3D Shock Propagation and Particle Acceleration: Insights from STEREO in-situ observations

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First STEREO Workshop

Paris, France March 18-20, 2002

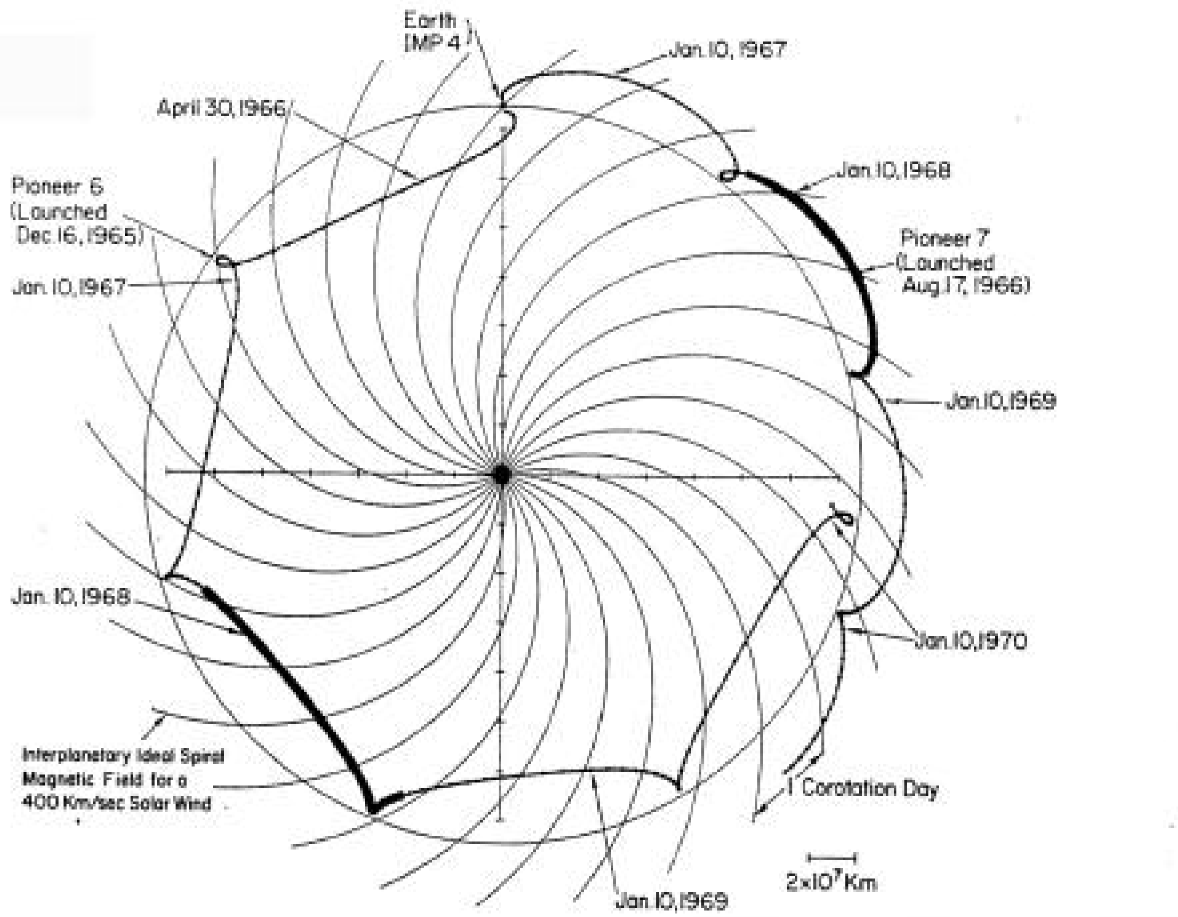


Fig. 1. Trajectories of the deep space probes Pioneer 6 and Pioneer 7 in a rotating coordinate system with the earth-sun line held fixed. Tics indicate the positions of the spacecraft every tenth day, starting on January 10 of each year.

R. B. McKibben, JGR, 77, 3957, 1972

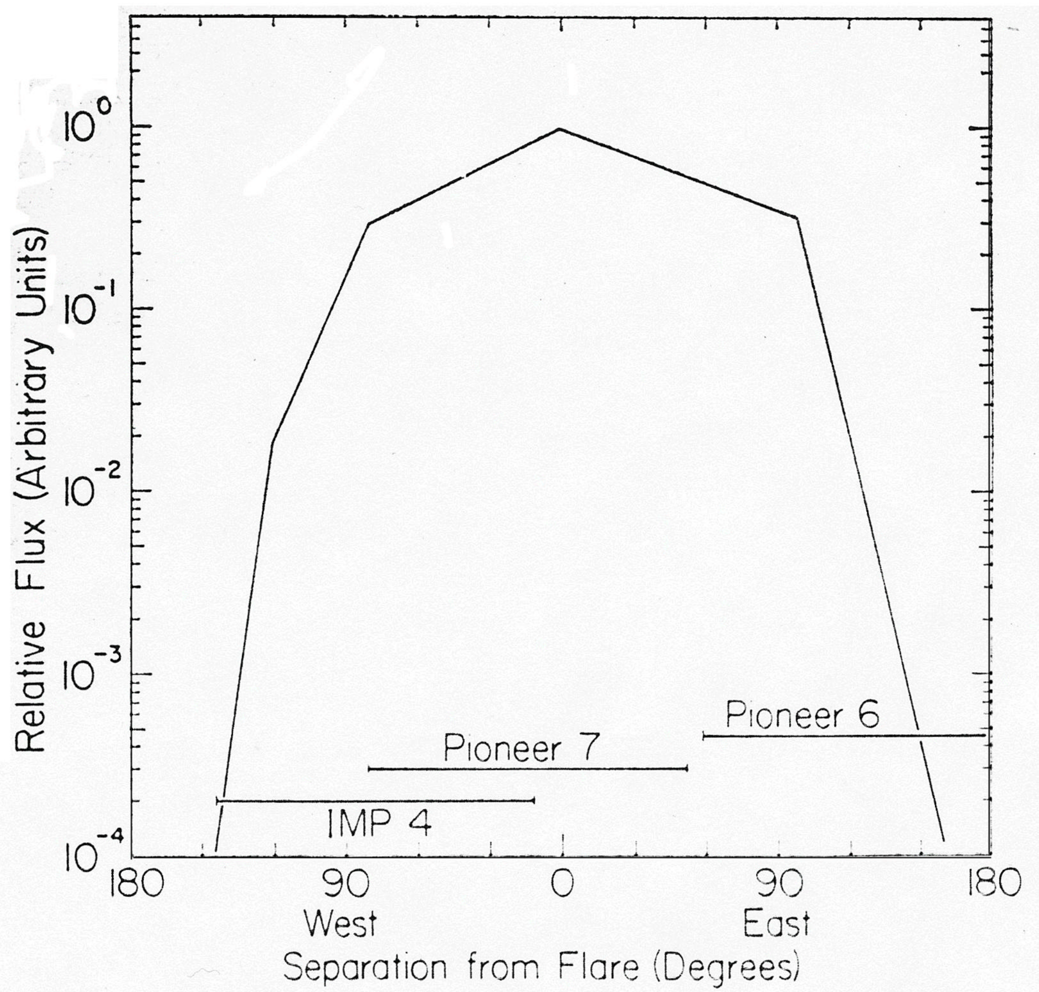


Fig. 12. An azimuthal intensity distribution for 15- to 18.7-Mev protons consistent with observations of the rise to maximum at Imp 4 and the decays at Imp 4, Pioneer 6, and Pioneer 7.

R. B. McKibben, JGR, 77, 3957, 1972

R. B. McKibben

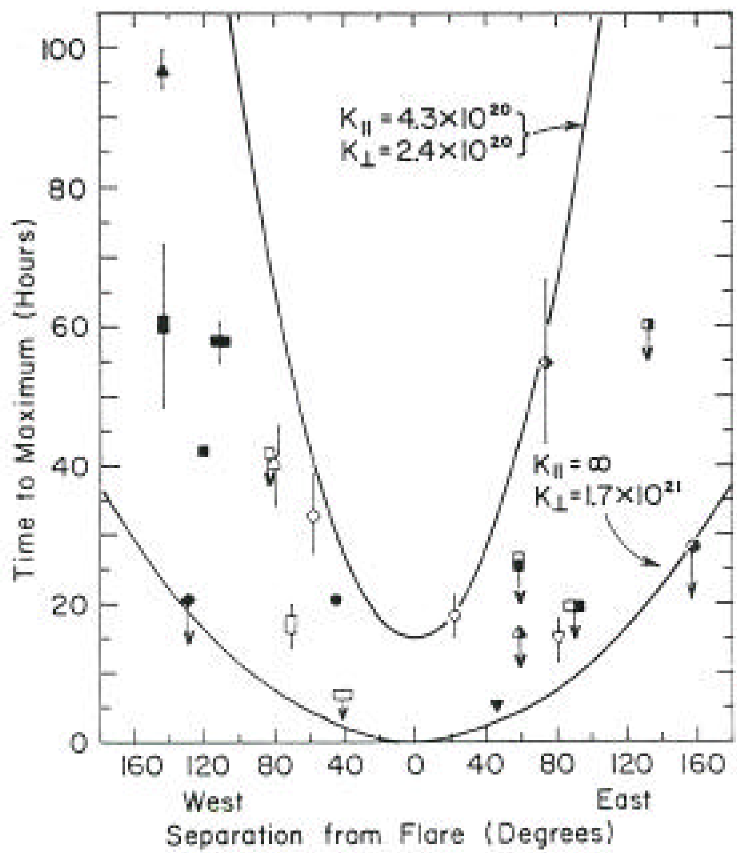


Fig. 14. The time to maximum intensity for fluxes of 15- to 18.7-Mev protons plotted as a function of azimuthal separation from the flare site.

R. B. McKibben, JGR, 77, 3957, 1972

SUPEREVENTS L99

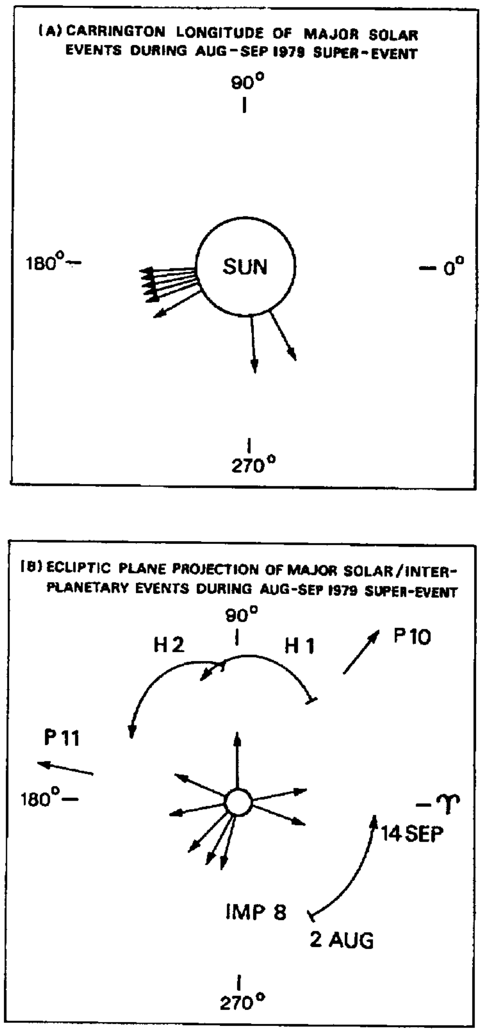


FIG. 2.—(*a*) Carrington longitudes of major solar events occurring from August 2 to September 14 responsible for the superevent of 1979 August/September. (*b*) Ecliptic longitudes of the major solar events from (*a*) and positions of near-Sun and distant spacecraft during 1979 August/September.

