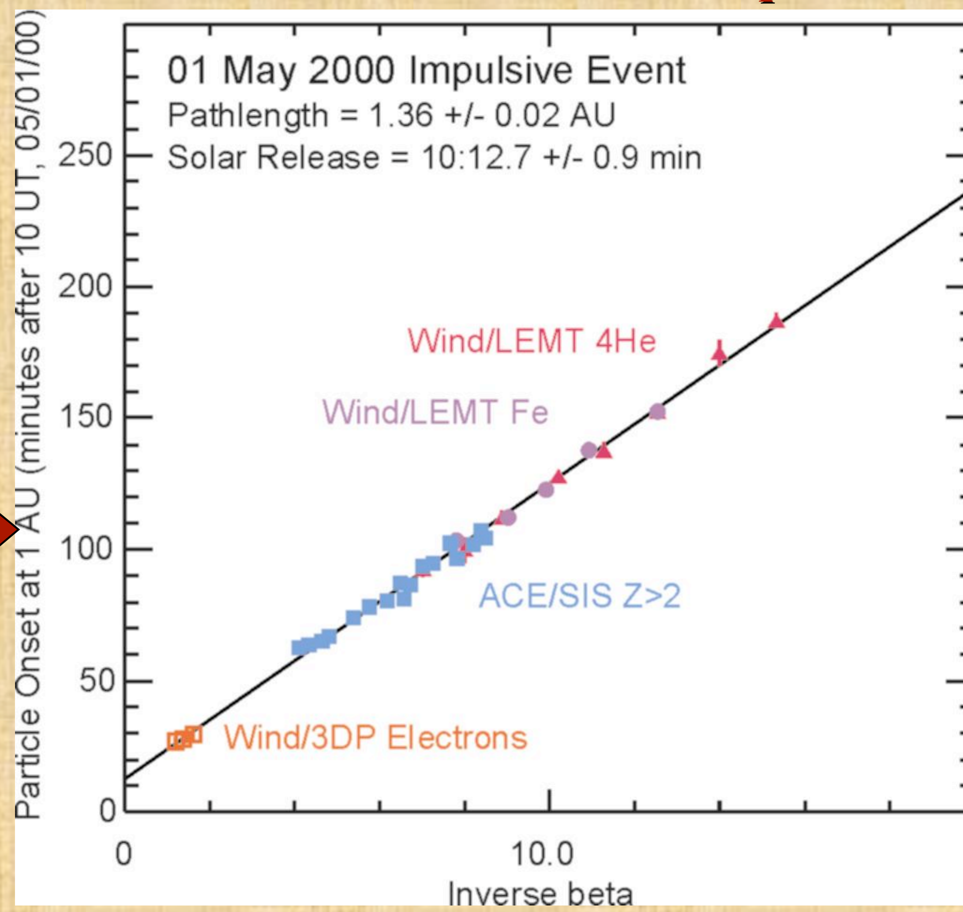
* *See also Shirk & Price, Proc. 13th ICRC (Denver) 2, 1474 (1973).*

Timing Studies and the Origins of SEPs

Particle Onsets at 2 Energies



Plot: Onset time at 1 AU vs. 1/speed



Onset determination:

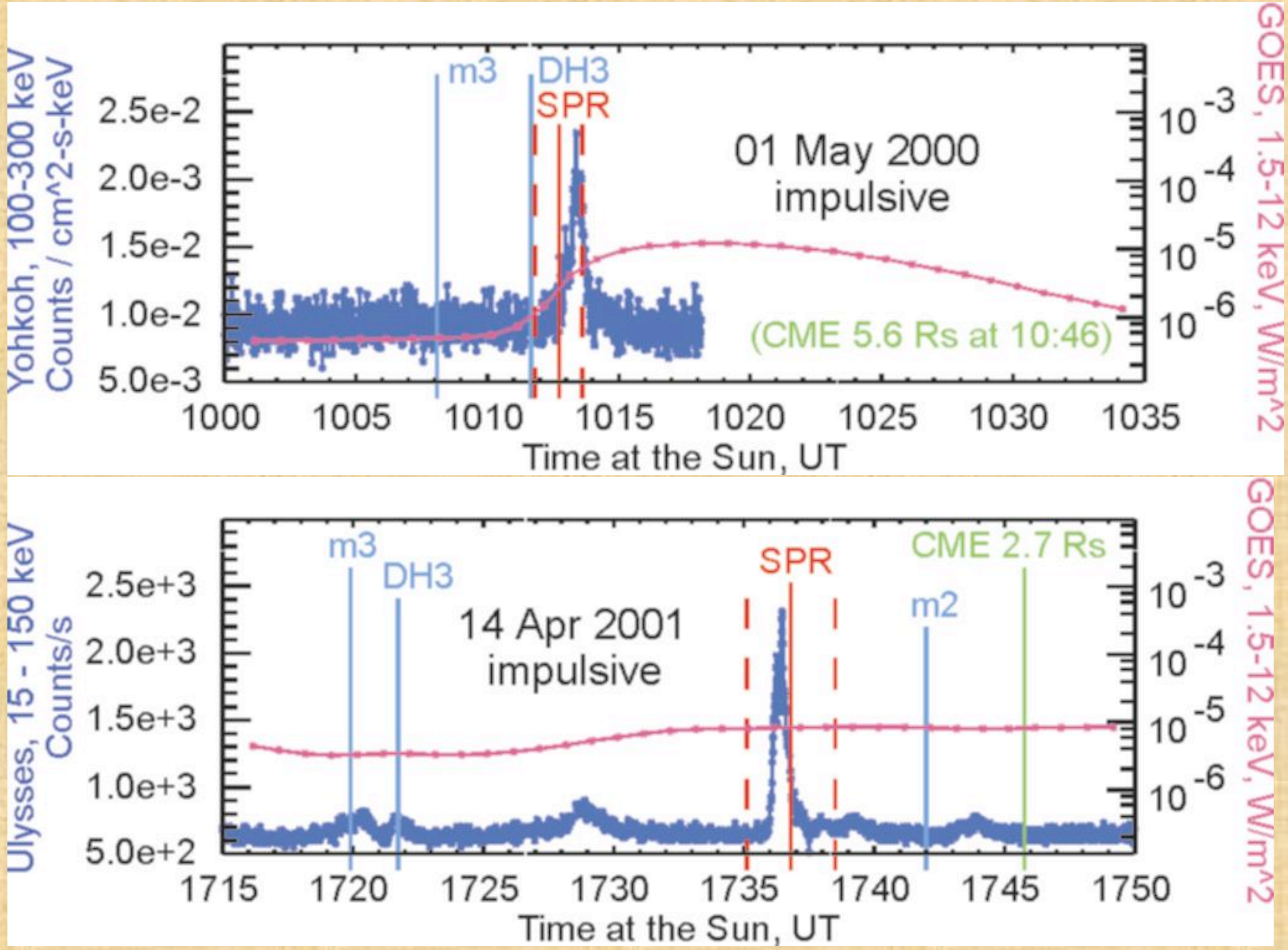
$$L = \beta \cdot (t - t_0)$$

$$\Rightarrow \quad t = t_0 + L \cdot 1/\beta$$

- ***y-intercept gives earliest departure time from the Sun.***
- ***Slope gives the pathlength***

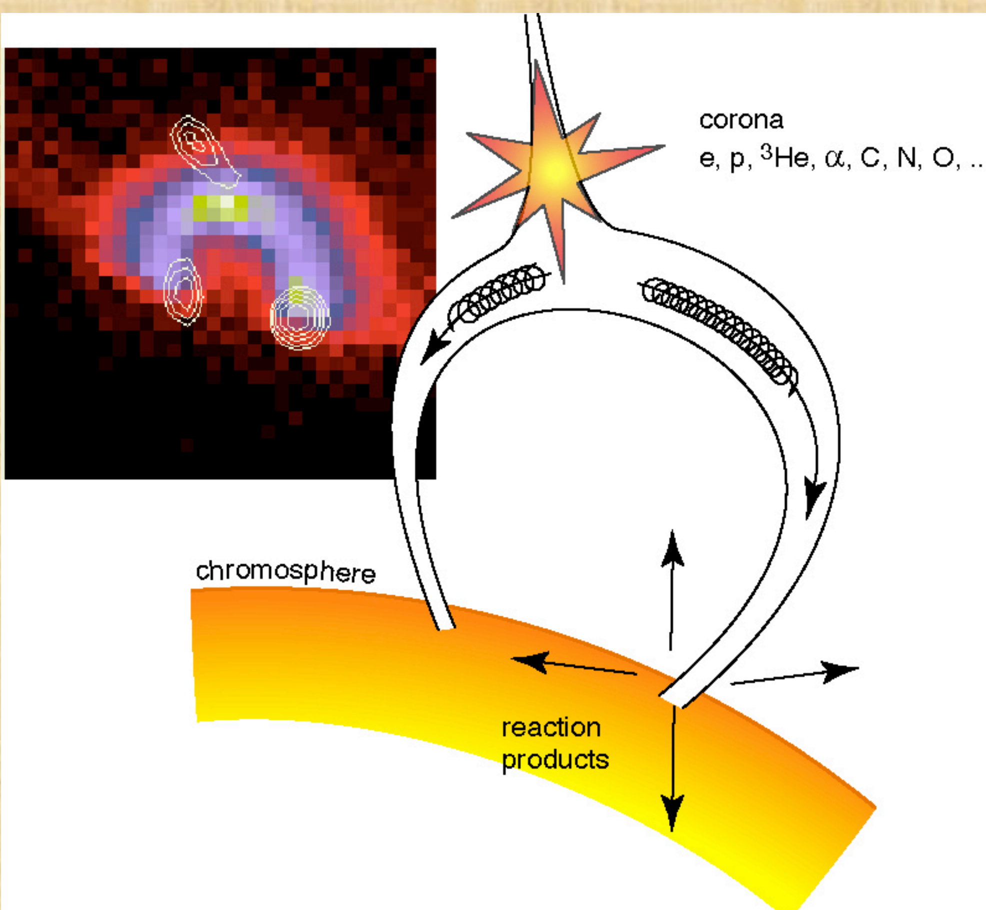
Caveat: Many people believe this is a reasonable way to analyze onsets. But not everyone agrees. Some people believe that scattering – even of the first-arriving particles – makes these results unreliable.

Timing in Impulsive Events



Solar Particle Release ("SPR", as determined with the just-shown "time vs. 1/β" method) in these two impulsive events coincide with hard x-ray flare, which lasts only ~1 minute.

Particle Acceleration at Flares



WG3 Session #2 Tuesday PM

Most widely-accepted mechanism involves resonant wave-particle interactions.

Particles absorb energy from Alfvén, EMIC (for ^{3}He), and other wave modes.

These waves are excited by streaming electrons generated by reconnection at the top of a loop.

- ***Some energetic particles escape to interplanetary space***
- ***Others crash into the solar atmosphere, making hard x-rays, γ-rays, and neutrons.***

Current models have been relatively successful in accounting for enhancements of Fe and lighter.

But can these models also account for the very large enhancements in ions heavier than Fe?

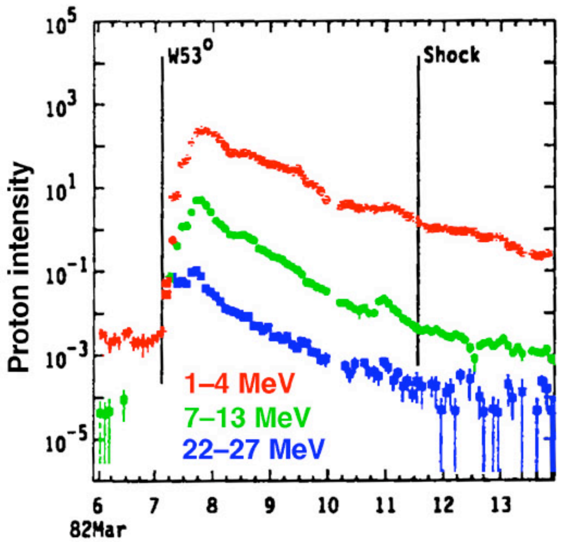
Gradual Solar Particle Events

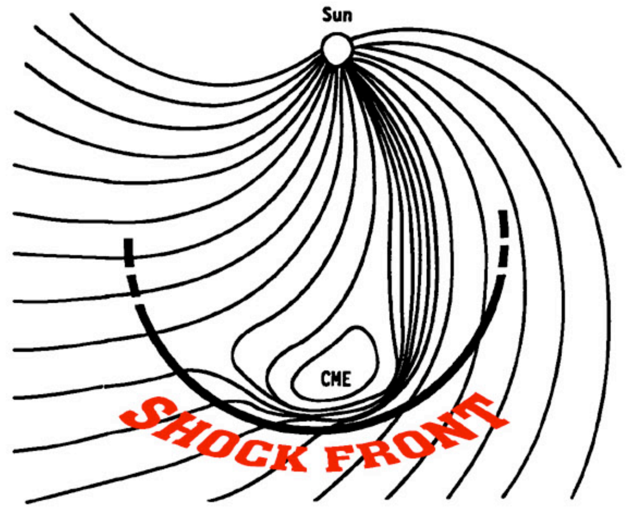
particles accelerated by CME-driven shocks

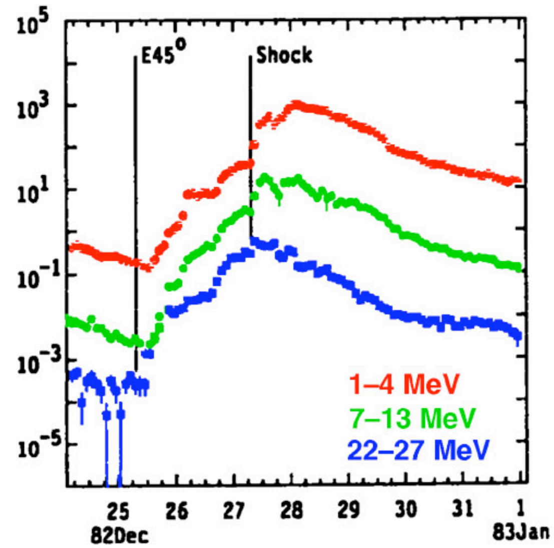
1. *Timing Studies*
2. *Seed Populations*
3. *Transport Effects*
4. *Spectral Characteristics*
5. *The Problem of Variability at High Energies*

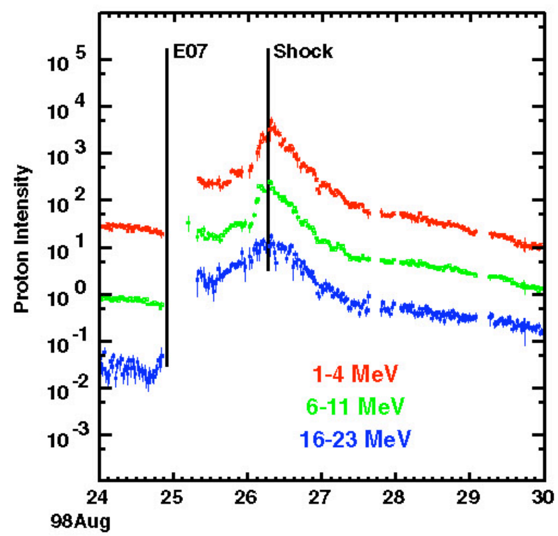
Solar Energetic Particles & CMEs

after Cane et al. (1988); Reames et al. (1996).





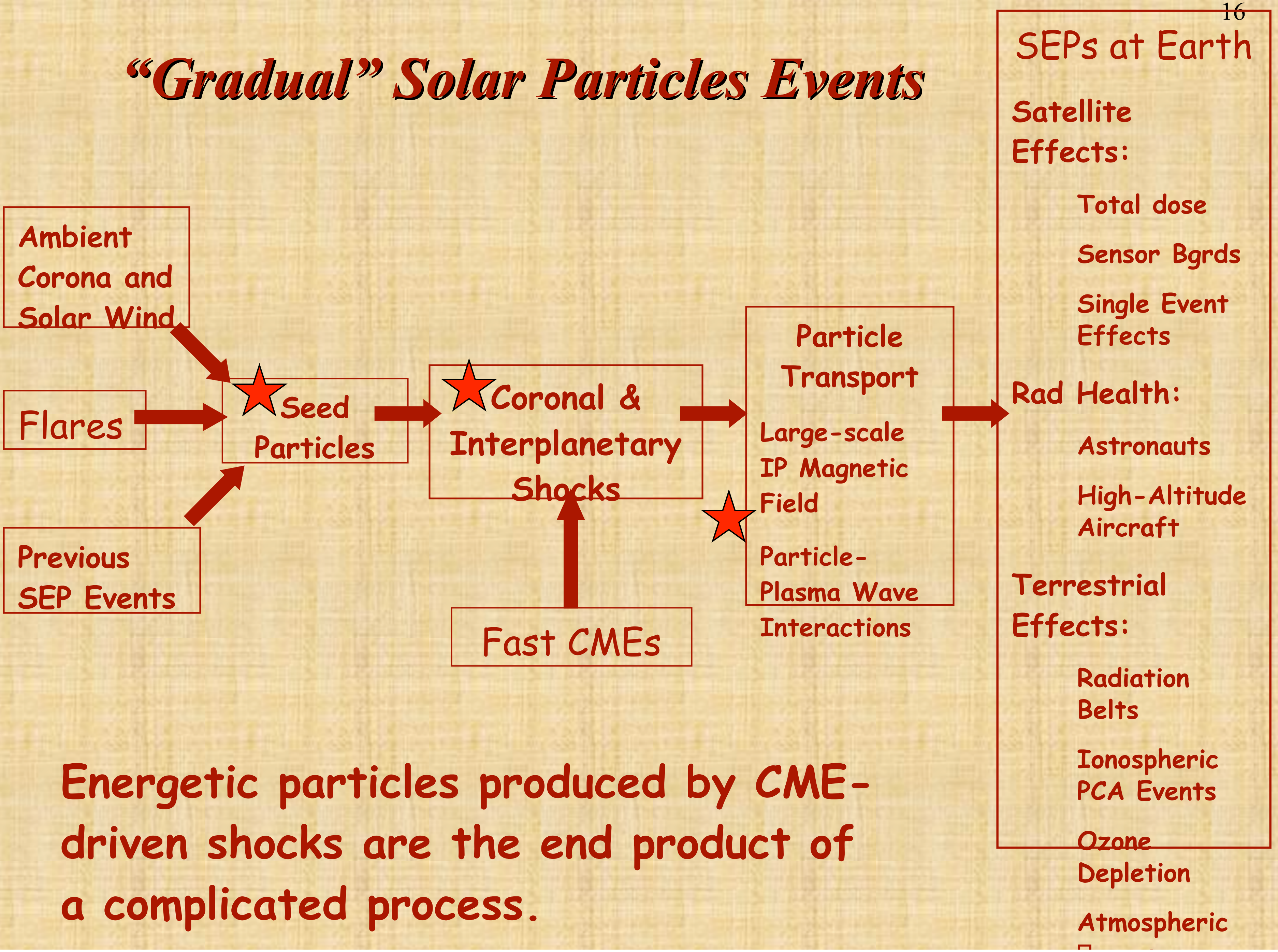




Only the fastest CMEs (top 1-2 %) drive shocks which make high-energy particles.