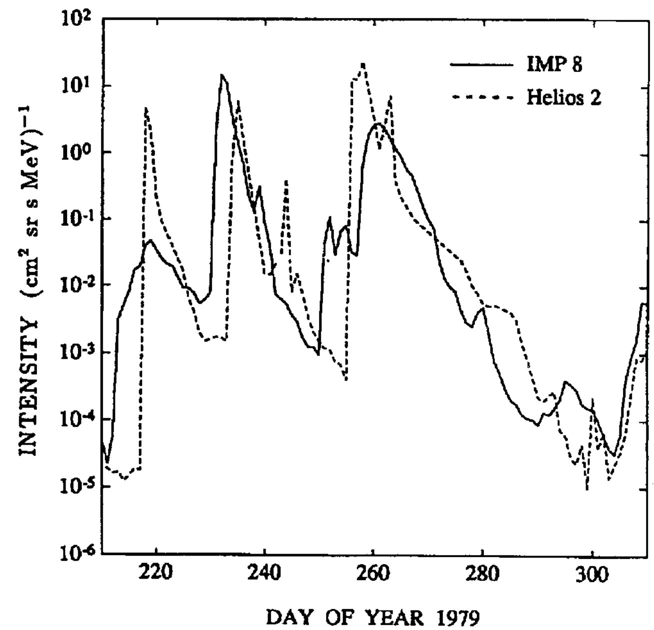
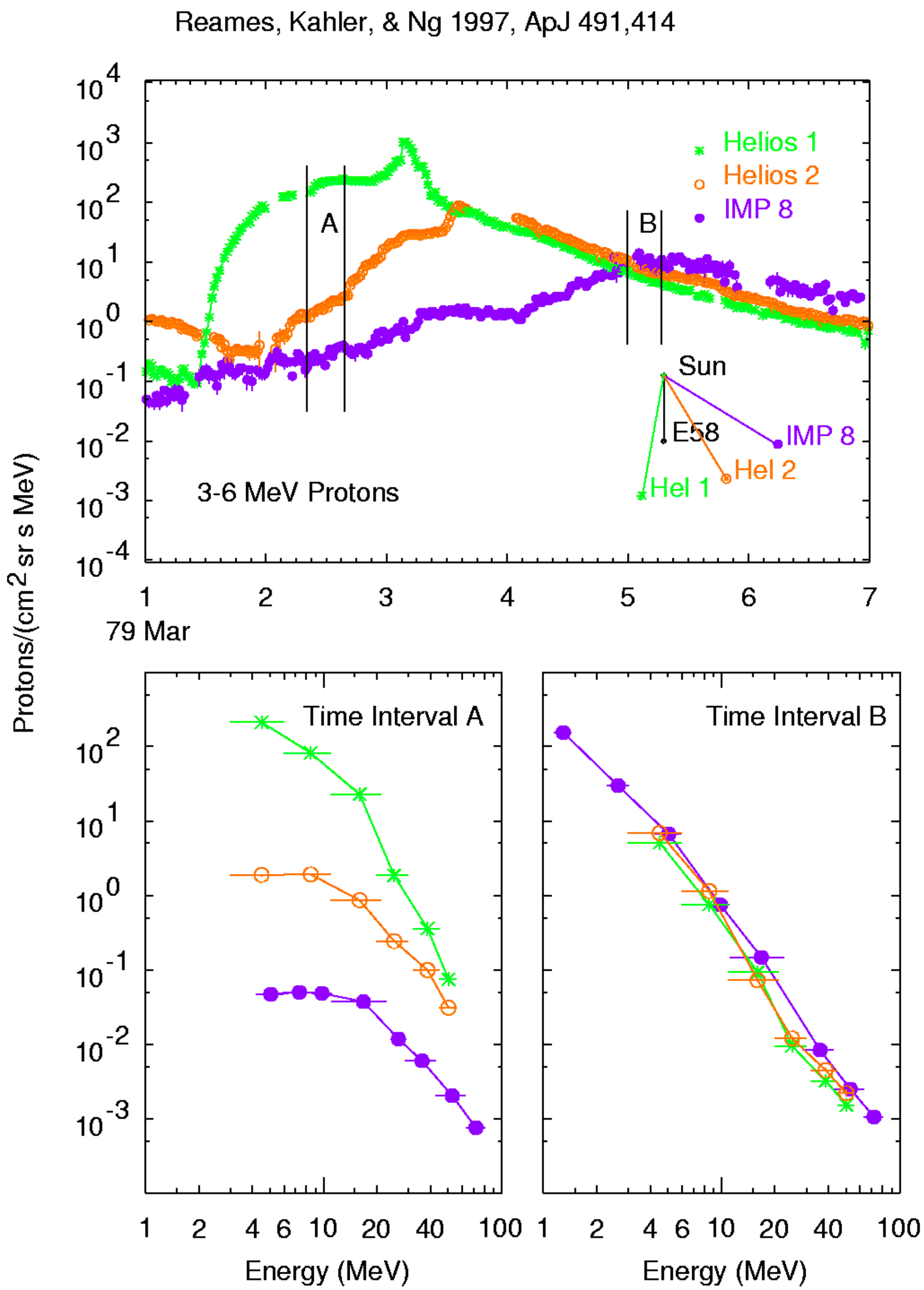


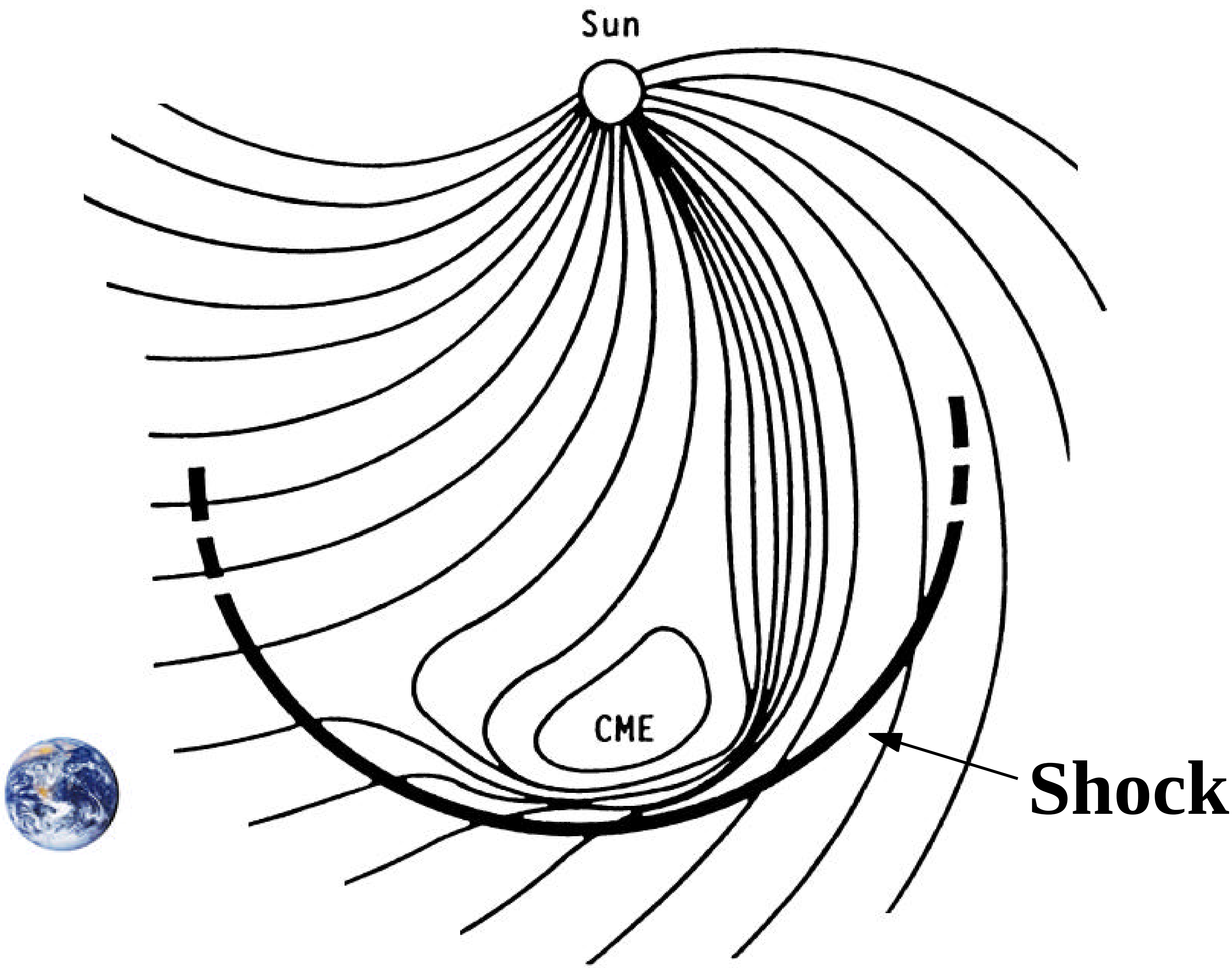
FIG. 3.—Daily averages of 11–20 MeV protons measured on *IMP 8* (*solid line*) and 13–27 MeV protons measured on *Helios 2* (*dashed line*) during the 1979 August/September superevent (No. 7).

Superevents: long lasting enhancements -- due to a series of CMEs, shocks, and particle events

Dröge, Müller-Mellin, and Cliver, Ap.J. (Letters), 387, L97, *1992.*

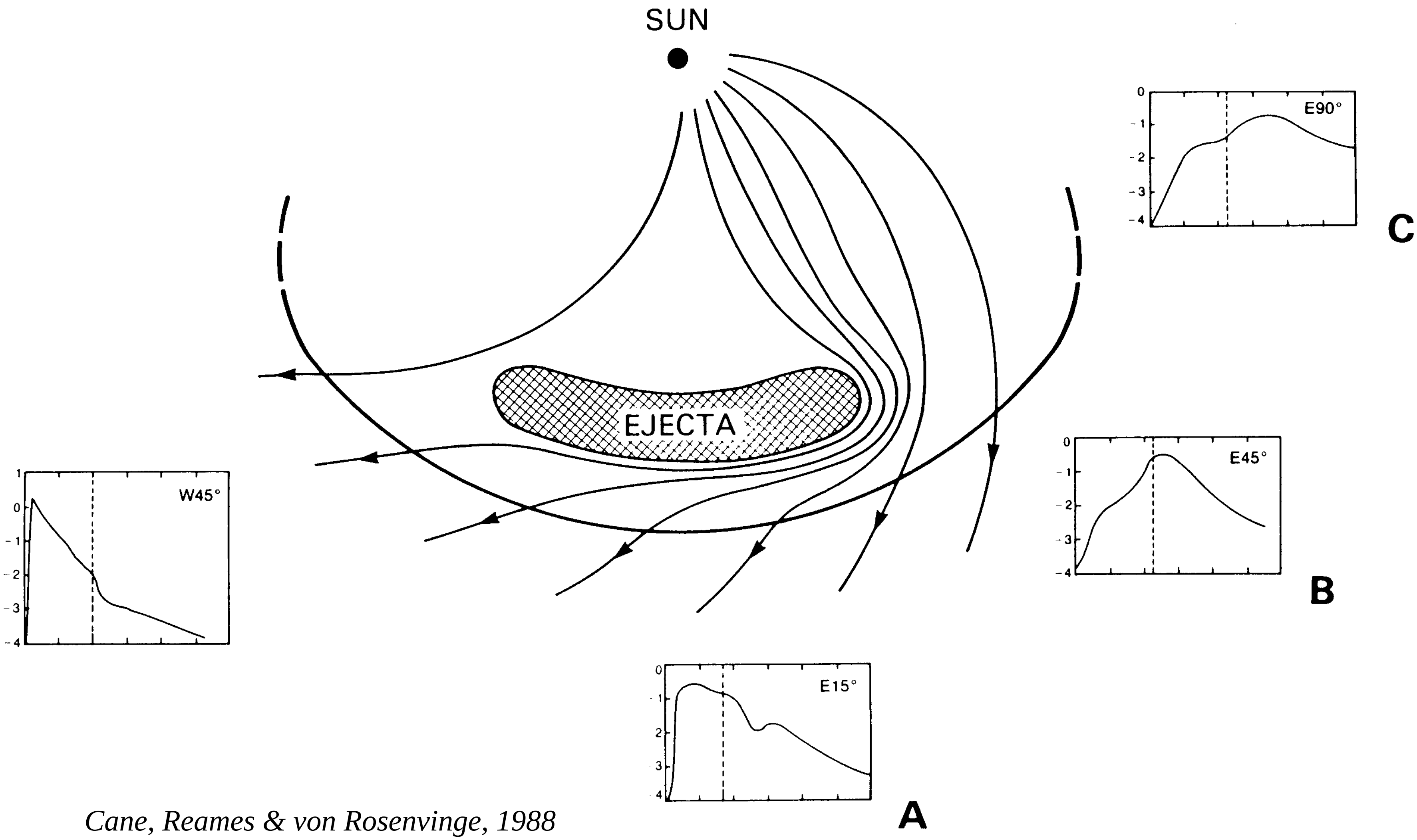
Longitude Distributions (Invariant Spectra)





from Reames et al., ApJ, 466, 473, 1996

Shock acceleration of 20 MeV protons vs. source location on sun



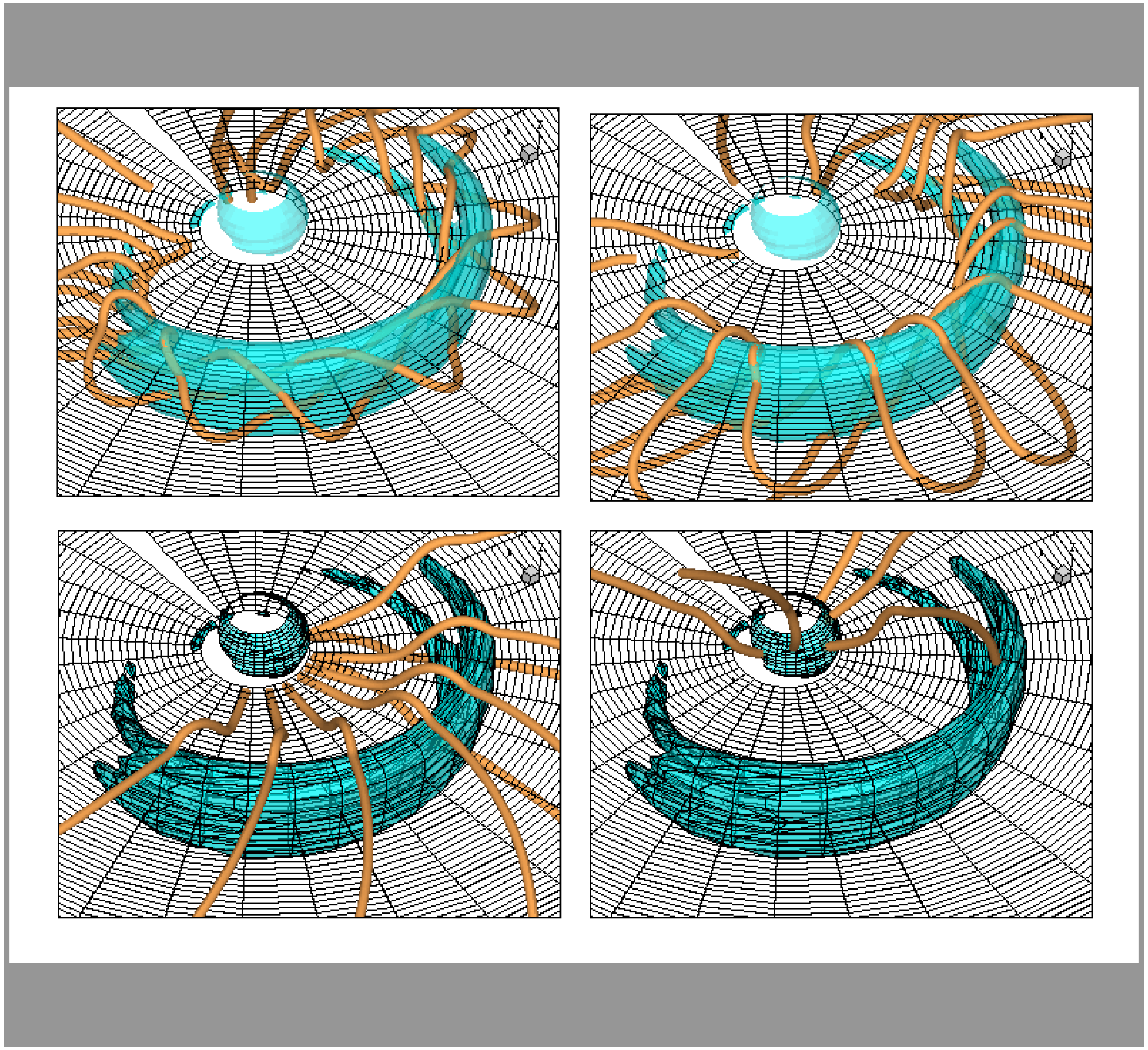
Cane, Reames & von Rosenvinge, 1988

The big picture --

- CMEs are large structures that drive shocks that can accelerate energetic particles
- Due to the winding of the interplanetary magnetic field, the events are not at all symmetrical: therefore the connection of the observer to the CME/shock has a large influence on the observed intensities

Outstanding issues --

- Only rough idea of CME/shock geometry
  - on small distance scales
  - on global distance scales
- We don't know the correspondence between CME images and the shocks & energetic particle population
- Shock acceleration theory predictions don't work well
- We don't know what the "seed particles" are
- We don't know where the early arriving particles are accelerated



Iso-density surface with magnetic field lines traced from different locations

courtesy Dusan Odstrcil

Shock acceleration theories --

- *diffusive shock acceleration theories*
  - steady state; particles accelerated in compression near shock; constant intensities downstream; decay scale length upstream *(Axford, Fisk, Lee, Bell, Forman, etc.)*
- *recent work*
  - attempting to include shock geometry, propagation to observer *(Zank & Rice, Lee, Ng, etc.)*

Key parameters for shock acceleration --

- *Angle between shock normal and local magnetic field θ_{Bn}*
- *Compression ratio of upstream to downstream plasma*
- *Seed population: what are the ions that are actually accelerated? solar wind? suprathermals?*
- *do single point observations give a correct picture?*

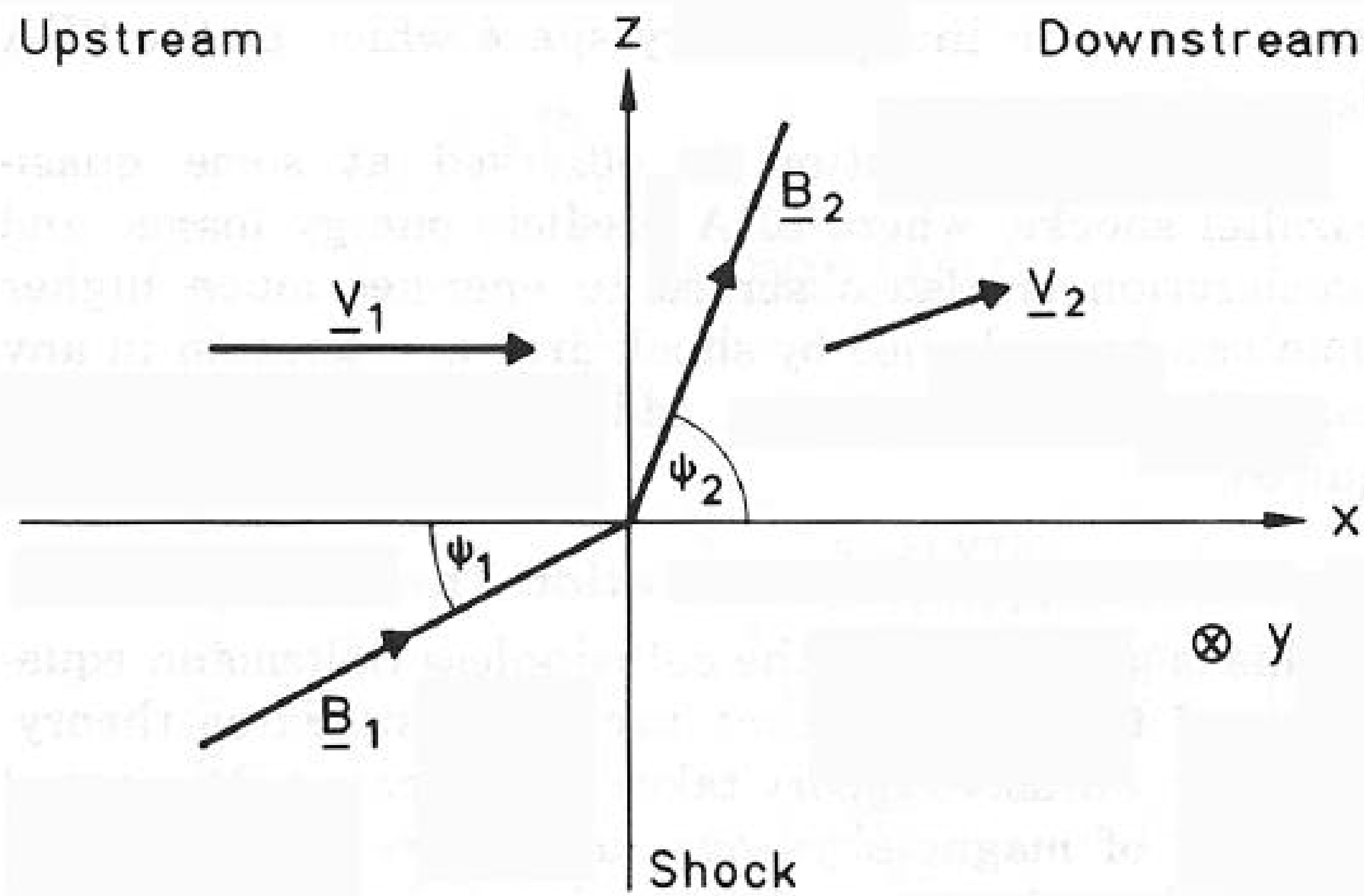


Fig. 1. Coordinate system for the shock frame.