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

"Gradual" Solar Particles Events



Energetic particles produced by CME-driven shocks are the end product of a complicated process.

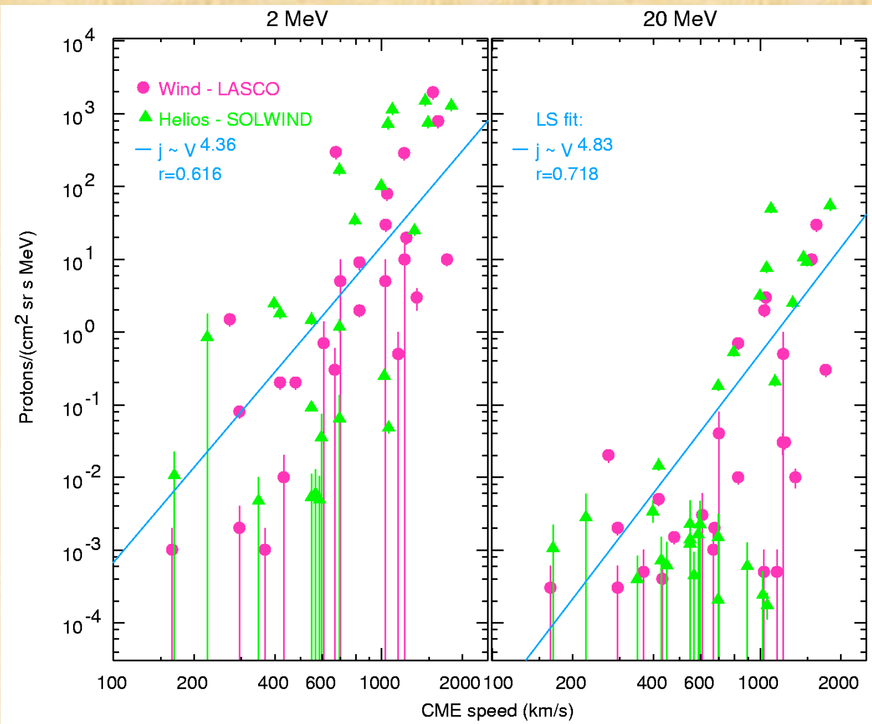
The Origin of Gradual Solar Energetic Particle Events:

These big events generally are seen with both fast CMEs and big flares.

How do we know that the CME-driven shock is the primary accelerator in these events?

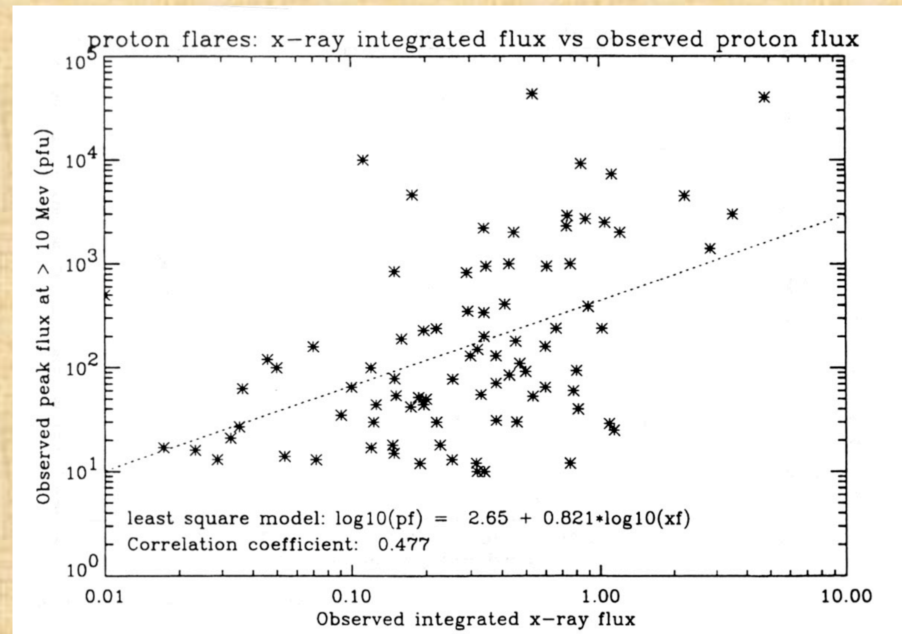
Empirical Correlations: Peak Proton Intensity vs. …

Observed CME Speed



Reames, AIP Conf. Proc. 516, 289, (2000)

Observed soft x-ray fluence

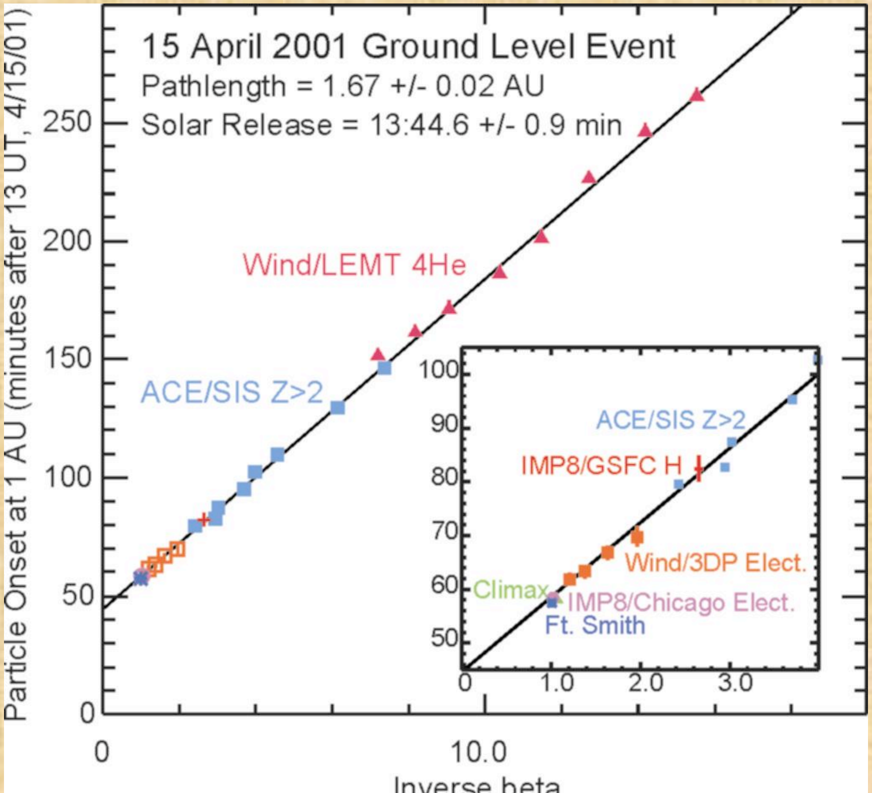


Balch, Radiat. Meas. 30 (3), 231, (1999)

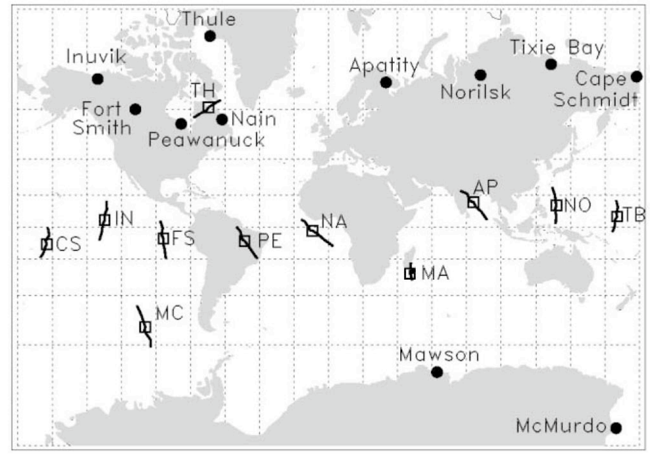
The cogency (or lack thereof) in correlations like these is a matter of opinion. Fortunately, we now have better information….

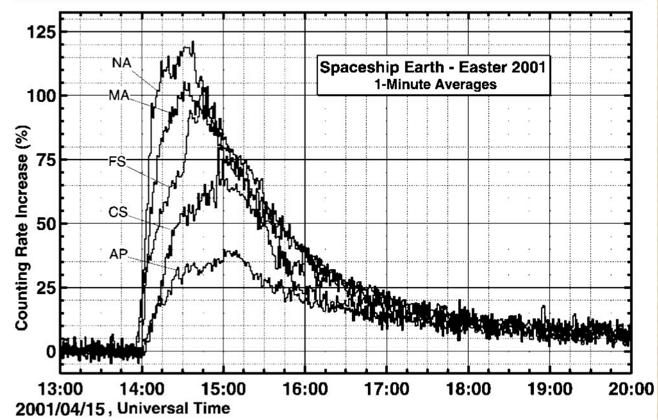
Timing in 2001 April 15 Ground-Level Event (GLE) -- the largest GLE of Cycle 23

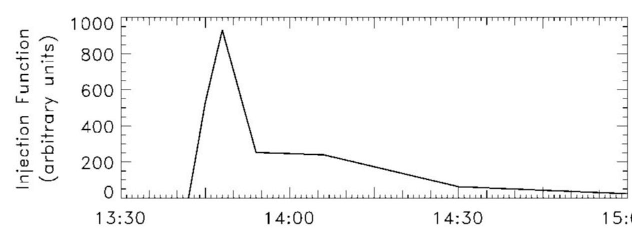
Tylka et al., Proc 28th ICRC 6, 3305 (2003)



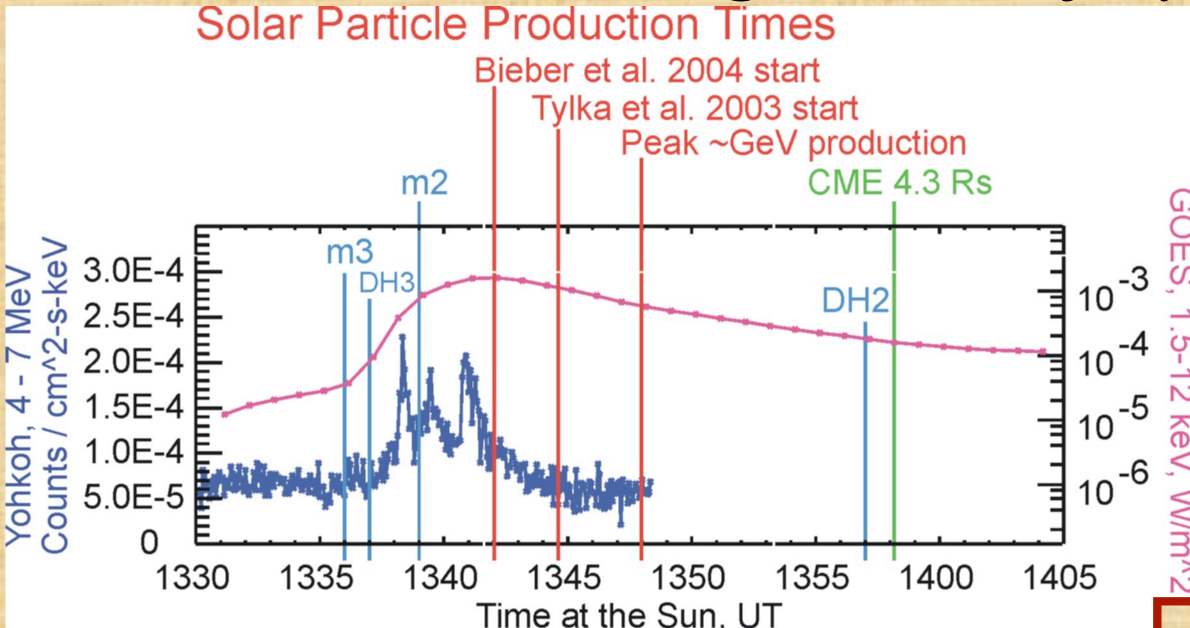
Bieber et al., Ap.J. Letters 601, L103 (2004)







Timing in 2001 April 15 Ground-Level Event (GLE) -- the largest GLE of Cycle 23



Also note:

SEP onset & peak of ~GeV production occurred when the CME was at ~2 R_S.

Two independent studies, using

- ***Different datasets***
- ***Different analysis techniques***
- ***Different assumptions about scattering.***

Both studies concluded that timing favors origin from the CME-driven shock, not the flare.

Here's a good question:

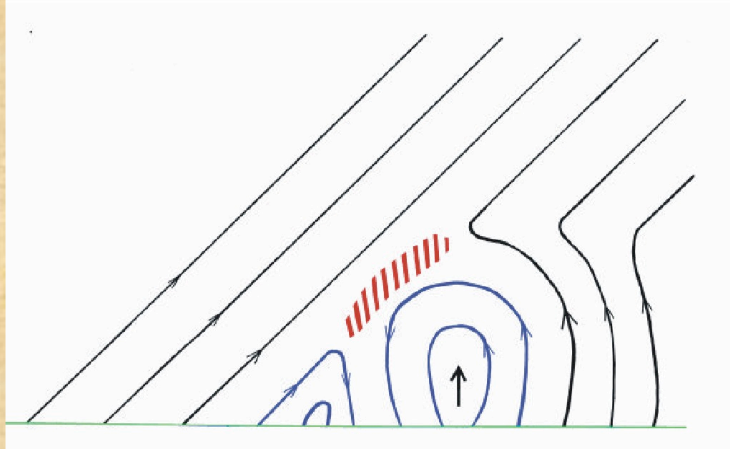
OK, so the particles here are coming from the shock.

But why <u>don't</u> we see particles from the flare too?

Magnetic Topology in Flare- and Shock-Accelerated SEP Events

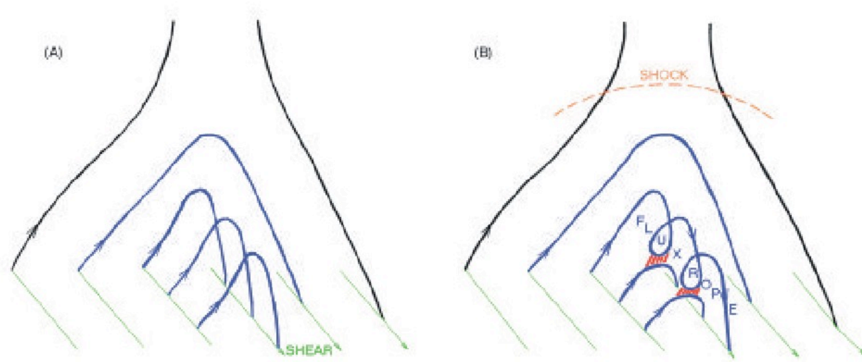
Reames, Ap.J. Letters 571, L63-L66 (2002)

Flare-Accelerated ("Impulsive") SEPs



Reconnection event simultaneously sends particles into solar atmosphere & out into interplanetary space.

CME-Shock-Accelerated ("Gradual") SEPs



Reconnection produces flare-accelerated particles on (mostly?) closed field lines beneath the CME. This process precedes formation of the CME-driven-shock.

Our timing results are consistent with these topological differences suggested by Reames (2002).