M. A. Forman and G. M. Webb, Geophys. Monograph #34, p 91, 1985

DECKER: PARTICLE ACCELERATION

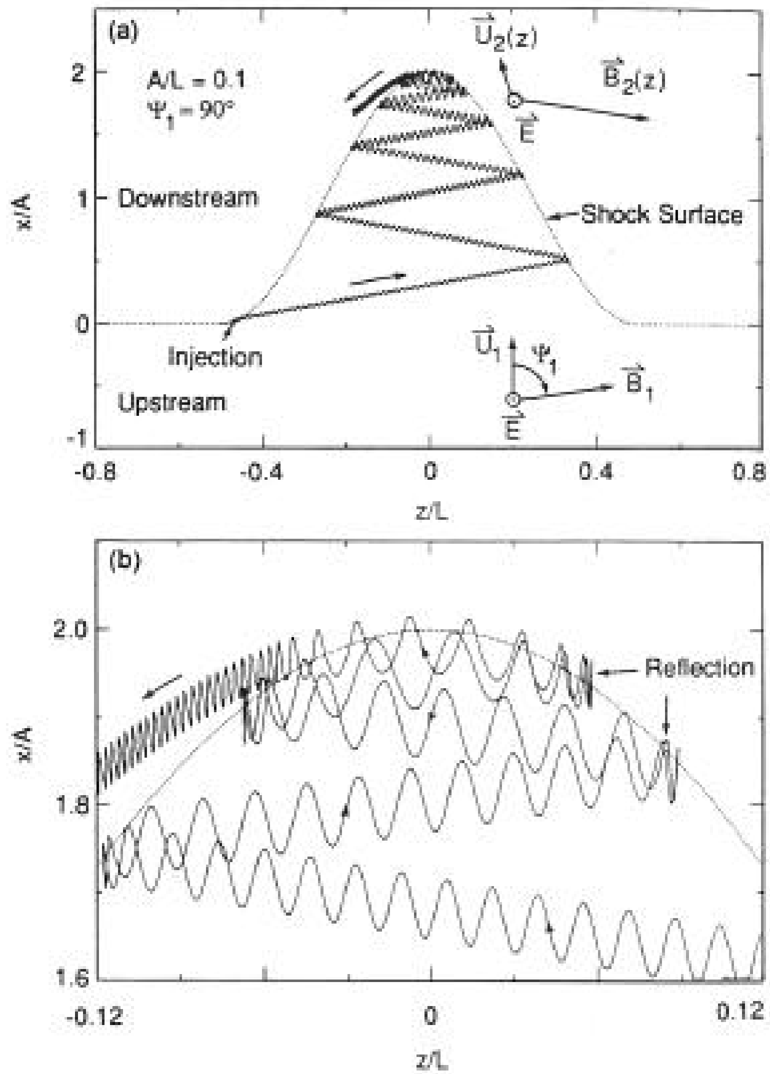


Fig. 1. (*a*) Illustration of shock surface (dashed curve) given by (1) and projection onto ($x - z$) plane of sample proton orbit as viewed from the shock frame.

R. B. Decker, JGR, 95, 11993, 1990

Study of shock with surface ripples:

- ***complex behavior within an event --***
    - ***multiple intensity spikes***
    - ***large variety of structures***
- ***flux-time profiles depend markedly upon path through ripple***

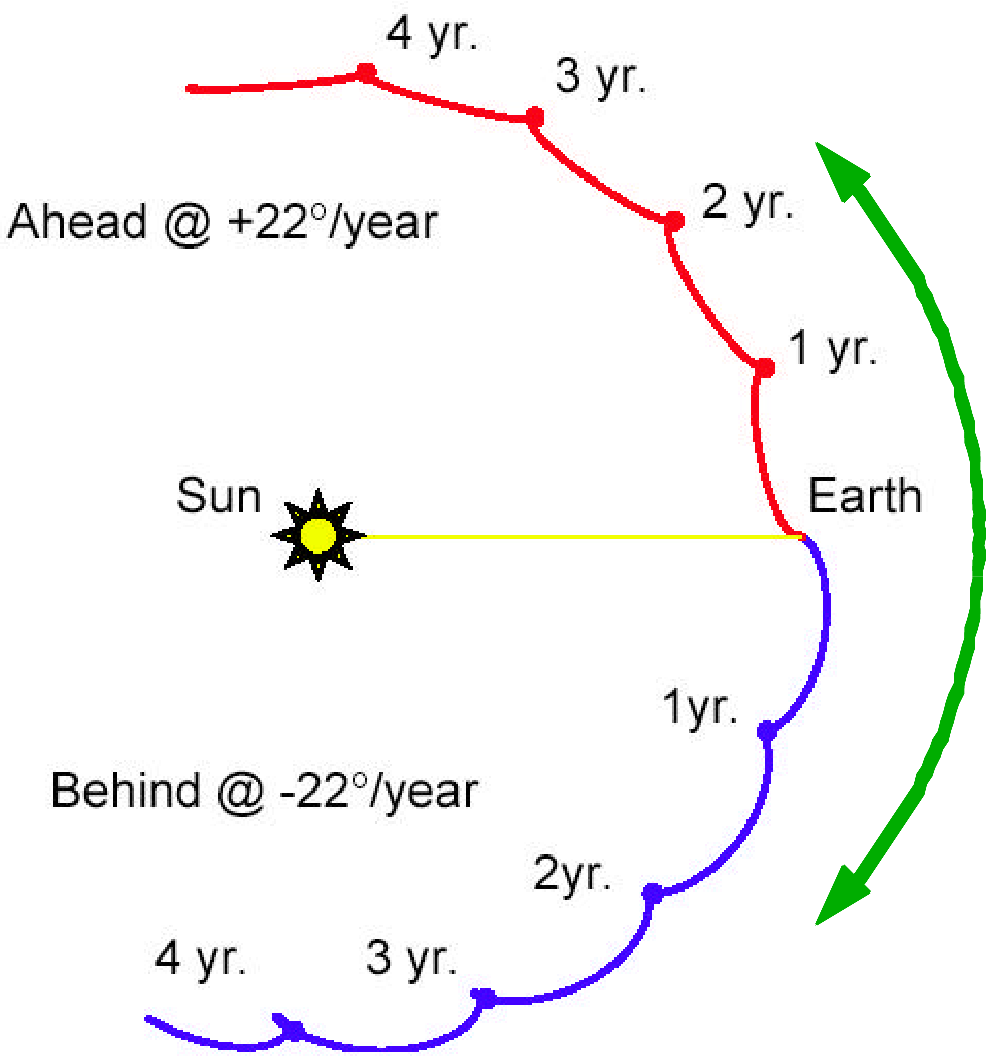


Figure: P. Sharer, STEREO PDR

Initial Studies:

- ***CME geometry***
- ***Shock surface roughness***
- ***Particle acceleration***
- ***Sites of Acceleration***

Correlation of peak flux and shock

(a) spectral index and (b) shock strength

VAN NES ET AL.: SHOCK ASSOCIATED ENERGY SPEC

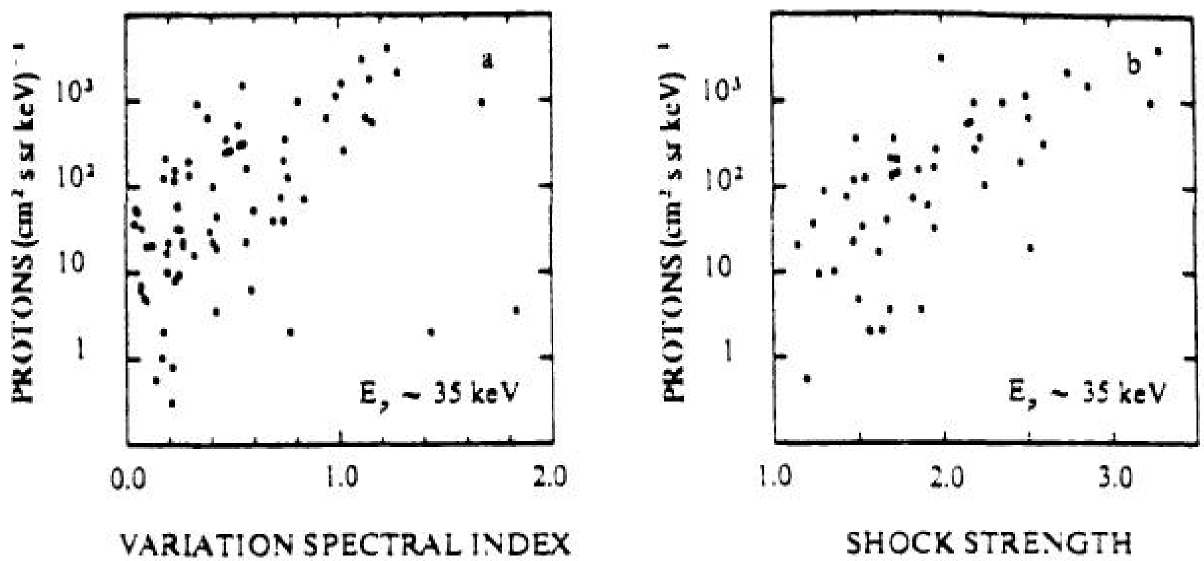


Fig. 7. Correlation between (*a*) variation in spectral index and peak flux, (*b*) hydroc

van Nes et al., JGR, 89, **2122, 1984.**

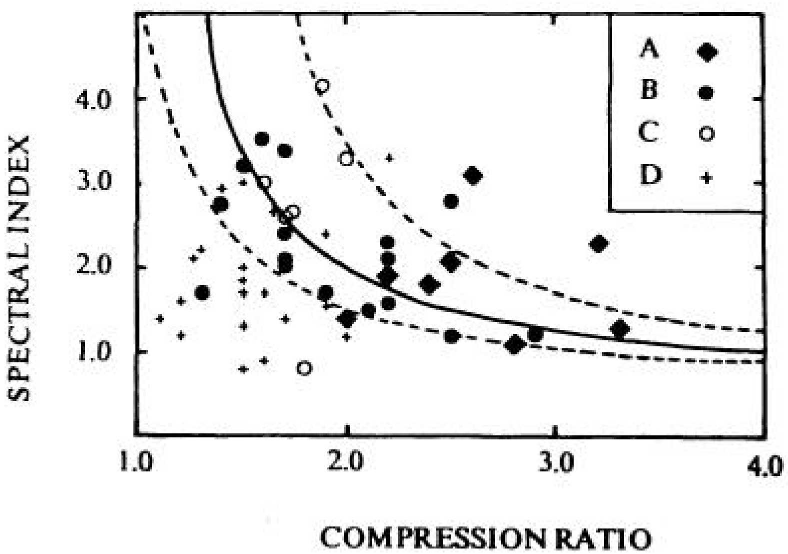


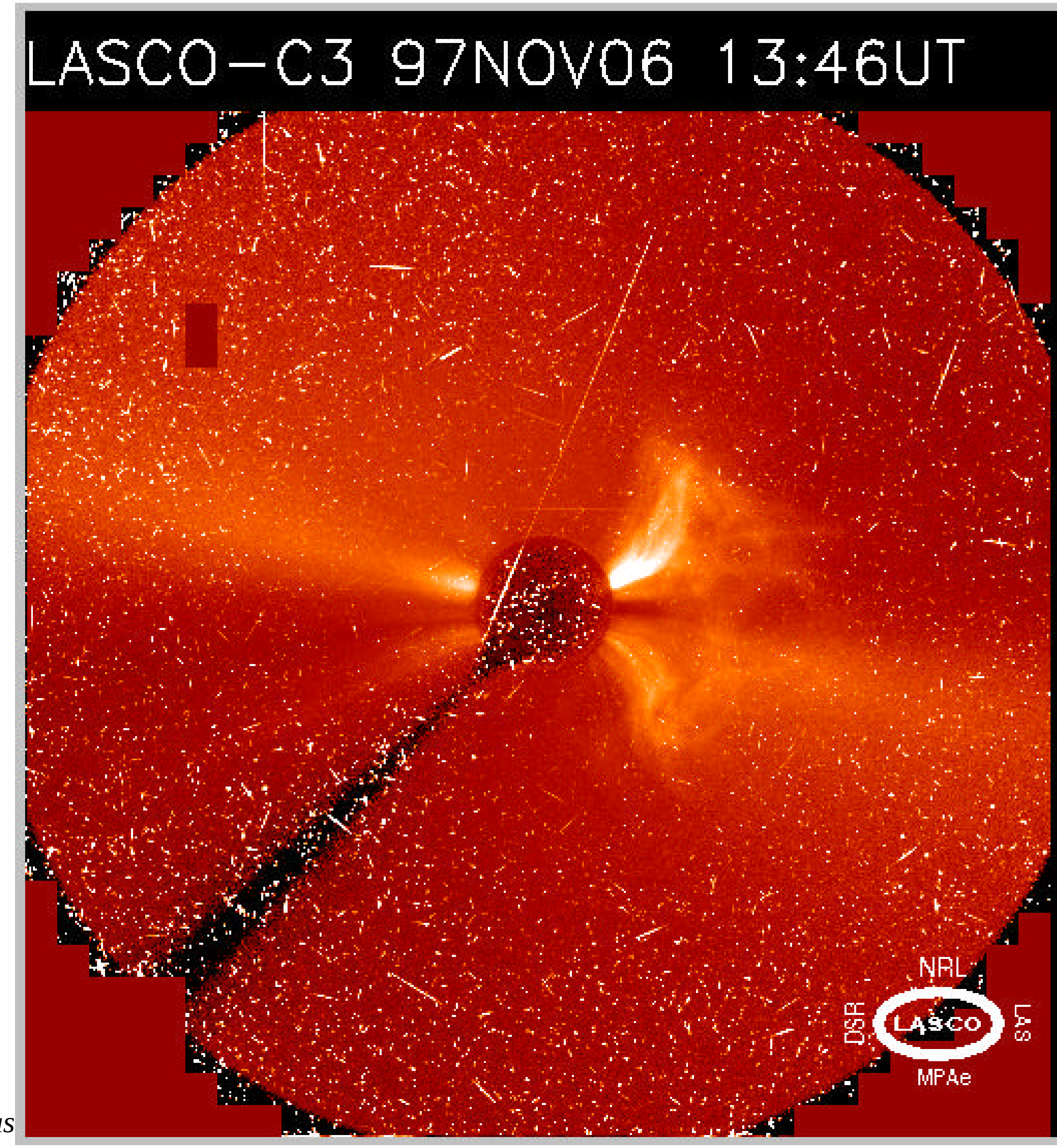
Fig. 12. Spectral index γ plotted as a function of the hydrodynamic shock strength H. The index was derived for the spectrum constructed from the average flux during 10 min immediately after the shock passage. The solid curve indicates the theoretical relation $\gamma = (H + 2)(2H - 2)^{-1}$. Points within the dashed lines are considered to follow the relation, because of the uncertainty of 25% in H. The events from the different classes are distinguished by different symbols.

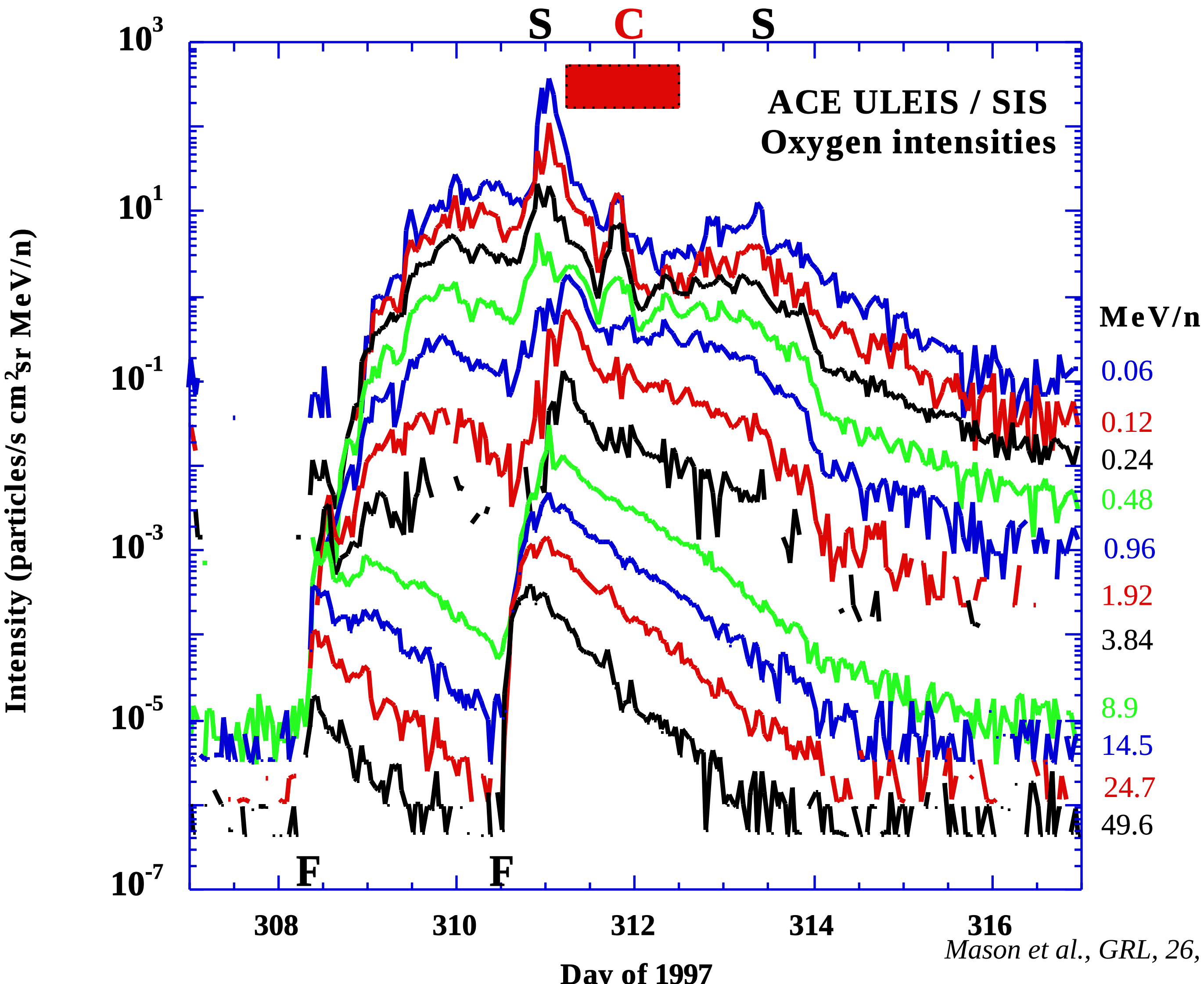
***van Nes et al., JGR, 89,* 2122, 1984.**

Shock accelerated particles:

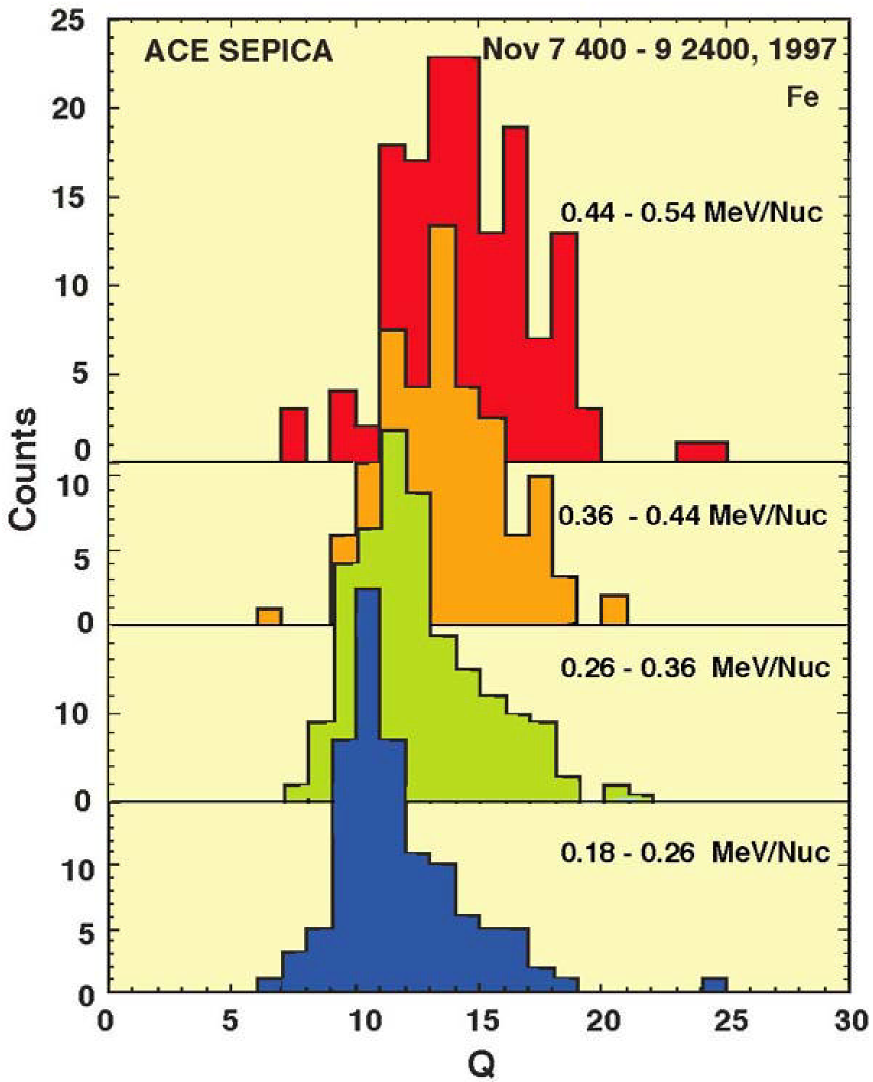
- ***survey on 75 shocks***
- ***correlation of spectral index vs. shock compression ratio***
- $\gamma = (H+2)/(2H-2)$