Seed Population:

^{3}He in Gradual Shock-Accelerated SEP Events

Mason, Mazur, & Dwyer (1999)

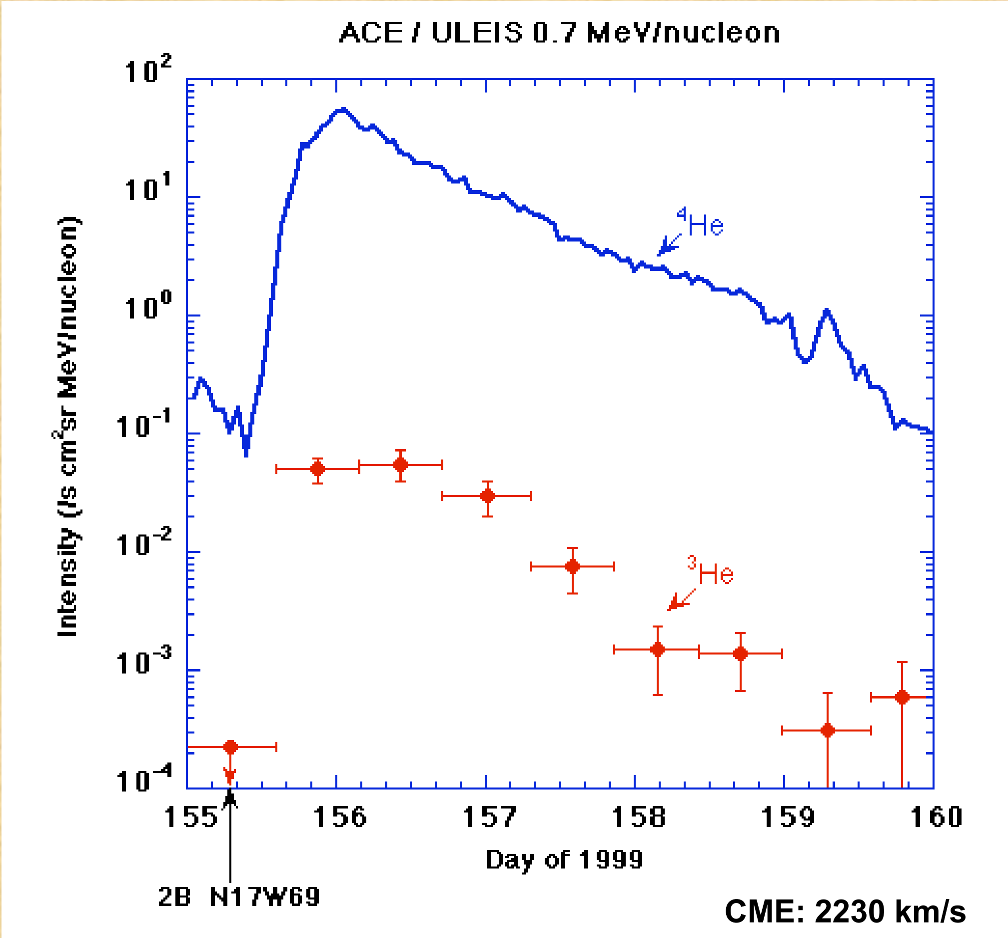
Earlier instruments were generally unable to measure ^{3}He/^{4}He in gradual events.

ACE found ^{3}He/^{4}He values in gradual events often significantly above the solar-wind value, ~0.04%.

Mason et al. (1999) interpreted these results as remnant flare particles, re-accelerated by the CME-driven shock.

At Solar Max, flare remnants are present in the IPM >60% of the time (Wiedenbeck et al. 2003).

The flare remnants are numerous: only 1% of remnant flare Fe would be needed to account for all enhanced Fe above ~10 MeV/nuc (Mewaldt et al. 2003).



See also Richardson et al. (1990), Tylka et al. (2001), Laivola et al. (2003).

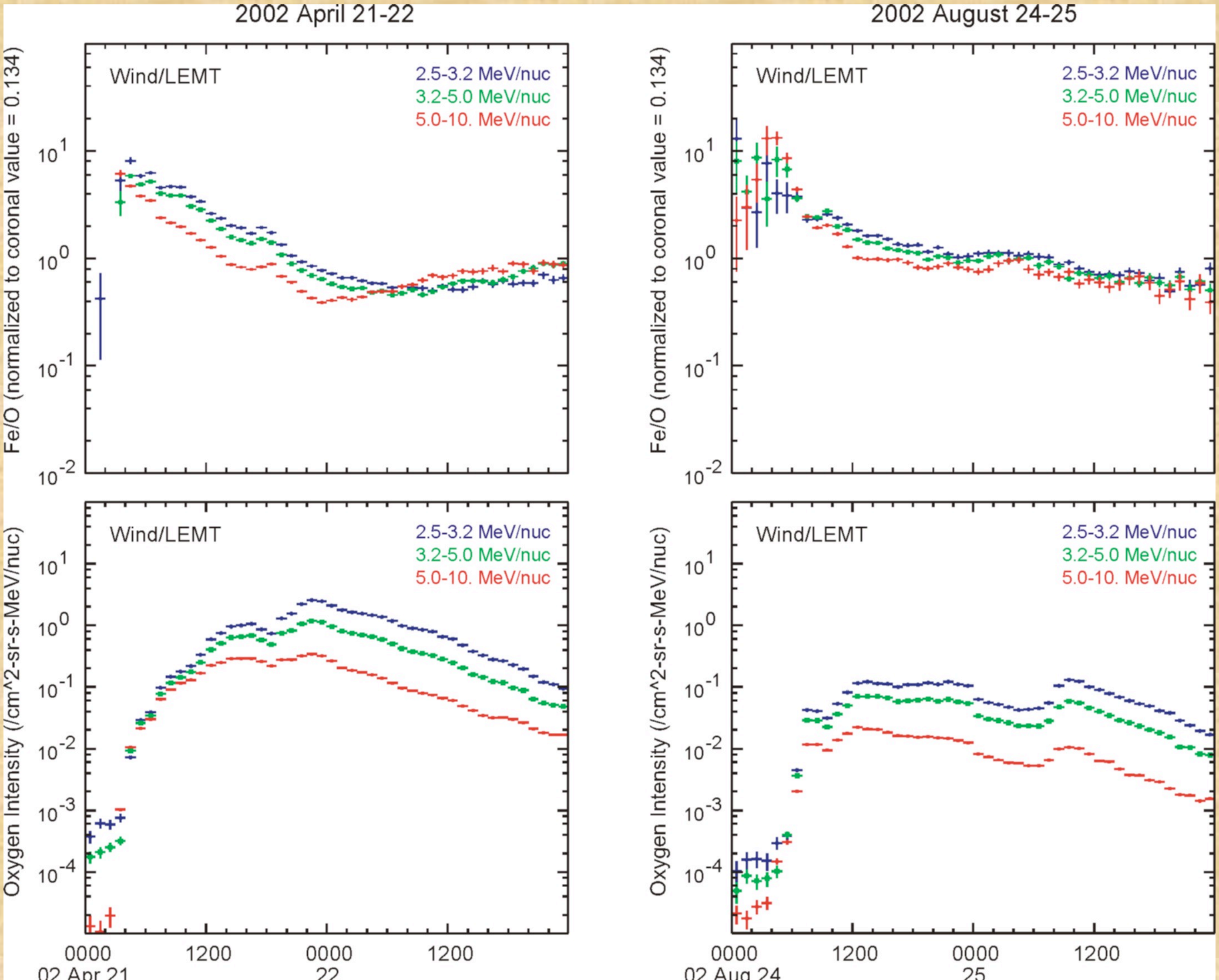
SEP Transport: A Reminder of Some Basics

- ***Particle transport in interplanetary space is a diffusive process.***
    - ***Governed by scattering from magnetic irregularities (Alfvén waves)***
    - ***The irregularities are both pre-existing and generated by the streaming energetic particles themselves.***
- ***Scattering is characterized by mean-free-path, λ***
    - ***λ depends on particle rigidity = momentum/charge = Mv/Q***
    - ***Different species of the same speed v but different M/Q have different λ***
    - ***Generally, λ increases with rigidity so that***
        - ***$\lambda_{SW\text{-}Fe} > \lambda_{SW\text{-}O} > \lambda_{He} > \lambda_{H}$ since M/Q = 56/10, 16/6, 4/2, 1/1***

Initial Enhancement in Fe/O because $\square_{Fe} > \square_{O}$

Fe/O/corona

Oxygen Intensity



Time

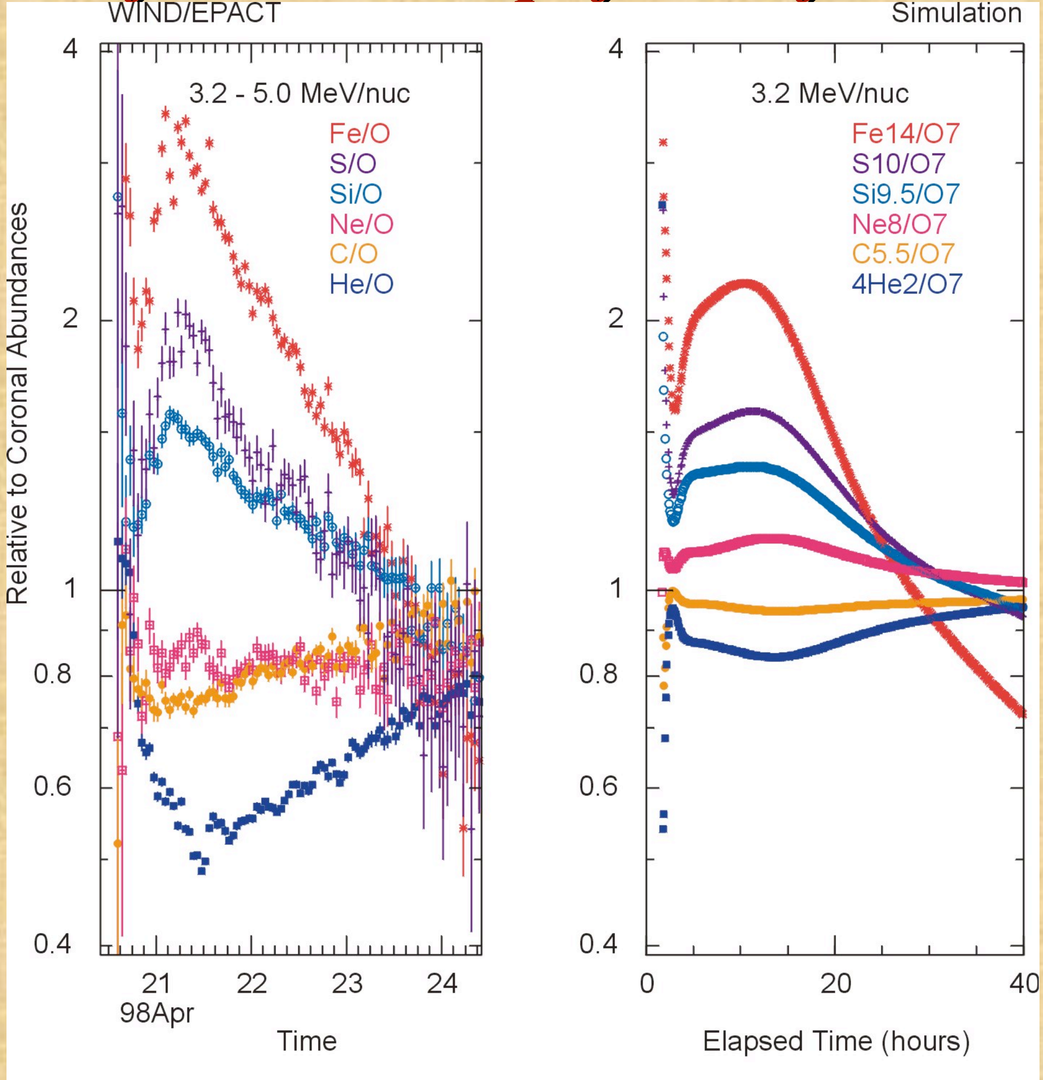
SEP Transport: The Role of Proton-Amplified Alfvén Waves

Hourly-Averaged X/O Abundance Ratios

vs.

Time

for 3 Days



Tylka, Reames, & Ng, GRL 26, 2141, (1999). *Ng, Reames, & Tylka, GRL 26, 2144, (1999).*

SEP Transport: The Role of Proton-Amplified Alfvén Waves

Couple Wave-Particle Equations

$$\frac{\partial f_s}{\partial t} + \mu v \frac{\partial f_s}{\partial r} + \frac{1-\mu^2}{r} v \frac{\partial f_s}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D^s_{\mu\mu} \frac{\partial f_s}{\partial \mu} \right) = G_s$$

$$\frac{\partial I_\sigma(k,r,t)}{\partial t} = \gamma_\sigma(k,r,t) I_\sigma(k,r,t)$$

$$\gamma_\sigma = 2\pi^2 g_\sigma e^3 c V_A \iint d\mu dP \frac{P^3}{E^2} \frac{R^\sigma_{\mu\mu}}{(1-\mu V_\sigma/v)^2} \frac{\partial f_{\mathrm{H}}}{\partial \mu}$$

$$D^s_{\mu\mu} = \frac{v^2}{4P^2} \sum_\sigma \int dk\, I_\sigma(k,r,t) R^\sigma_{\mu\mu}(\mu, v, P, k, V_\sigma)$$

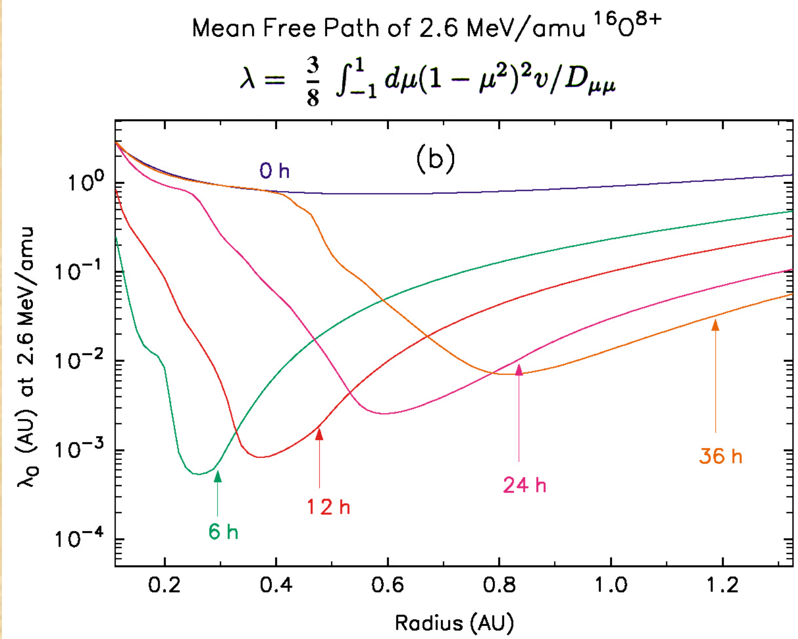
Particle quantities in red.

Wave quantities in blue.

Ng, Reames, & Tylka, GRL 26, 2144, (1999).

Mean Free Paths

Ng, Reames & Tylka, Proc. 26th ICRC 6, 151-154 (1999)



Other Consequences:

- *Streaming-limited intensities*
- *Flattened Spectra*
- *Decay of Anisotropies*
- *Multiple-Event Effects*

See Reames, AIP Conf. Proc. 528, 79, (2000).
Tylka, JGR 106, 25333, (2001).

Differential Energy Spectra of Shock-Accelerated Ions

Inspired by Ellison & Ramaty, *Astrophys. J.* **298**, 400-408 (1985)

$$F_X(E) = C_X \cdot (E^2 + 2ME)^{-\gamma} \cdot \exp(-E/E_{0X})$$

Spectral Index γ
- **determined by shock compression ratio**
- **in principle, same for all species**
- **can be modified by transport effects**

C_X **= normalization constant**
M = 938.3 MeV/nuc

Exponential Rollover E_{0X}
- **Due to finite shock size/lifetime**
- **Species dependent**
- **If**

$$\lambda_{SHOCK} \sim R^{\alpha} \text{ with } \alpha = 1$$

then

$$E_{0X} \sim Q_X / A_X$$

- **More generally,**

$$E_{0X} \sim (Q_X / A_X)^{\delta}$$

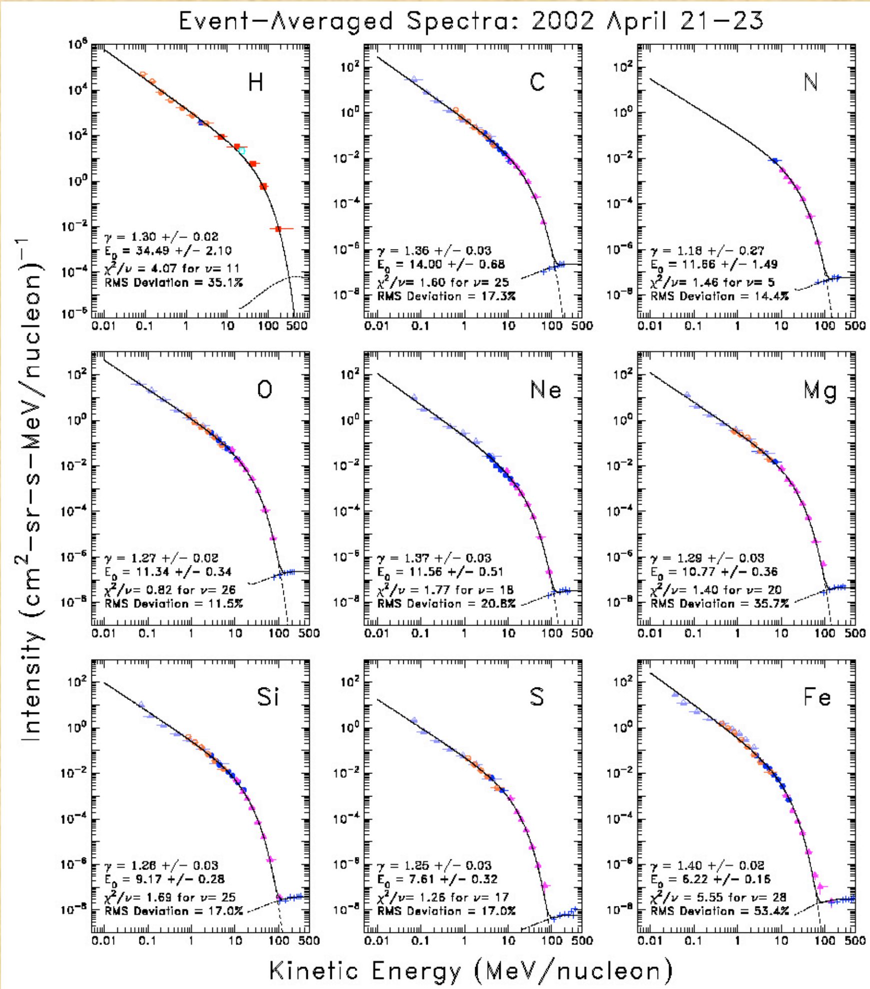
See Tylka et al. (ACE2000 Proceedings) for application to 20 April 1998 and 25 August 1998 events.