(H = ratio of downstream and upstream plasma density)


LASCO-C3 97NOV06 13:46UT
NRL
DSR
LASCO
LAS
MPAe



Mason et al., GRL, 26, 141, 1999



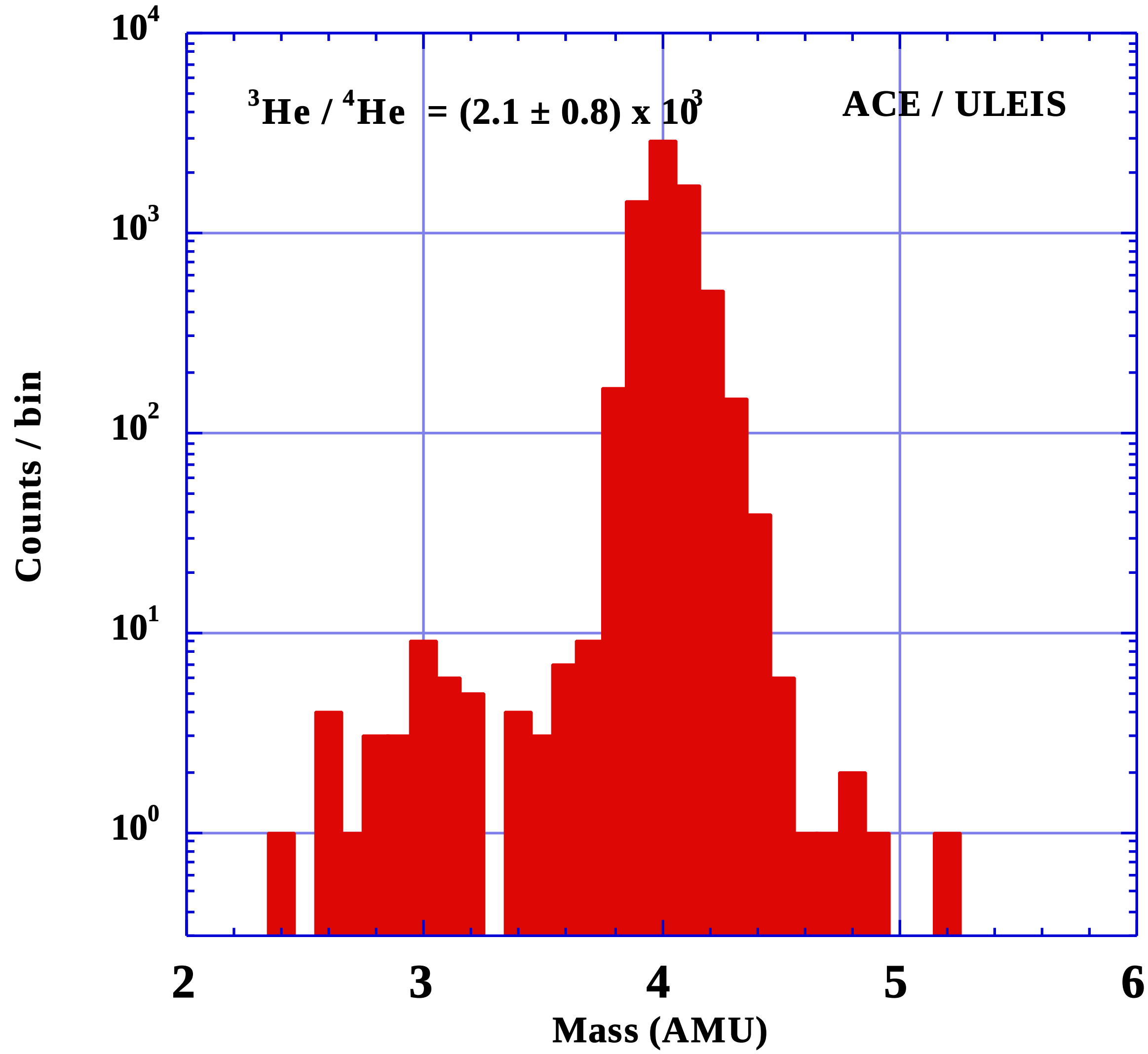
Ionization states >> than solar wind. What causes that?

- *stripping near Sun?*
- *acceleration bias?*
- *seed population?*

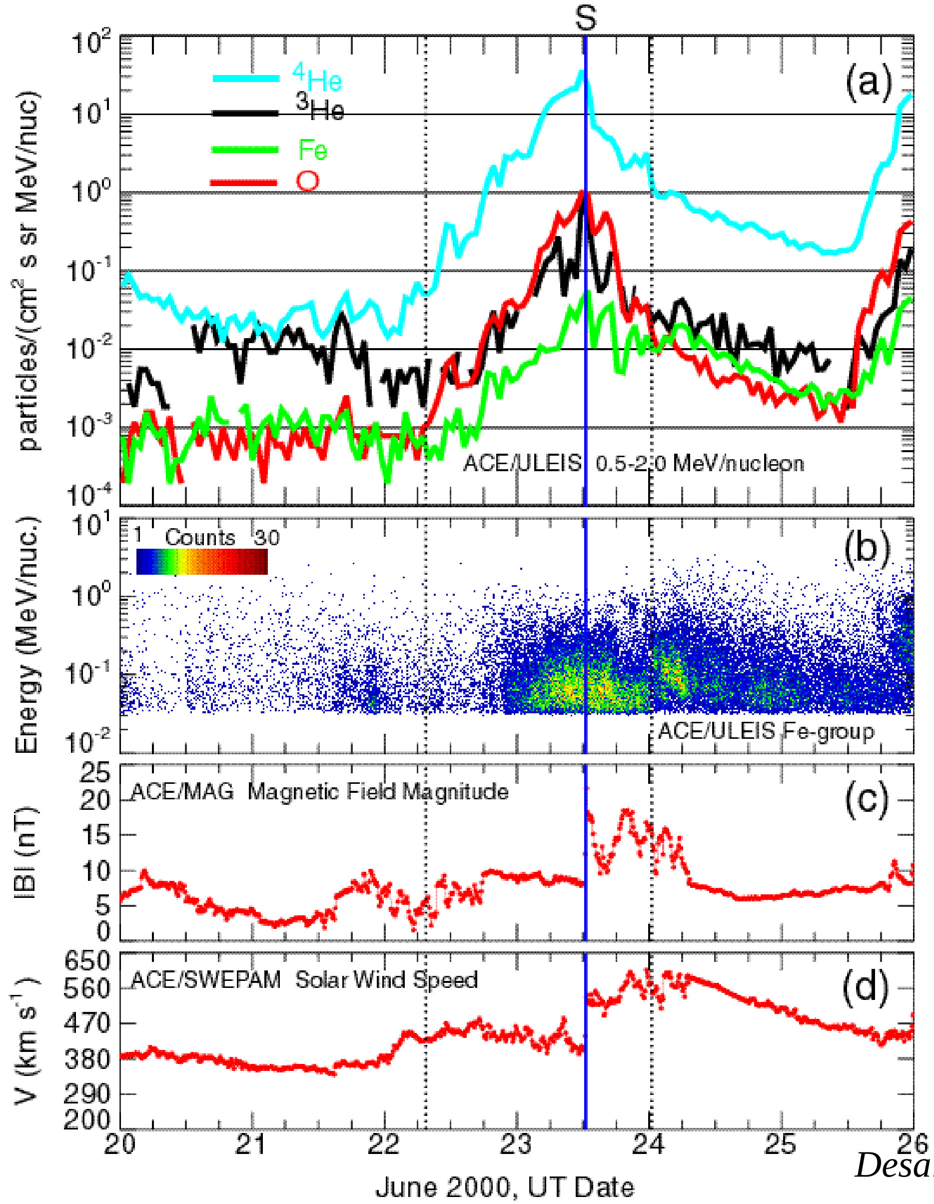
Solar wind-like ionization states

Möbius et al., GRL, 26, 145, 1999

^{3}He enhancement in large Nov. 6, 1997 CME related solar particle event: 0.5-2.0 MeV/n