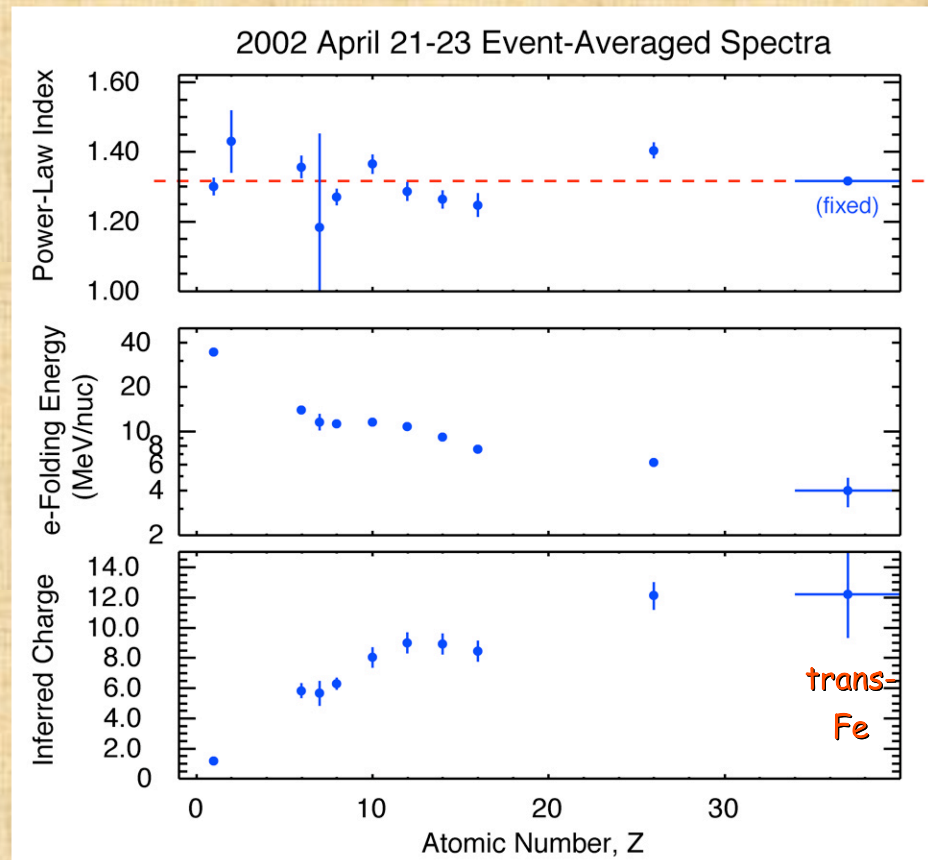
Spectral Origin of Highly Suppressed Fe/O at High Energies

$$F_x(E) \sim E^{-\gamma} \exp(-E/E_{0x})$$

with $E_{0x} \propto Q_x/A_x$

(Ellison & Ramaty 1985)

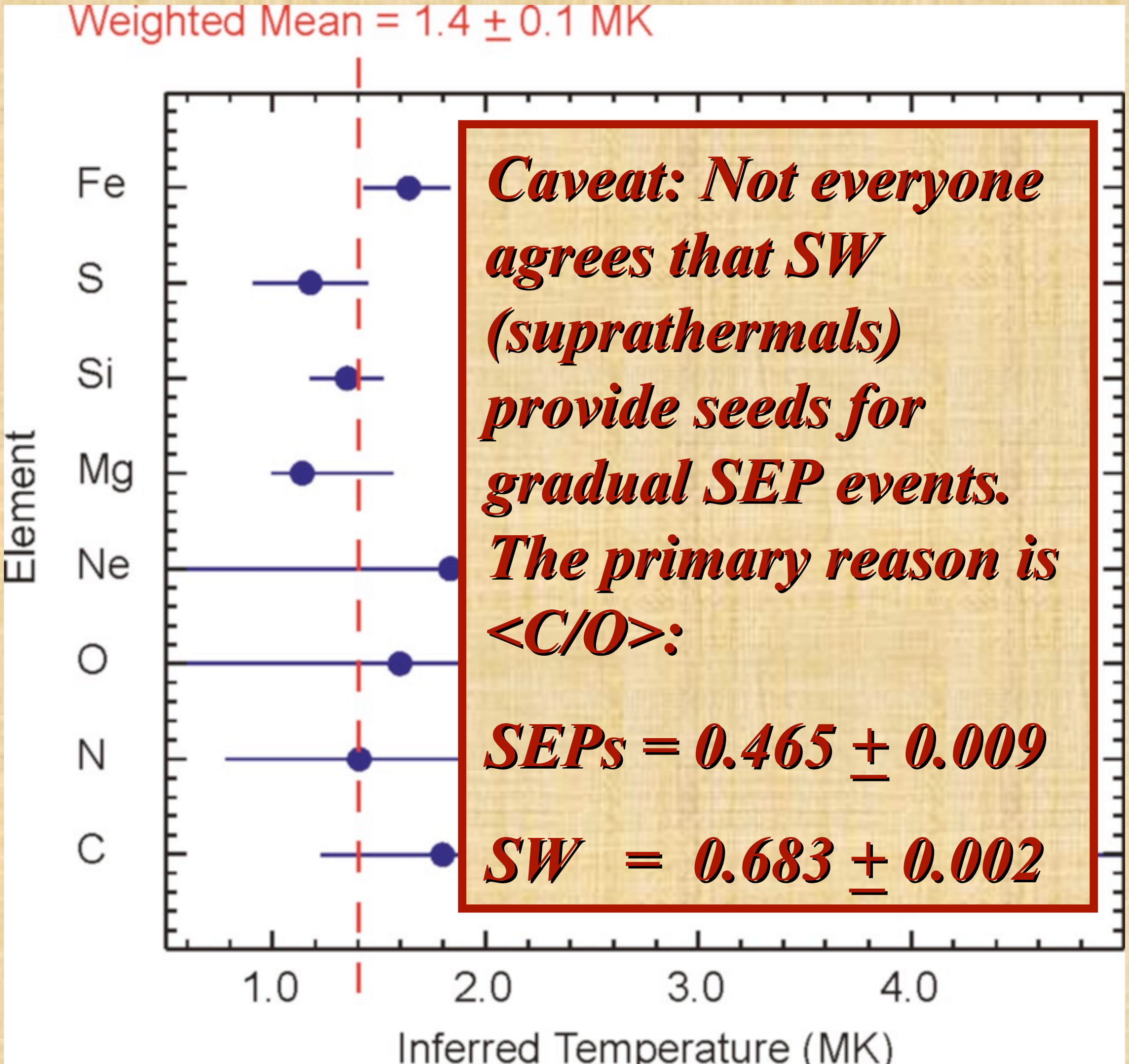




Data from 8 instruments, 5 satellites

- ***Oxygen charge state measured by SAMPEX***
- ***Others inferred by scaling according to fitted E_0***

Solar-wind Seed Population in the 2002 April 21 Event



Caveat: Not everyone agrees that SW (suprathermals) provide seeds for gradual SEP events. The primary reason is <C/O>:

SEPs = 0.465 ± 0.009

SW = 0.683 ± 0.002

- *Use theoretical calculations to determine temperatures of the source plasma from the mean ionic charge states*

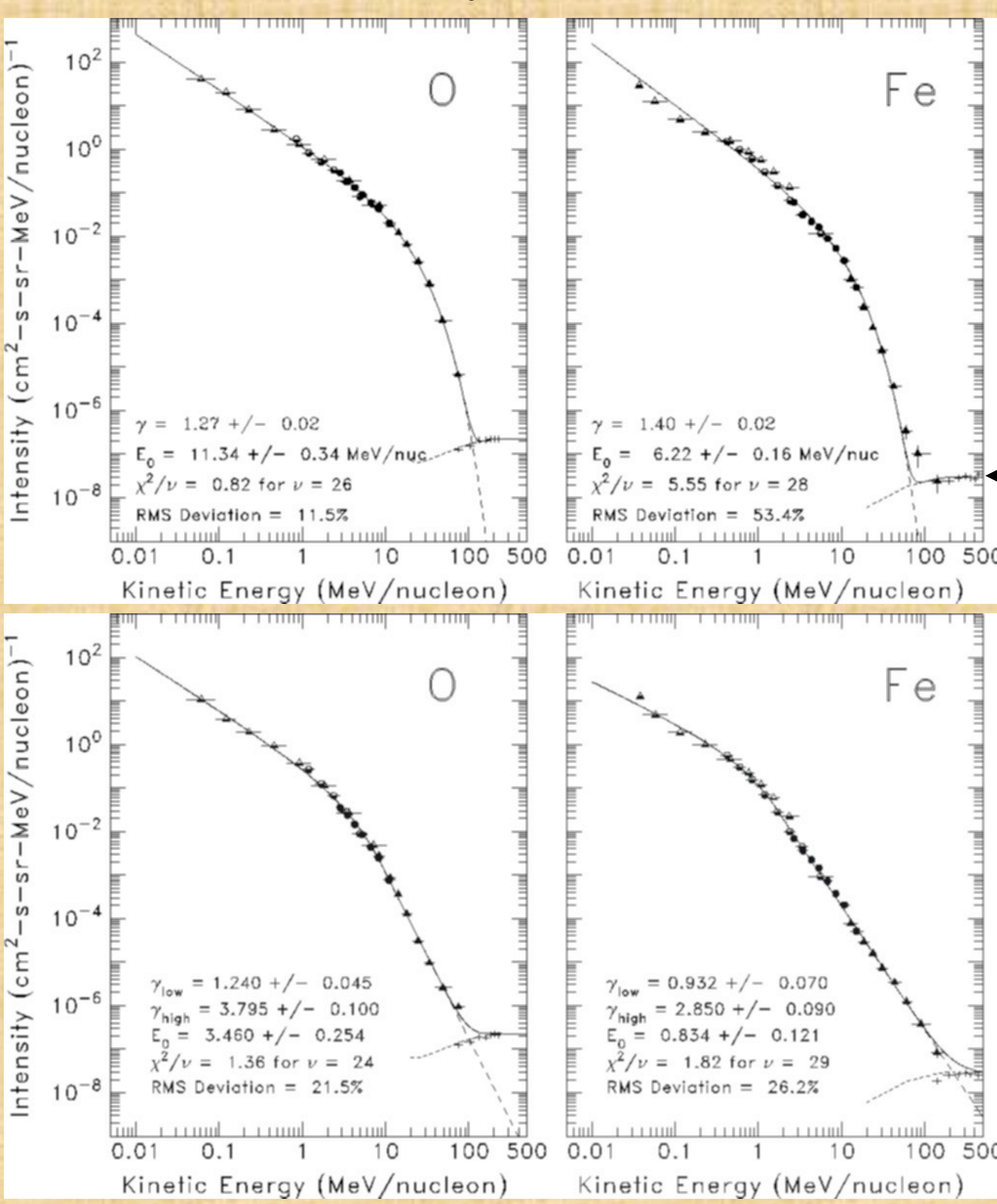
  Arnaud & Rothenflug 1985
  Arnaud & Raymond 1992

- *All species consistent with 1.4 MK, typical of the solar wind.*

- ***These charge states are our justification for identifying solar wind (suprathermals) as the dominant seed population in this event.***

Spectral Variability: Compare 2002 April 21 & 2002 August 24

(Data from ACE/EPAM, ACE/ULEIS, Wind/LEMT, and ACE/SIS)



Galactic Cosmic Rays

2002 April 21:

- *Fits to* **F(E) ~ $E^{-\gamma}$ exp(-E/E_0)**
- *At high energies:*

  Fe softer than O (and C)

2002 August 24:

- *Double power-laws:*

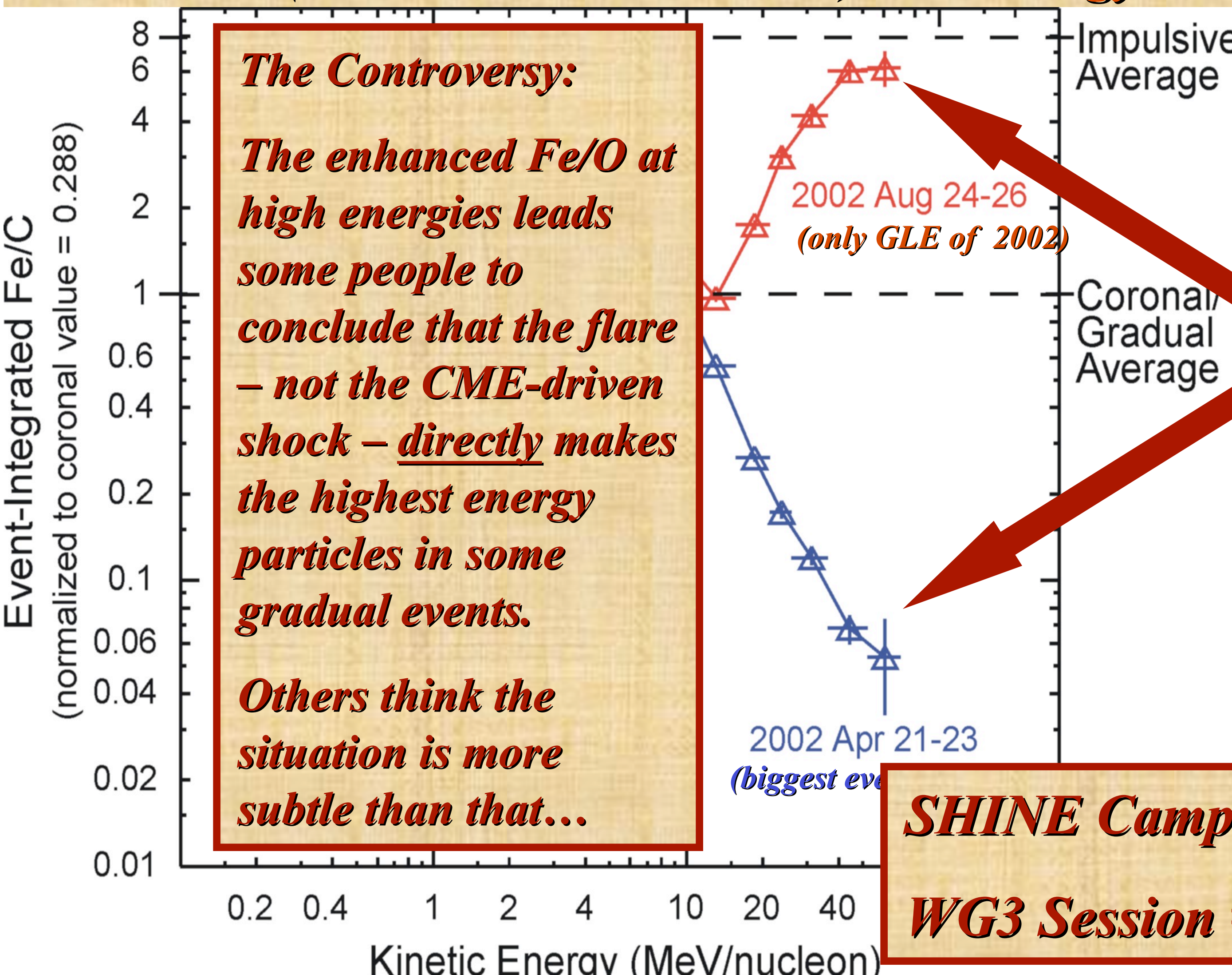
  Fits to Band et al. (1993) fcn
- *At high energies:*

  Fe harder than O (and C)

SEP Variability at High Energies

(above a few tens of MeV/nuc)

Fe/C (normalized to corona) vs. Energy



The Controversy:

The enhanced Fe/O at high energies leads some people to conclude that the flare – not the CME-driven shock – directly makes the highest energy particles in some gradual events.

Others think the situation is more subtle than that…

Here's the puzzle:

What makes these two events different at high energies?

SHINE Campaign Events

WG3 Session #1, Tuesday AM

Insert Huge Caveat Here

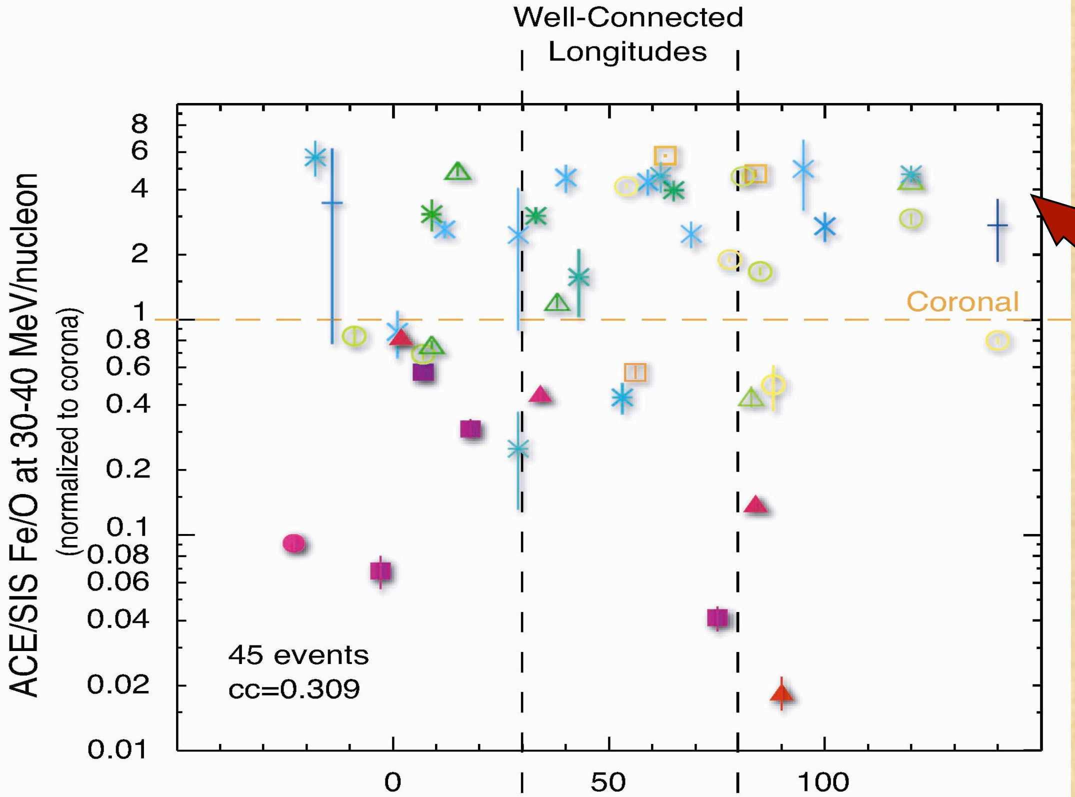
When we look at the gradual SEP events at high energies, we see large event-to-event variability in:

- Spectral Shapes
- Elemental Composition (especially Fe/O and Fe/C)
- Mean Ionic Charge States (especially Fe)

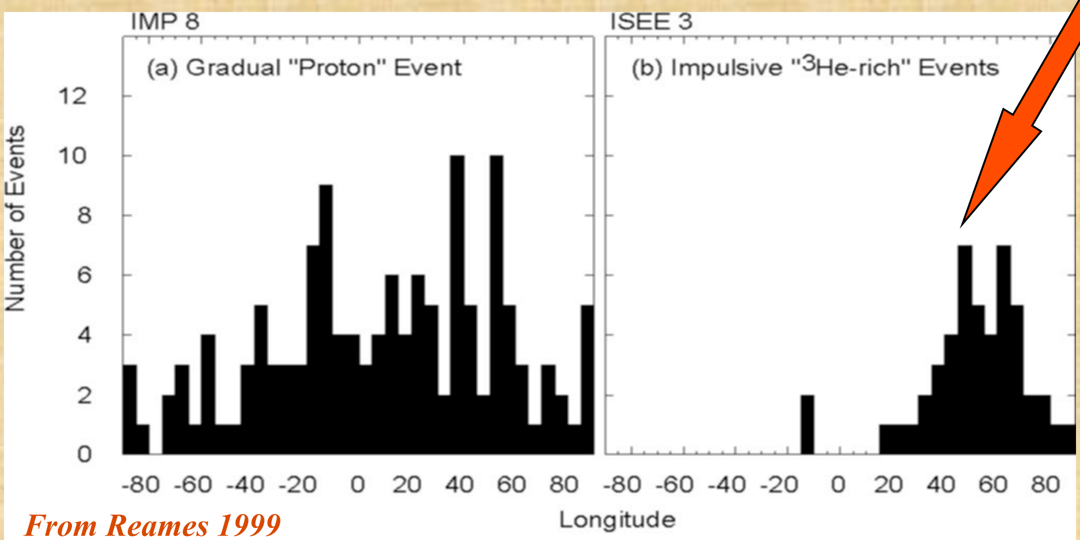
The origin of high-energy variability is a controversial problem in the SEP community.

The following slides reflect this speaker's efforts to understand this problem.

Longitude Distribution of SEP Events



From Tylka et al. 2004

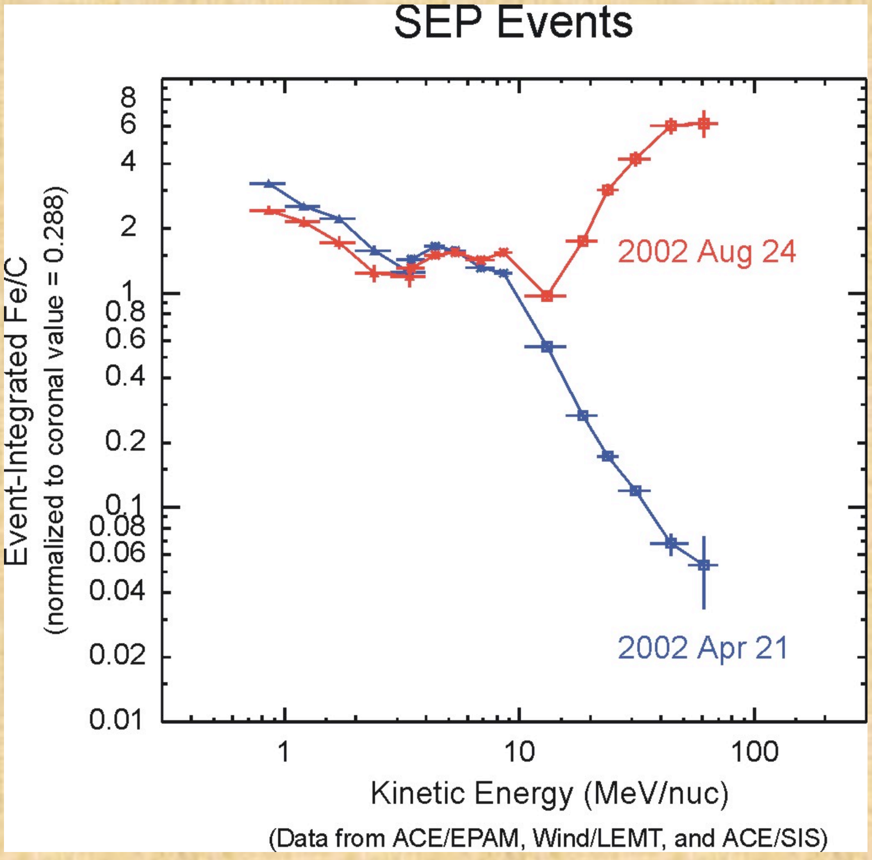


From Reames 1999

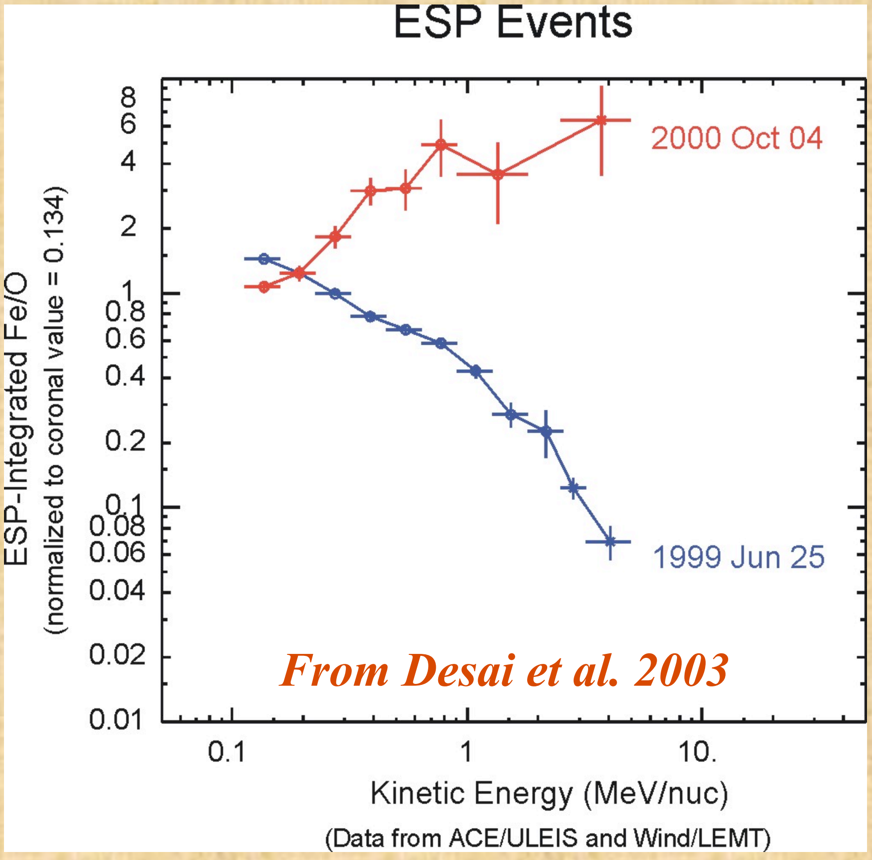
- *These large Fe-rich events are observed from sources all across the Sun*
- *Unlike classic ^{3}He-rich "impulsive" events:*
  - *observable only at magnetically-connected solar longitudes:*
  - *85% between W30 and W80.*
  - *Spread primarily due to variation in solar wind speed.*

SEPs and ESPs

Solar Energetic Particles
(accelerated near the Sun)



Energetic Storm Particles
(accelerated locally, near 1 AU)



Same range of behavior observed in both SEP and ESP events.

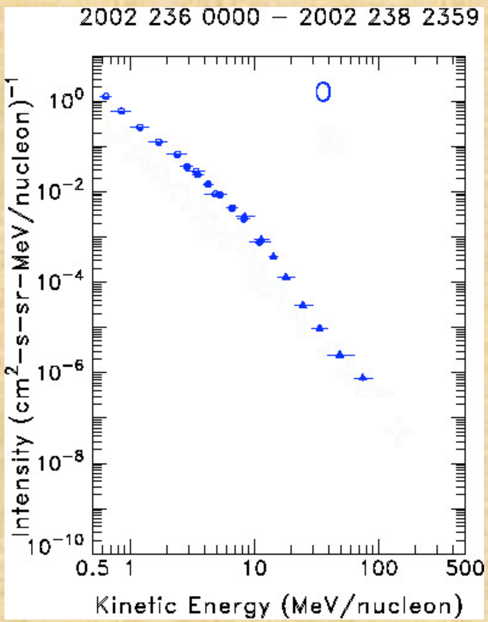
- *Suggests a common mechanism, associated with shocks.*

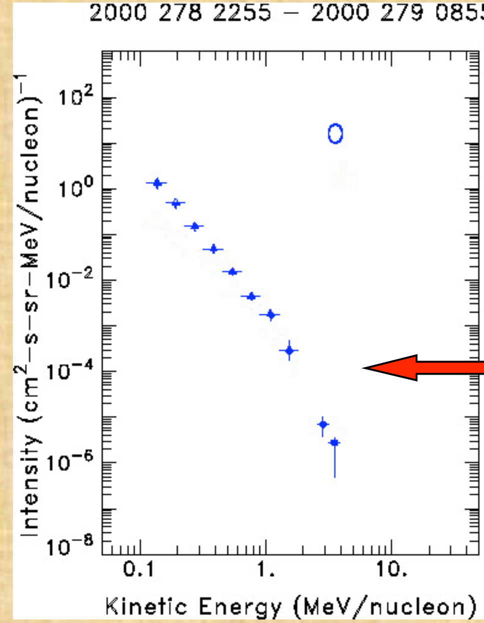
What other differences can we find between Fe-rich & Fe-poor events?

SEP Events

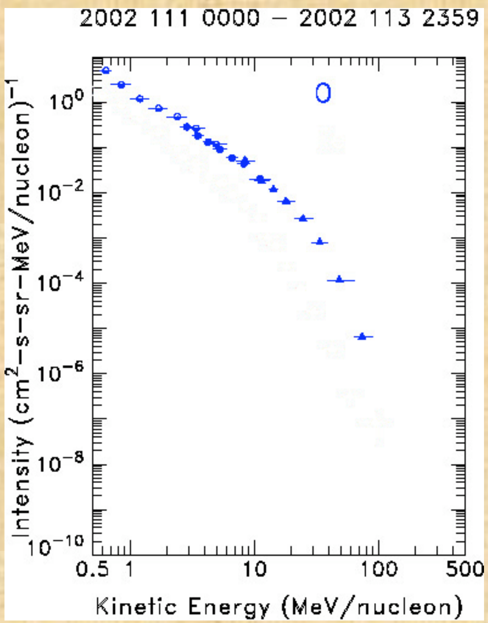
ESP Events

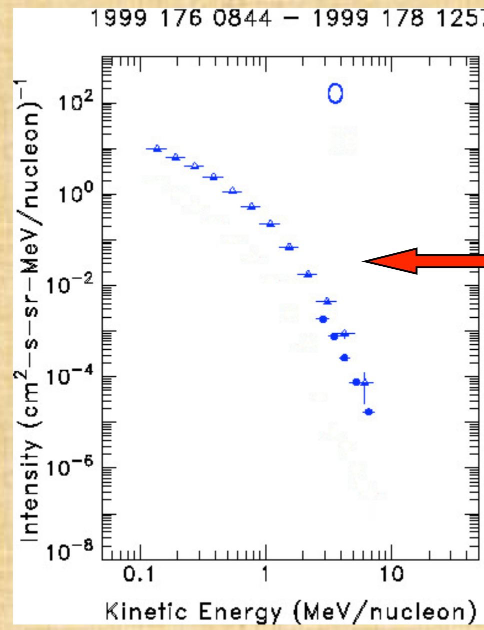
Fe- Rich *at the highest energies*





Fe- Poor *at the highest energies*





Compare oxygen spectra:

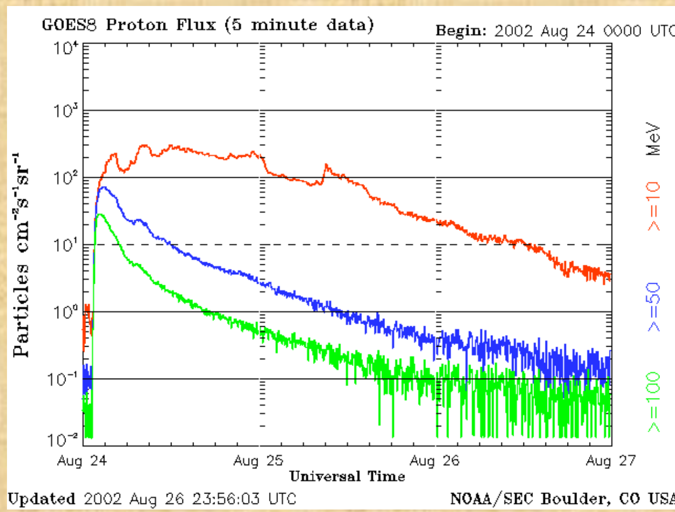
Nearly power-laws in Fe-rich events.

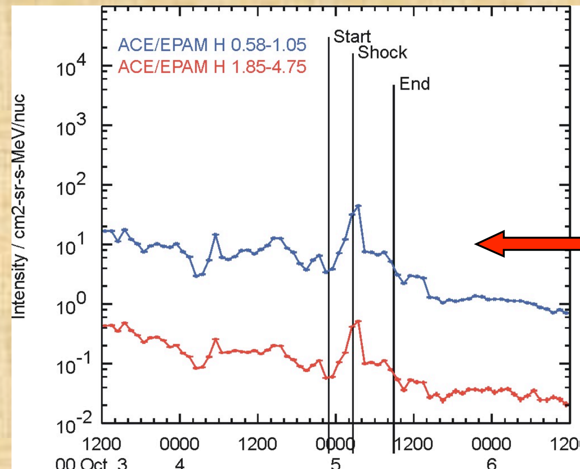
But clear rollovers in Fe-poor events

SEP Events | *ESP Events*

GOES Protons (>10, >50, >100 MeV) | *ACE/EPAM Protons (0.6, 2.0 MeV)*

Fe- Rich *at the highest energies*



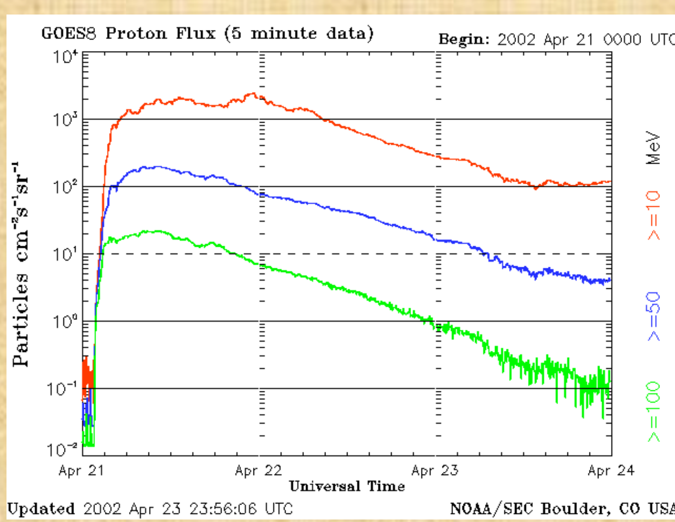


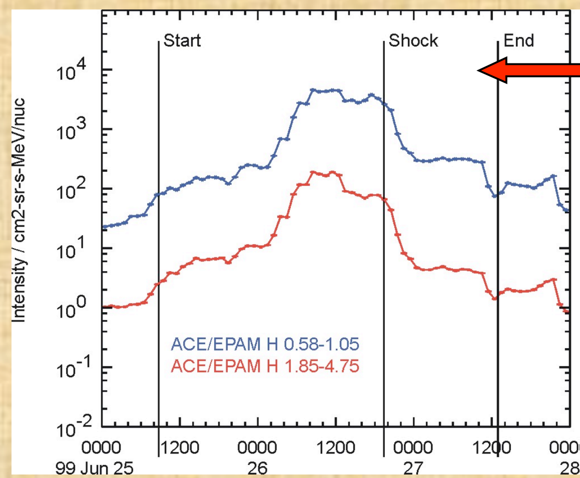
Compare proton time profiles:

"Spikes":

Small size

Fe- Poor *at the highest energies*





Extended enhancements

Big fluence

For shocks at 1 AU, Tsurutani & Lin (1985) showed that these differences are associated with shock geometry.