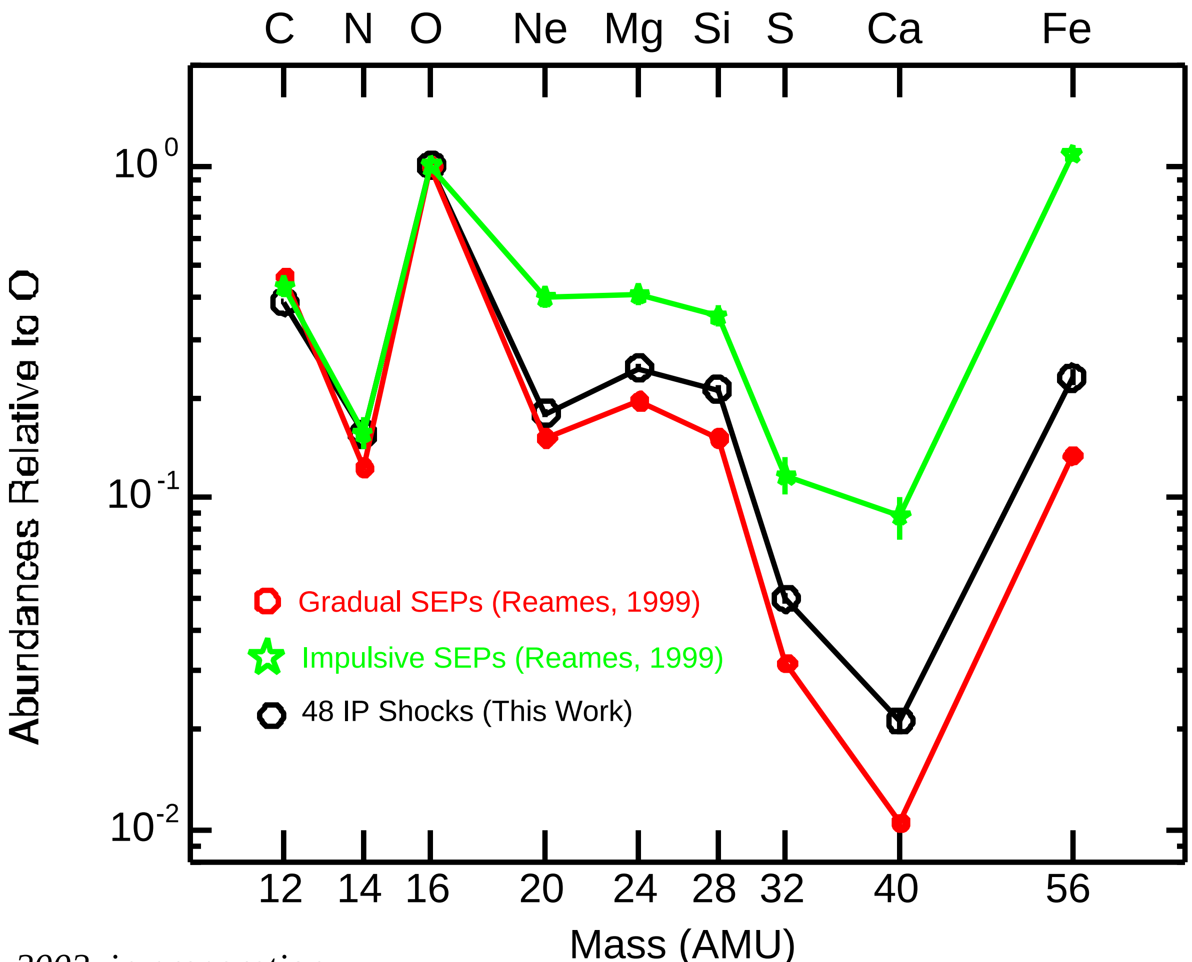


Mason et al., GRL, 26, 141, *1999*

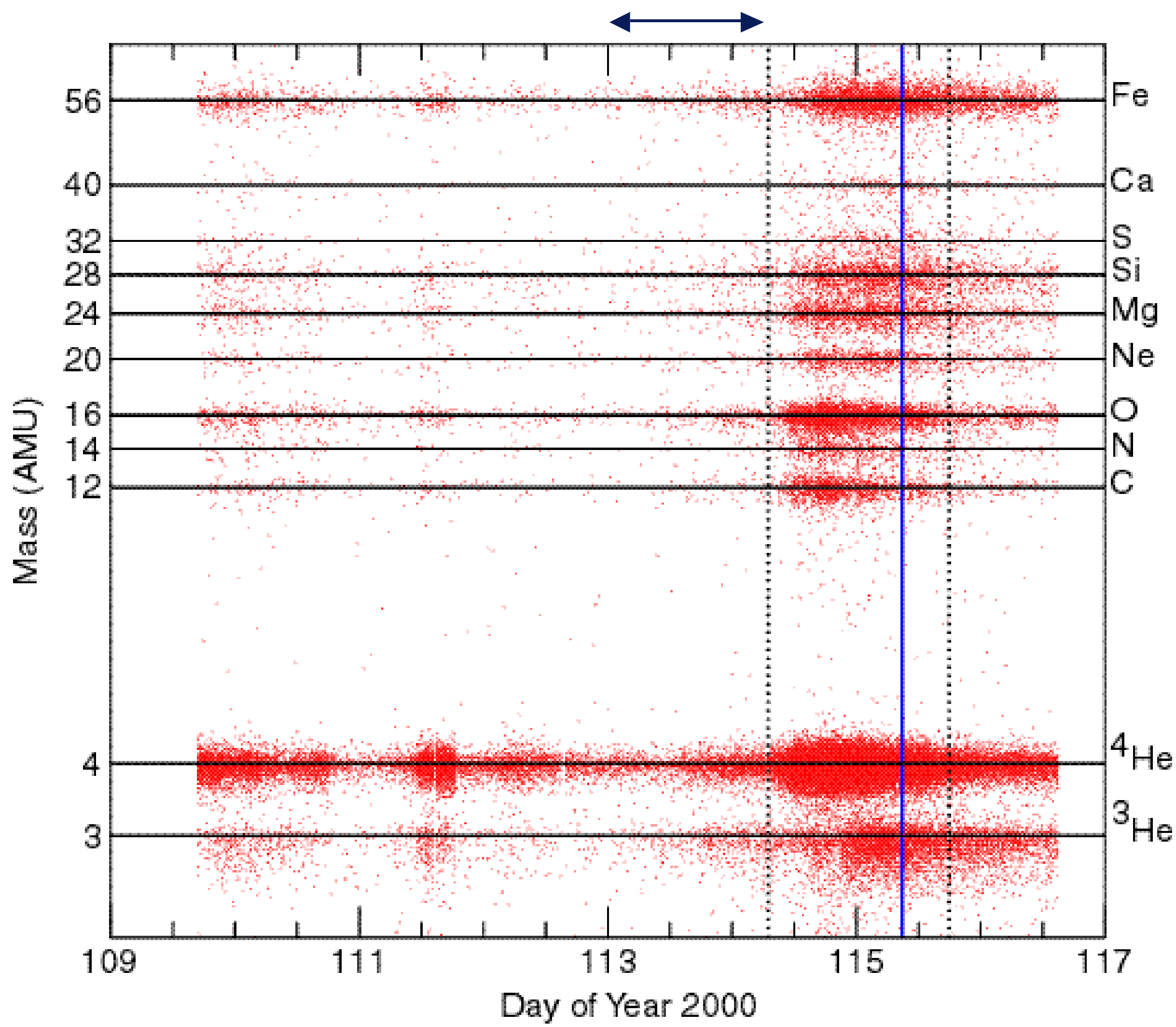


Desai et al., Fall AGU, 2000

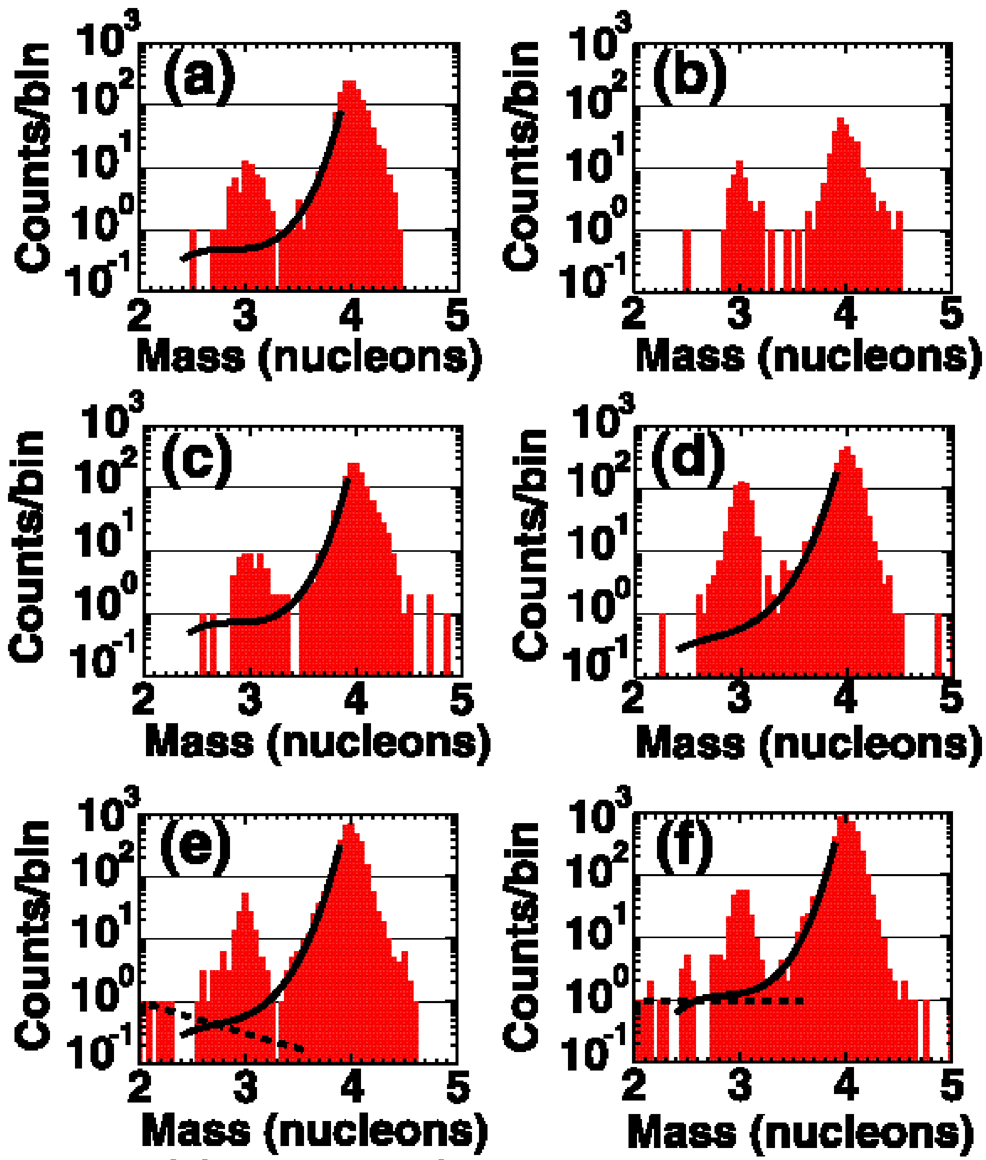
Heavy ion abundances in interplanetary shocks intermediate between gradual and impulsive solar particle events