Hey, wait a minute. There's a pattern here…

For both SEP events ("shocks near the Sun") and ESP events ("shocks at 1 AU"), we see characteristics grouped together:

- *Fe/O falling with energy & Fe-poor at high energies*
- *Bigger Event*
- *Longer Duration*
- *Softer spectrum, with exponential rollovoer*

- *Fe/O rising with energy & Fe-rich at high energies*
- *Smaller Event*
- *Shorter Duration*
- *Harder spectrum, nearly power-law, with no rollover*

Can we find a hypothesis that addresses this pattern?

Yes: Quasi-parallel v. Quasi-perpendicular shocks

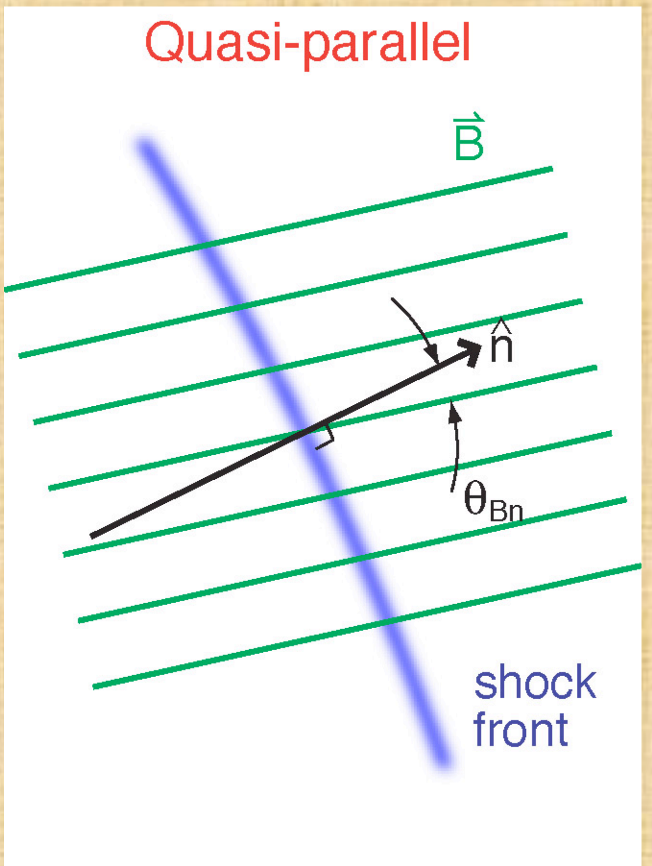
Shock Geometry

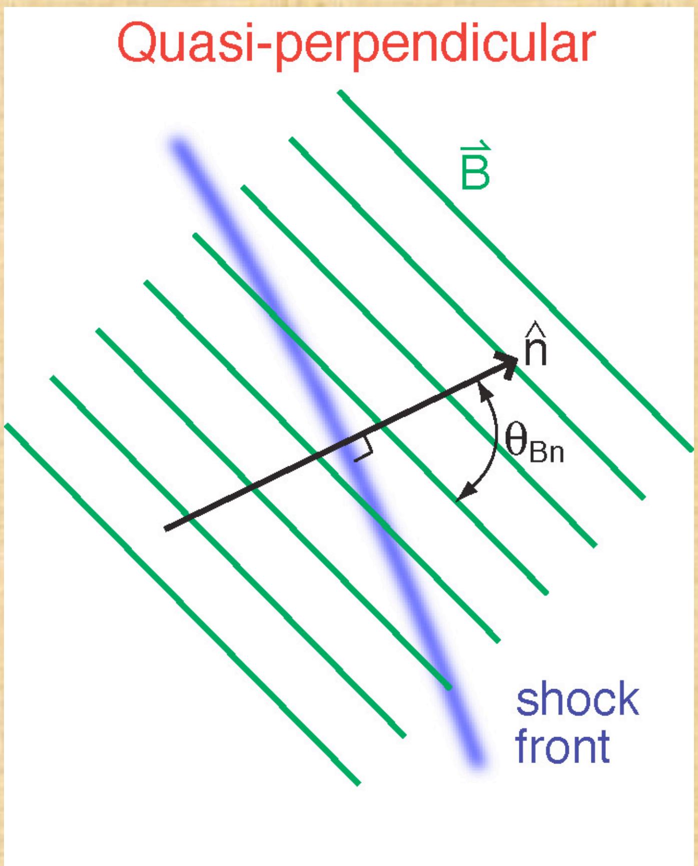
Shock rides over a given field line for a long time.

➢Extended time profiles

Easy escape from shock region:

➢Soft spectra at high energy





Shock quickly crosses a given field line.

➢'Spike' in the time profile

Field helps to retain particles in the shock region

➢Quick acceleration

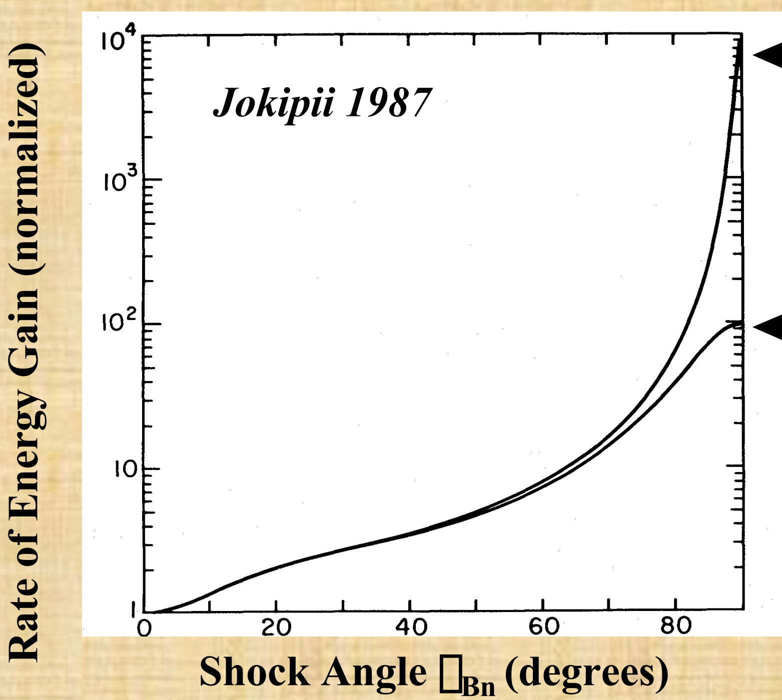
➢Hard spectra at high energy

Notes:

1. *Terminology refers to B-field and shock-normal.*
2. *θ_{Bn} changes as the CME moves out.*
3. *For high-energy SEPs, near-Sun geometry is important.*

A Theoretical Insight about Quasi-Perp Shocks (A Suspicion?)

Rate of energy gain is higher at quasi-perpendicular shocks.



$\kappa = \kappa_{\parallel} / r_g = 100$

$\kappa = \kappa_{\parallel} / r_g = 10$

Similar results also derived by Webb et al. (1995).

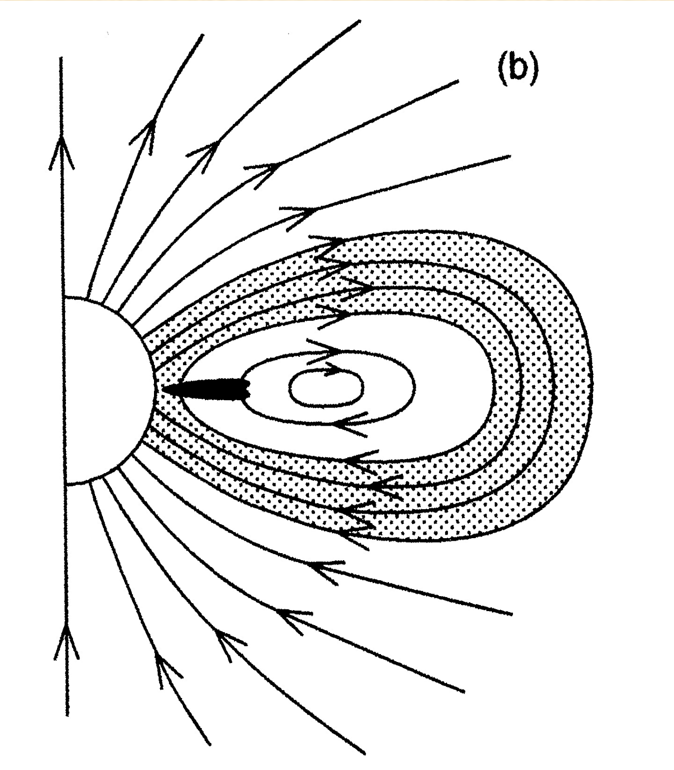
If a shock takes on a range of θ_{Bn} values, high-energies will be dominated by particles produced at θ_{Bn} ~ 90°.

Are there quasi-perp shocks near the Sun? Do they make SEPs?

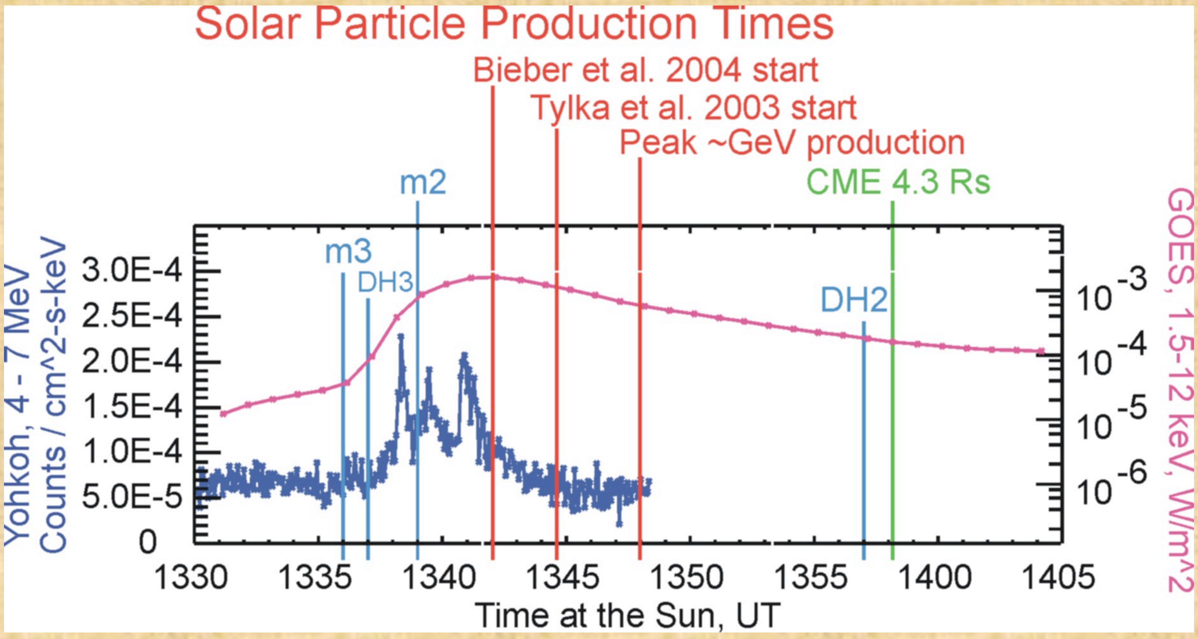
-- almost surely!

2001 April 15 GLE

(like 2002 August 24, but bigger)

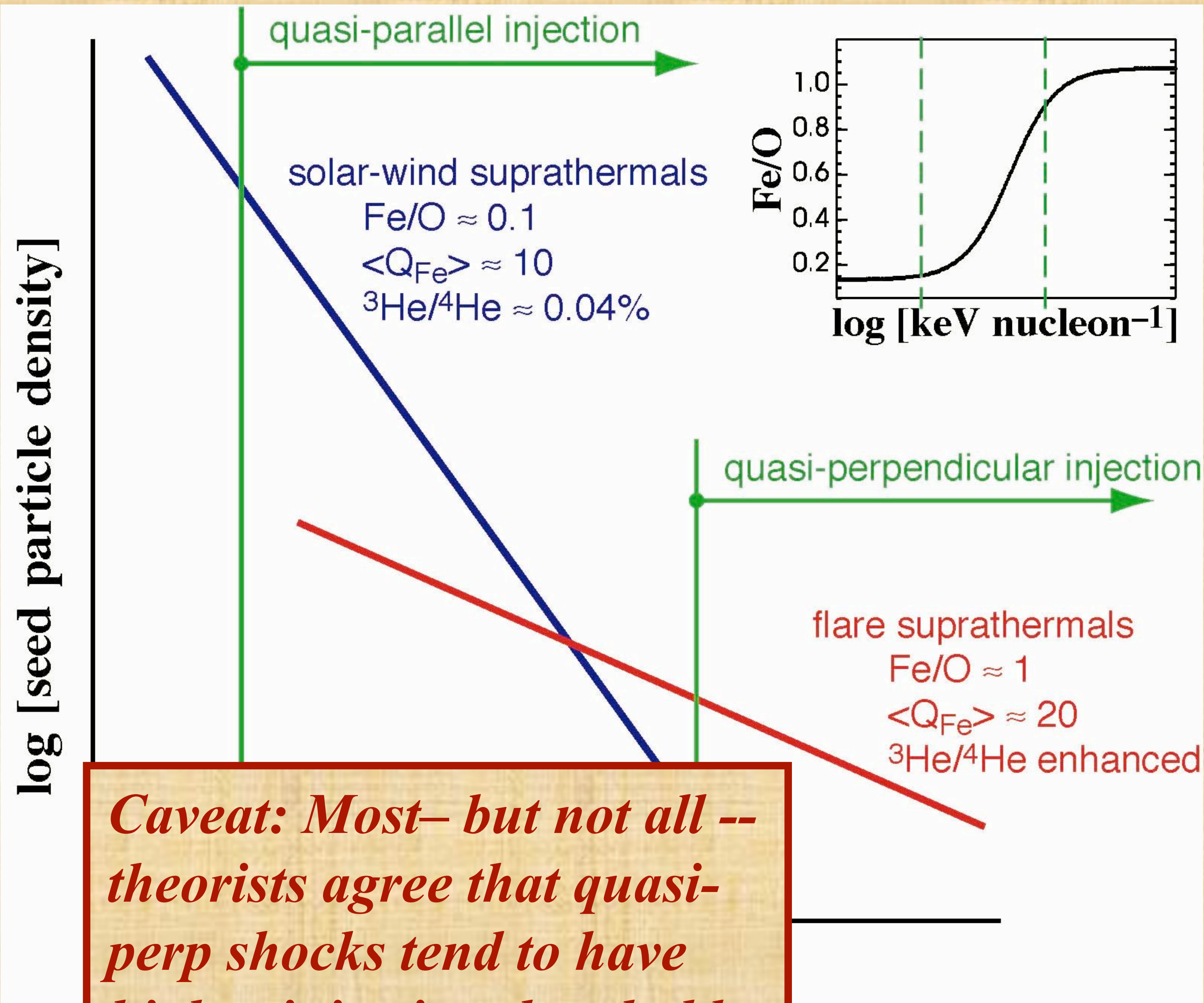


From B.C. Low, JGR 106, 25141, 2001



SEP onsets & peak of ~GeV production occurred when the CME was at ~2 R_S.

How can we get Fe/O increasing with energy?



Caveat: Most– but not all -- theorists agree that quasi-perp shocks tend to have higher injection thresholds.

- ***These two components naturally lead to energy-dependent composition in the seed population.***
- ***Quasi-perp shocks require particles to have have a higher initial speed.***
- ***Quasi-perp shocks will preferentially draw from the flare suprthermals.***

Consider varying θ_{Bn}, including both quasi-perp and quasi-parallel.

Effects of Averaging over a Varying Shock Angle

M.A. Lee & A.J. Tylka

$$F_X(E, \theta_{Bn}) = C_X E^{-\gamma} \exp(-E/E_{0x})$$

where $E_{0X} = E_0 [Q_X/A_X] [(\sec\theta_{Bn})^{2/(2\gamma-1)}] \equiv \breve{E}_{0X} [(\sec\theta_{Bn})^{2/(2\gamma-1)}]$

Let $\mu = \cos\theta_{Bn}$. Average the shock-spectrum over $0 \le \mu \le 1$.

- The flare component is accessible to the shock at all θ_{Bn} values.
- For the solar-wind component, introduce a heuristic weighting factor of μ.
  - Solar-wind component makes no contribution at a perpendicular shock.

$$F_{x,flare}(E) = C_{x,flare} E^{-\gamma} \int_0^1 \exp(-E\mu^{2/(2\gamma-1)}/\breve{E}_{0X,flare})\, d\mu \;/\; \int_0^1 d\mu$$

$$F_{x,sw}(E) = C_{x,sw} E^{-\gamma} \int_0^1 \mu \exp(-E\mu^{2/(2\gamma-1)}/\breve{E}_{0X,sw})\, d\mu \;/\; \int_0^1 \mu\, d\mu$$

To get closed-form results, consider $\gamma = 1.5$:

$$F_{x,flare}(E) = C_{x,flare} E^{-\gamma} (\breve{E}_{0X,flare}/E) [1 - \exp(-E/\breve{E}_{0X,flare})]$$

$$F_{x,sw}(E) = 2C_{x,sw} E^{-\gamma} (\breve{E}_{0X,sw}/E)^2 [1 - (1+E/\breve{E}_{0X,sw})\exp(-E/\breve{E}_{0X,sw})]$$

Other parameters: Nominal flare & coronal composition:

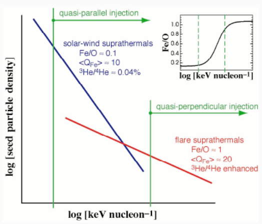
Flare Fe/O = 1 and coronal Fe/O =0.134

Observed flare & SW charge-state distributions:

Flare: $\langle Q_{Fe}\rangle = 17$, $\langle Q_O\rangle = 8$; SW: $\langle Q_{Fe}\rangle = 10$, $\langle Q_O\rangle = 6$

Relative size of flare- and SW-seed components:

$R = (C_{oxygen, flare}) / (C_{oxygen, SW})$



Power-law index the same for all species.

Species "X" and □$_{Bn}$ dependence reside in rollover, E_{0X}

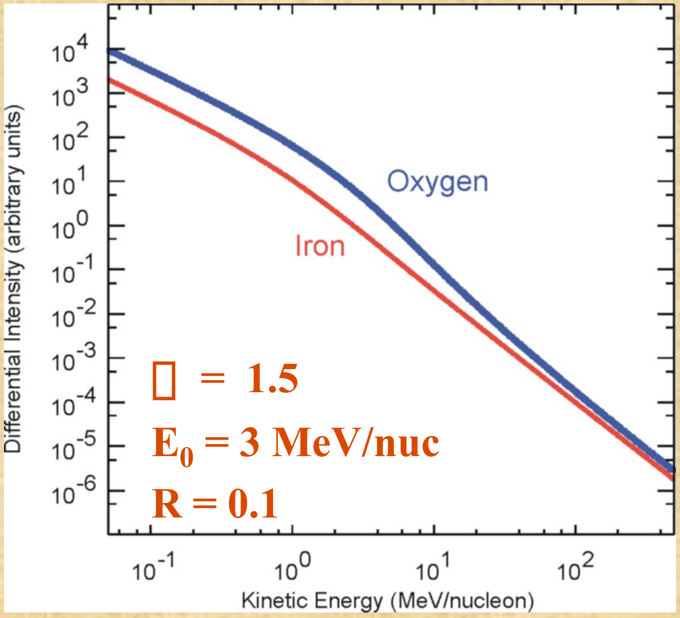
SW component has steeper spectrum by E^{-1}

Flare & SW components have different Q/A dependence

Parameters :

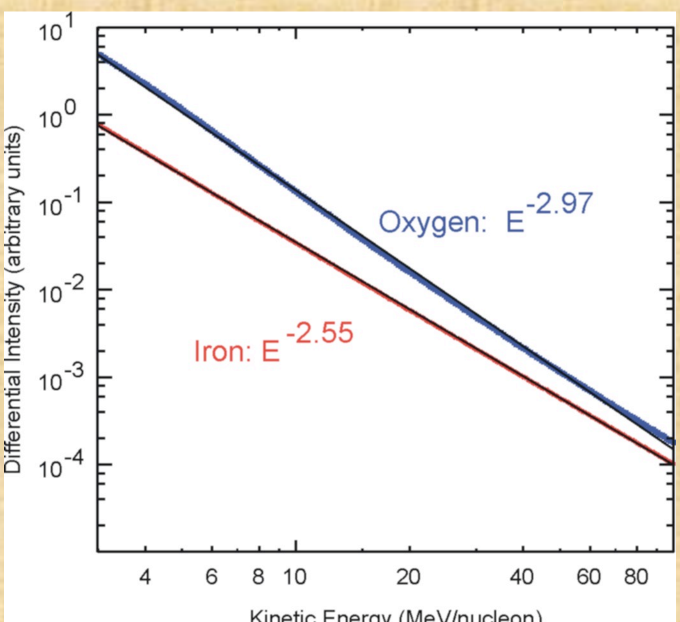
□, E_0, R

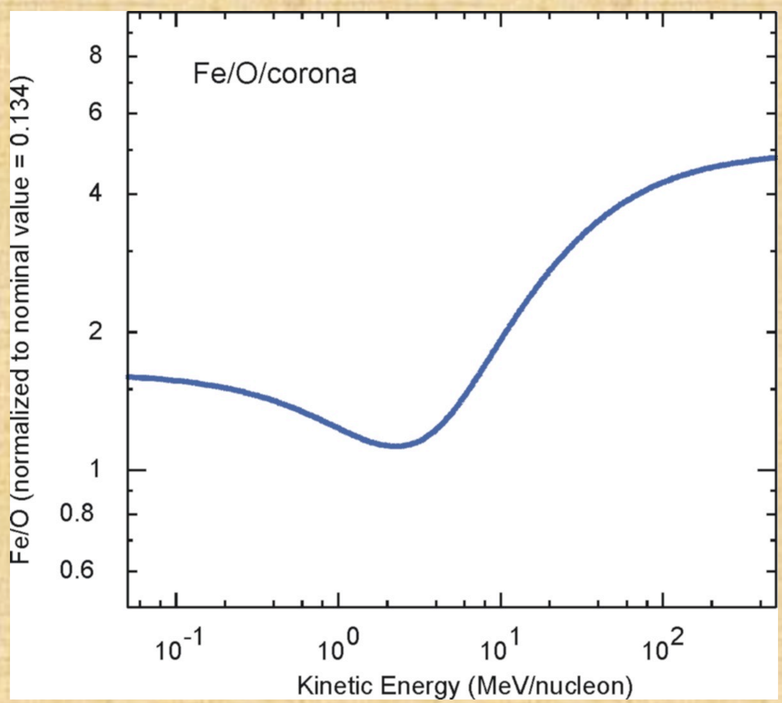
Effects of Averaging over a Varying Shock Angle



This simple, heuristic calculation reproduces significant features of the data:

- ***Roughly double power-law spectra***
- ***(Nearly) power-laws at high energy, with Fe harder than O***
- ***Fe/O increasing with energy***

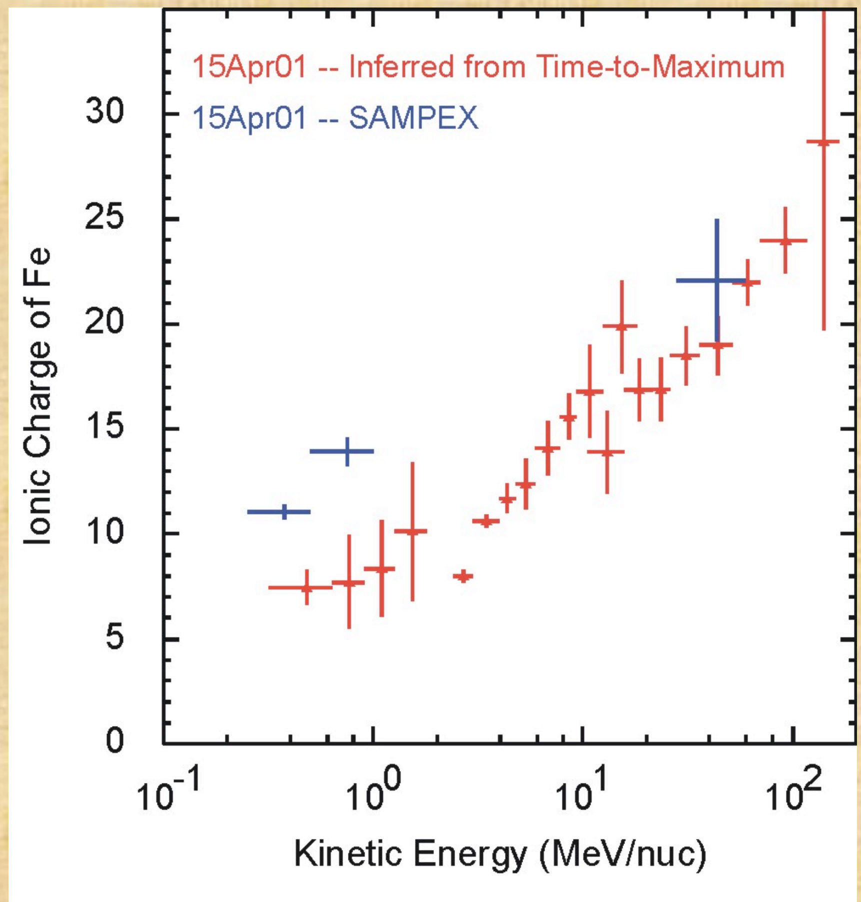




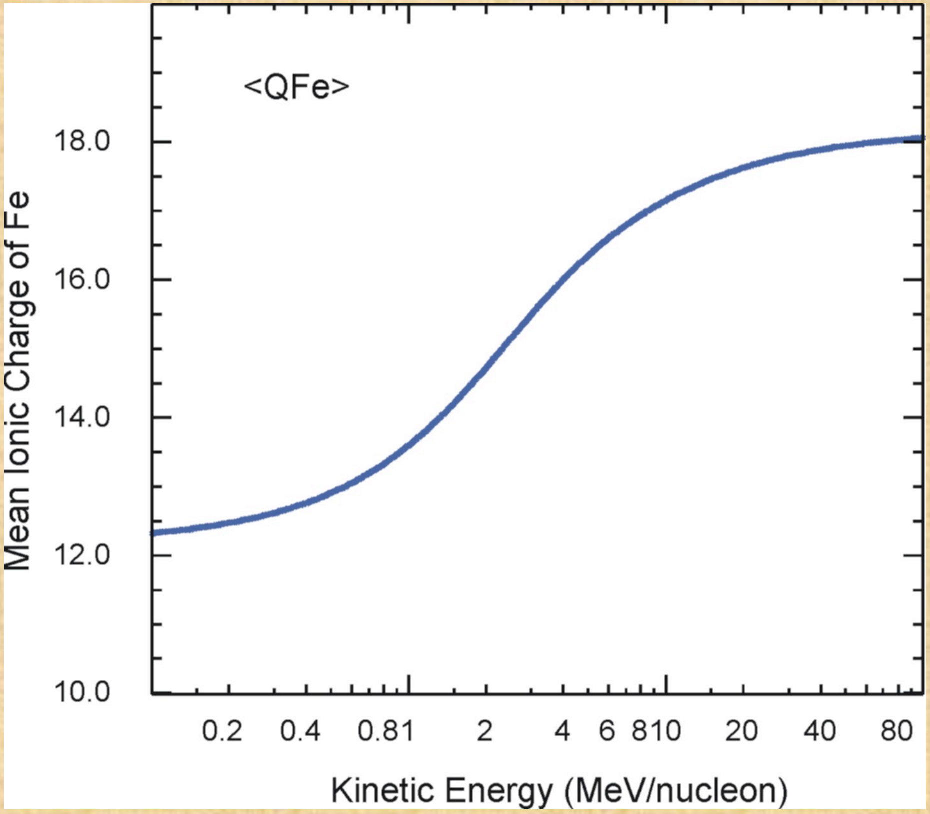
Energy-Dependent Fe Charge States

2001 April 15 GLE

(like 2002 August 24, but bigger)



From these calculations



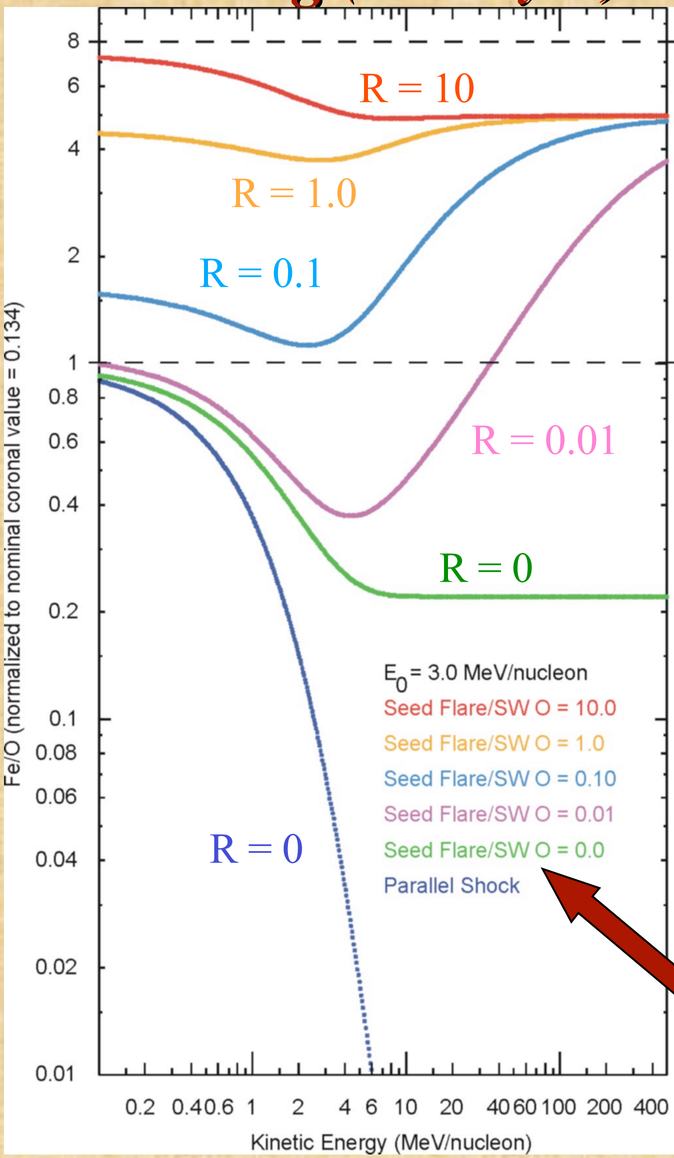
SAMPEX: Labrador et al. 2003

Mazur, private communication.