Desai et al., 2002, in preparation



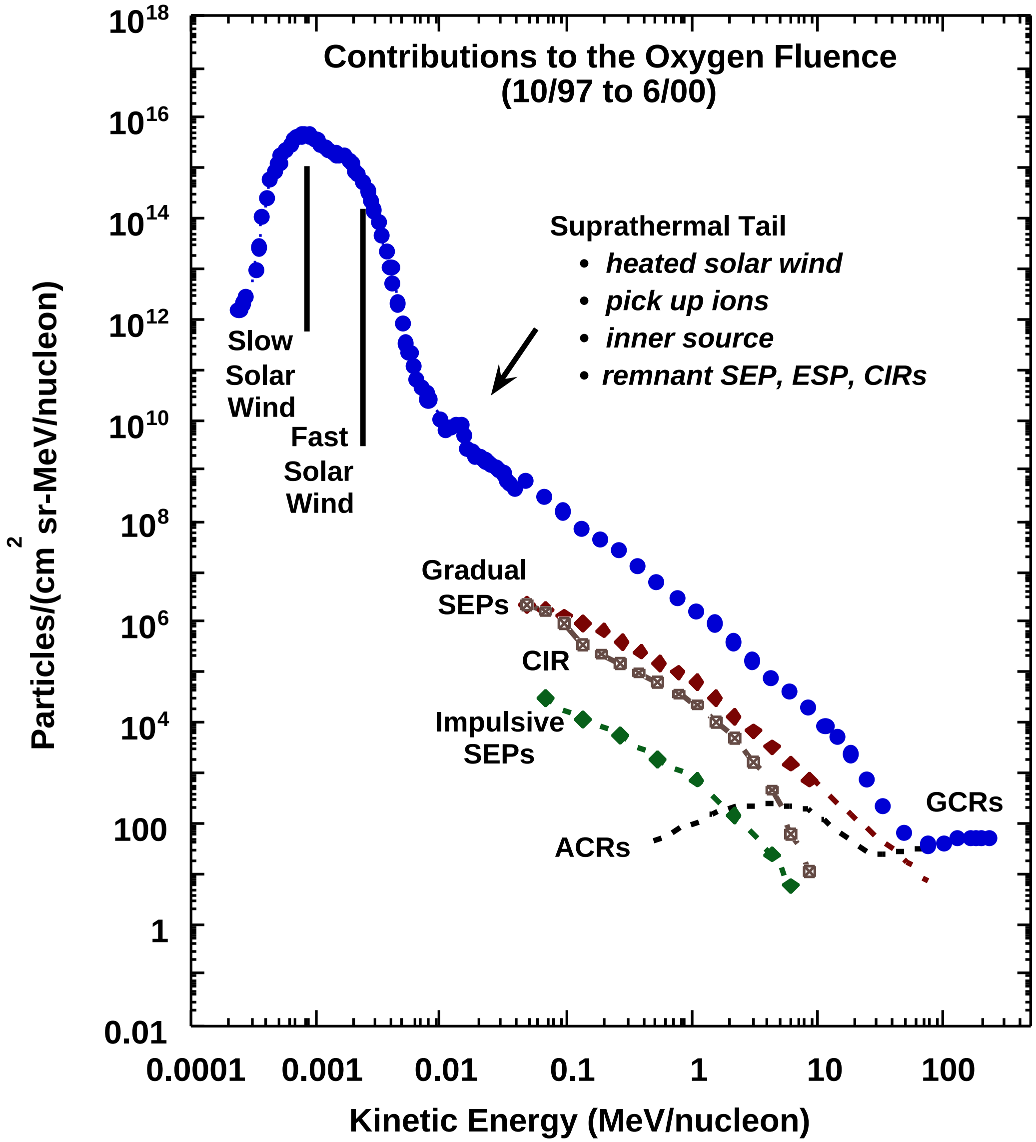
Desai et al. 2001



Desai et al., ApJ Letters, 553, L89, 2001

Shock acceleration: problems

- ***Intensities wrong or unaddressed***
- ***Spectral indices wrong***
- ***Composition wrong (i.e. seed population is not bulk solar wind)***
- ***Solutions:***
  – use right seed population *but what else?*
  – improved theory vs. OK theory but inadequate treatment of shock geometry / surface?

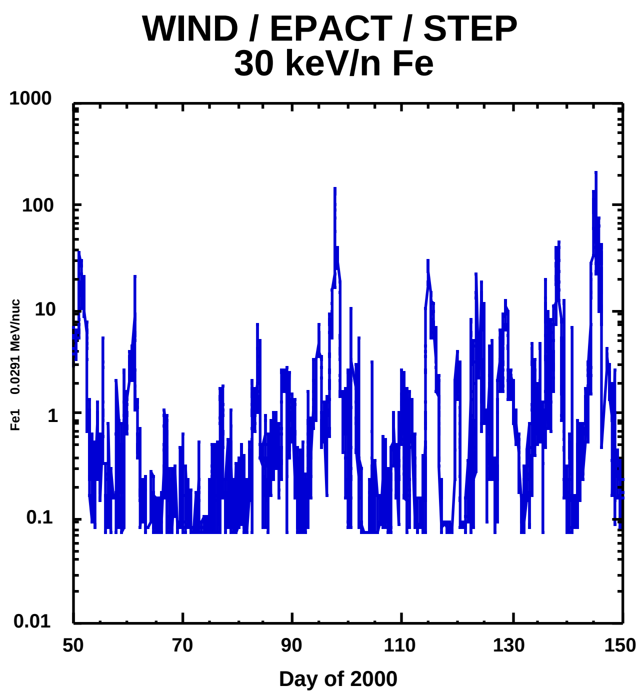


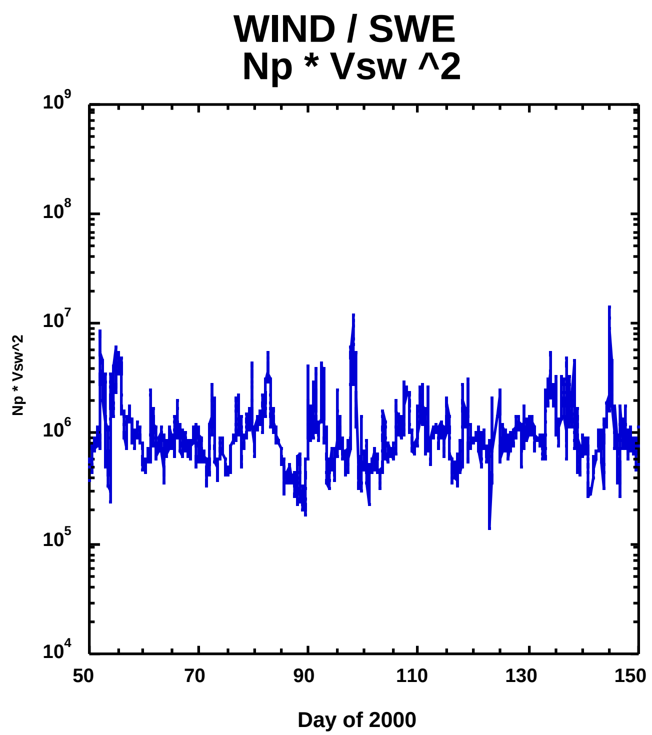
adapted from Mewaldt, Mason, Gloeckler et al., AIP CP#598, 165, 2001

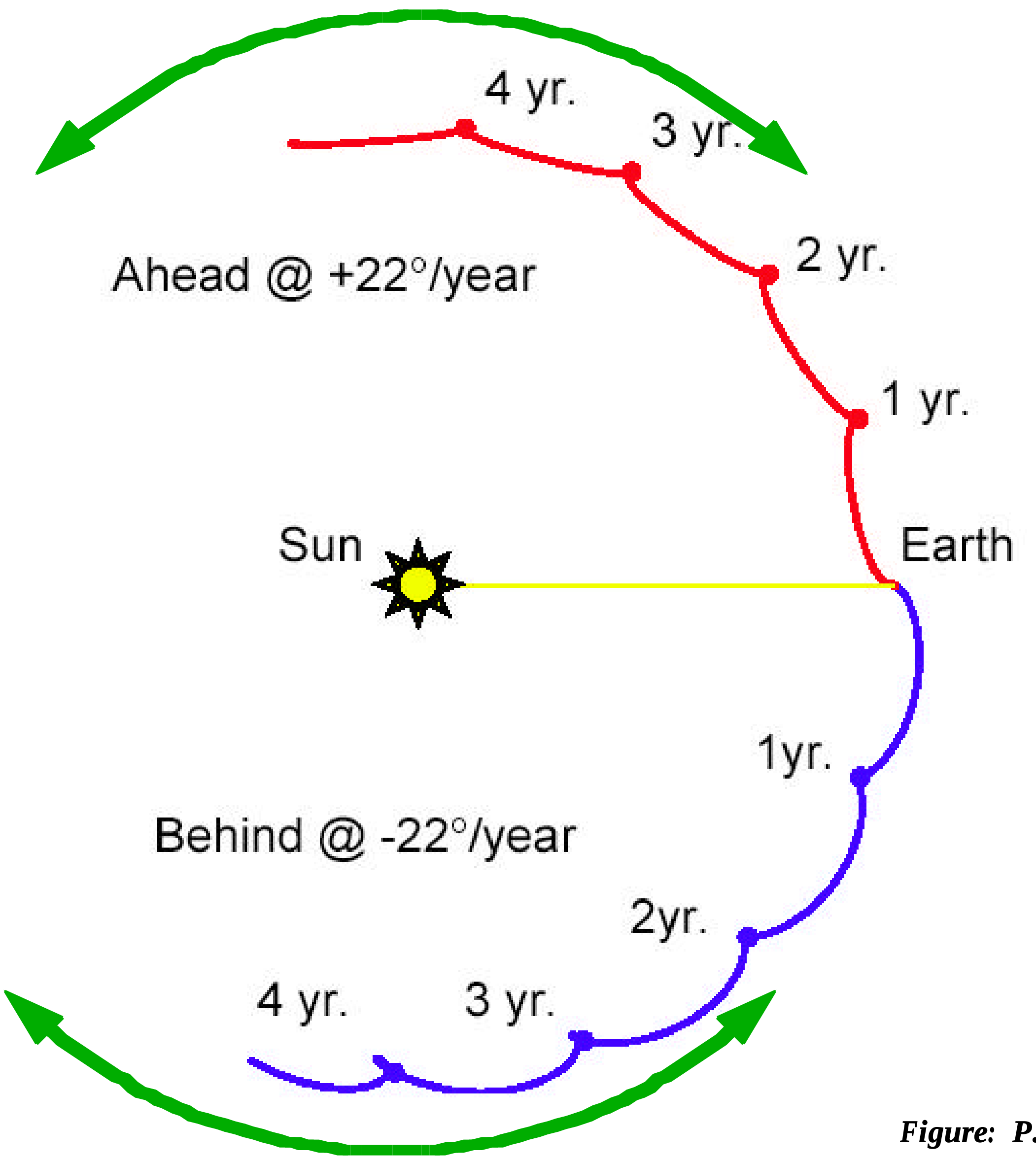
Suprathermal tail:

- *many contributors*
- *spatial and temporal variations*

Suprathermals show 10-100 times more variation in intensity than solar wind -- likely critical issue in energetic particle intensities







Later Studies:

- ***CME images & in-situ properties***
- ***Particle acceleration sites (maybe)***

Figure: P. Sharer, STEREO PDR

STEREO contributions:

- Only rough idea of CME/shock geometry
  - on small distance scales
  - on global distance scales

  STEREO will allow systematic mapping for the first time (S/C < 120° apart)
- We don't know the correspondence between CME images and the shocks & energetic particle population

  STEREO/SECCHI & in-situ experiments will determine this correspondence near 1 AU - extrapolation inward may be possible (wide range of separations)
- Shock acceleration theory predictions don't work well

  Knowledge gained of shock geometry, speed, surface roughness will permit more definitive comparisons of theory & observations (S/C < 120° apart)
- We don't know what the "seed particles" are

  Improved comparisons of theory & observations will help, but full suprathermal range not covered on STEREO (S/C < 120° apart)
- We don't know where the early arriving particles are accelerated

  possible progress if we can extrapolate CME/in-situ correspondence close to the Sun. (wide range of separations)