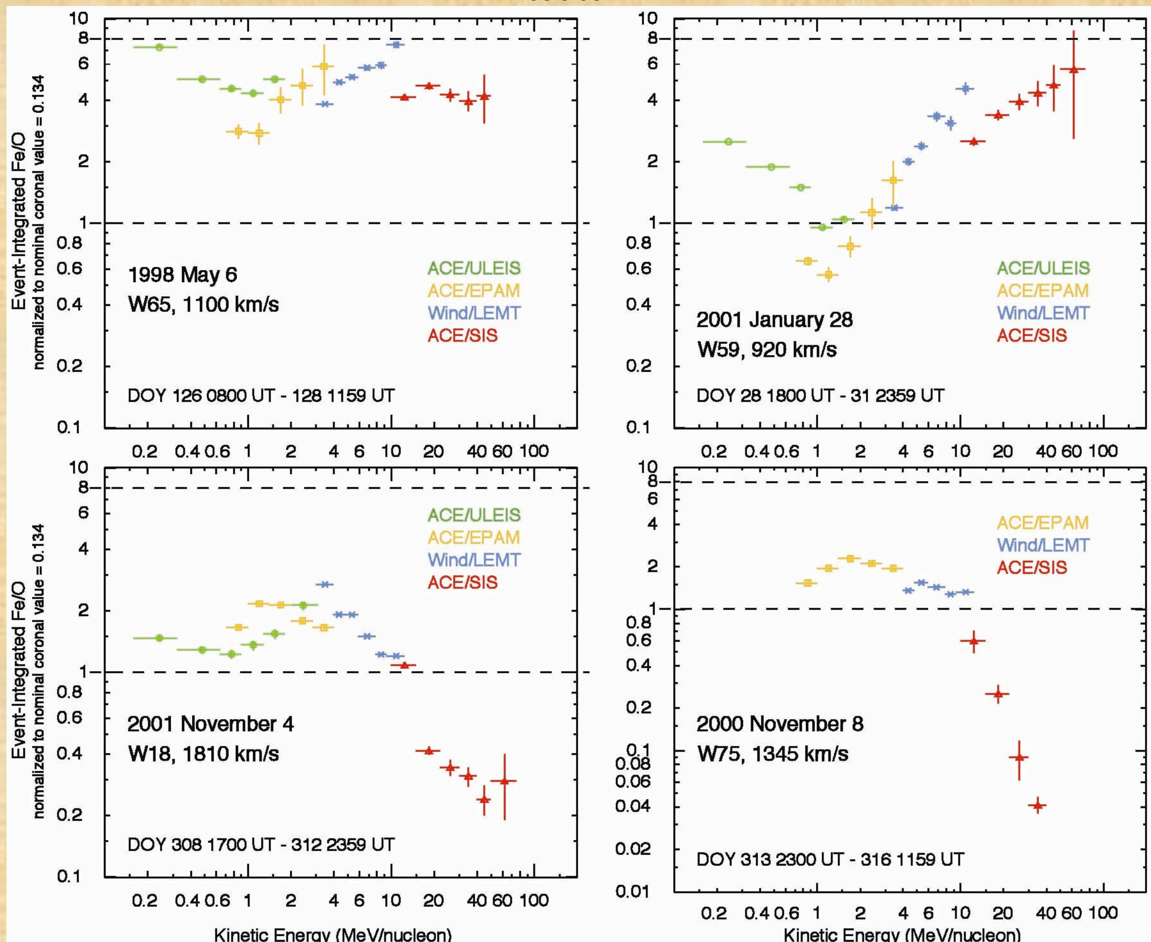
TTM: Dietrich & Tylka 2003

The "Zoo" of Fe/O vs. Energy

Modeling (Lee & Tylka)



Data



Tylka's Talk, Tues AM

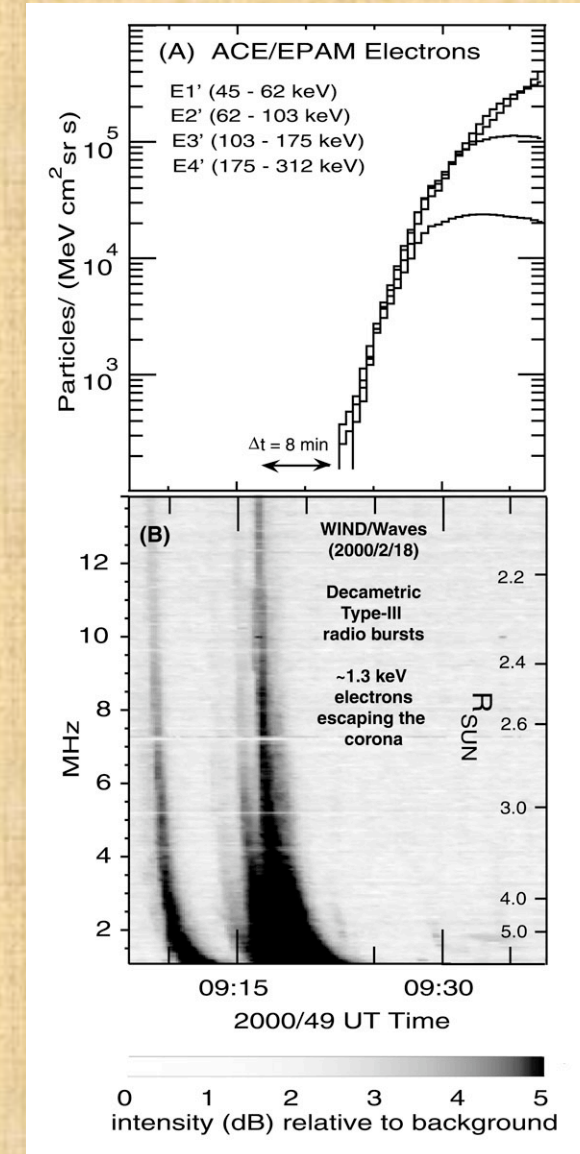
Modeling based on:

Variable shock geometry (quasi-perp & quasi-parallel)

Variable seed population (SW & flare suprathermals)

End
Huge Caveat
Here

WG3 Session #3 (Wed AM): "Solar Electrons"



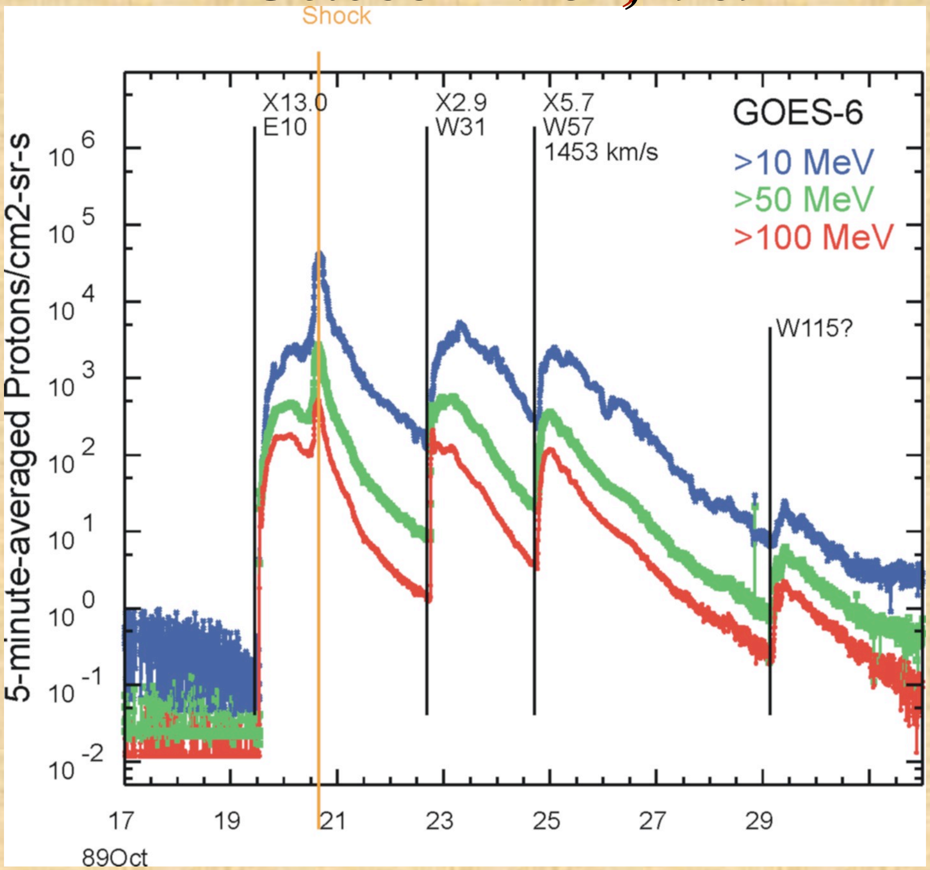
Haggerty & Roelof, ApJ 579, 841 (2002)

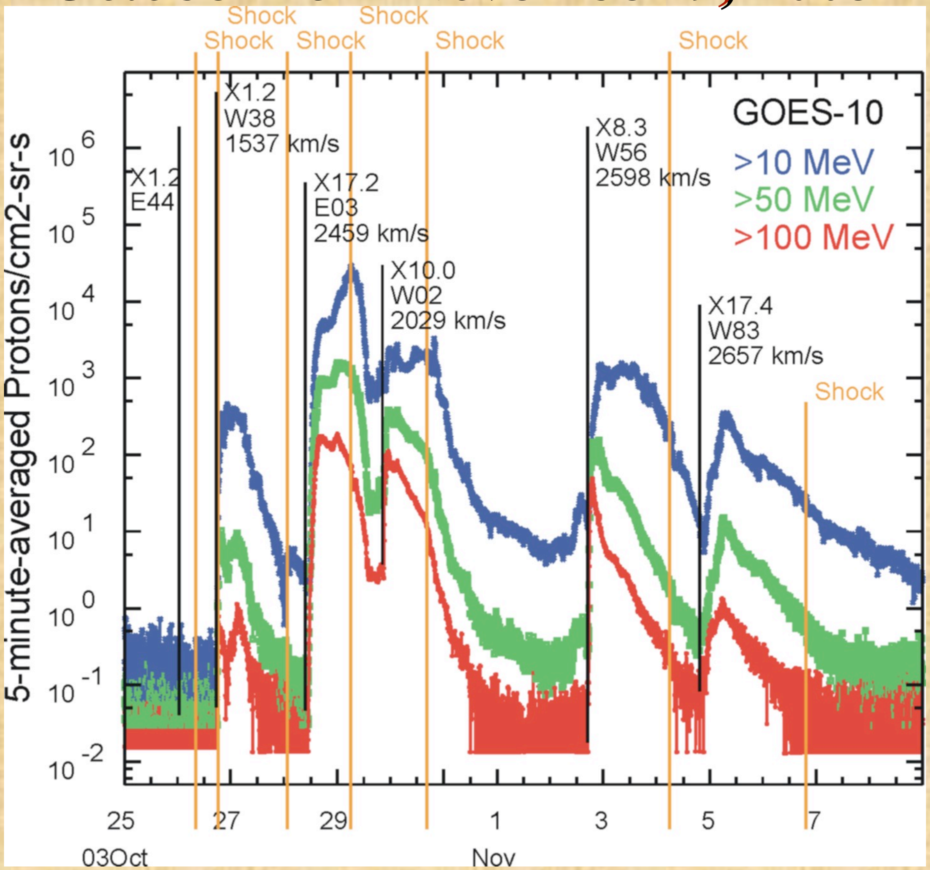
Except for their use in some of the timing studies, we haven't discussed electrons, which are also accelerated over a wide range of energies.

This session will discuss solar electrons and the additional information they provide on the sites and mechanisms of acceleration and on transport.

WG3 Session #4 (Thurs AM): "Extreme Events"

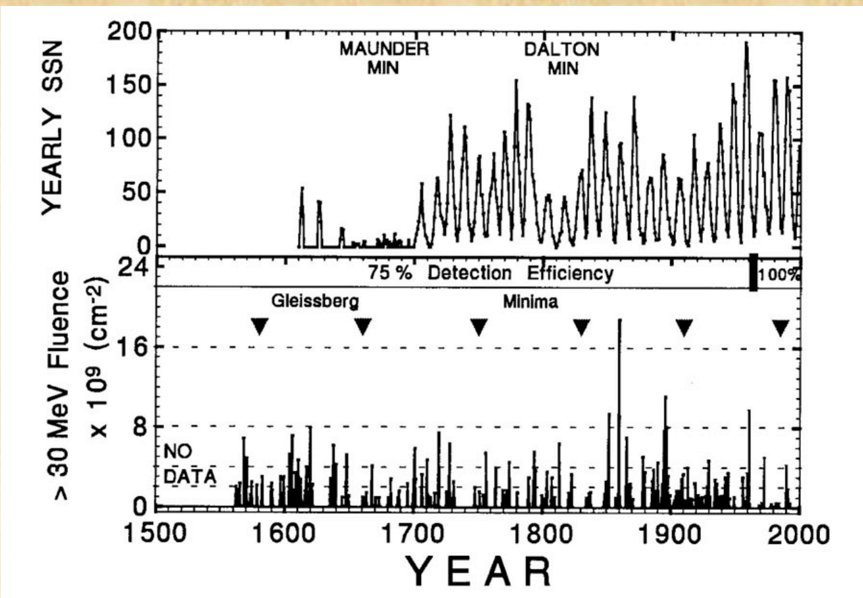
October 17-31,1989   *October 25 – November 9, 2003*

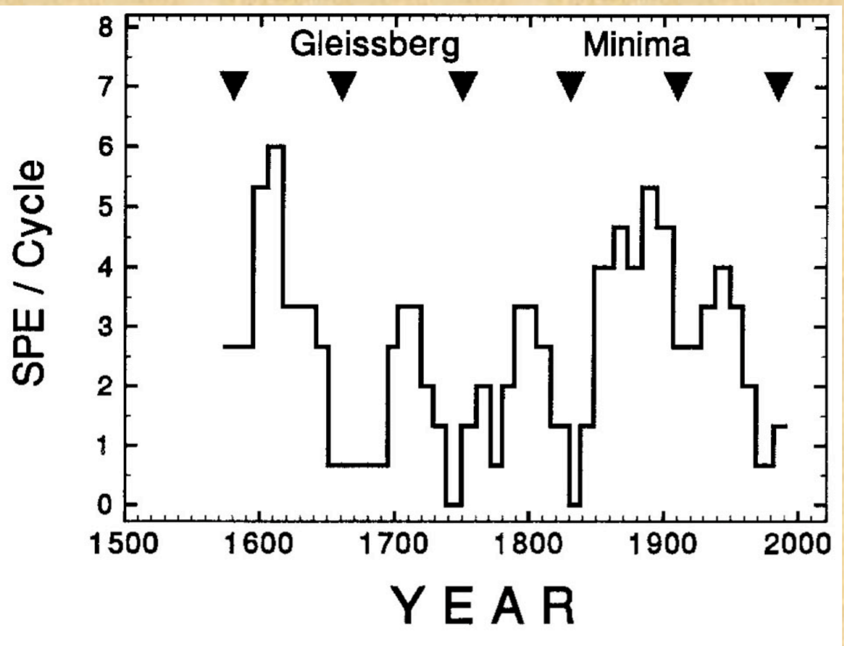




- ***These should really be called "episodes", since we have multiple large events erupting from the same active region in just a few days.***
- ***In the Space Age, we've see about one such "episode" per Solar Cycle.***

WG3 Session #5 (Thurs AM): "Long Term Variability"





McCraken, Dreschoff, Smart, & Shea, JGR 106, 21599 (2001).

- *Solar proton events (> 30 MeV) from arctic ice cores, going back to 1500 AD!*
- *Note the relatively small fluence and numbers of events in the Space Age.*

WG3 Session #5 (Thurs PM): "Long Term Variability"

- *McCracken et al. (2001) write:*
    - *"We predict that the frequency of large solar proton (episodes) may increase from its present low value by a factor of 6 to 8, commencing perhaps in Solar Cycle 24. Should this prediction be correct, the Earth will experience substantially more solar proton events and ground level events than has been our experience since 1950. This will have major implications for space flight and engineering."*

McCraken, Dreschoff, Smart, & Shea, JGR 106, 21599 (2001).

Summary

- *Solar Energetic Particles:*
  - *Interesting & challenging physics*
  - *Very important for Space Weather & Human Exploration*
- *Two distinct acceleration mechanisms:*
  - *"impulsive" events – accelerated at flares*
  - *"gradual" events -- accelerated by CME-driven shocks*
- *The two kinds of SEP events are distinguished by:*
  - *Timing studies*
  - *Longitude distribution*
  - *Composition at ~ 1 MeV/nuc:*
    - *3He/4He, Fe/O, trans-Fe – strongly enhanced in impulsive events.*
- *The connection between the two types of events arises through seed population:*
    - *Particles from flares are further accelerated by shocks*
- *"Gradual" Events are complicated due to*
  - *Multi-component seed population*
  - *Dynamic transport processes*
  - *The details of shock acceleration (quasi-parallel vs. quasi-perp ?)*
- *Wind, ACE, SoHO, other satellites, and neutron monitors in Cycle 23 have allowed us to make substantial progress in understanding these complexities.*

For more information on ionizing radiation effects on spacecraft electronics, see:

Cosmic-Ray Effects on Micro-Electronics (CREME96)

https://creme96.nrl.navy.mil

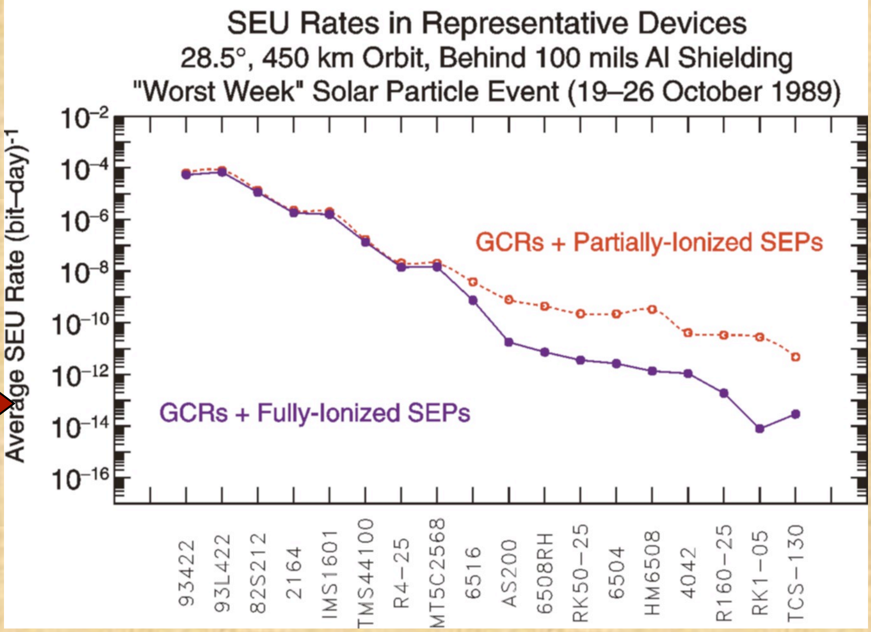
On-line space-system design tool to:

- *Create numerical models of near-Earth ionizing radiation environment for arbitrary orbits.*
- *Calculate transmission through Earth's magnetic field*
- *Propagate particles through shielding*
- *Estimate SEE rates and ion-dose.*

Applications:

- *Part selection for microelectronics*
- *Background estimates for sensors*
- *Analysis of spacecraft anomalies*

Estimated "bit-flip" rate for various parts in a low-Earth orbit during a very severe SEP episode (October 1989)



Tylka et al., IEEE NS 44, 2150 (1997)