The Two Sources of Solar Energetic Particles

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2012 Hale lecture

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A Brief History of Two SEP Sources

- 1860 Carrington – first flare observation
- 1946 Forbush - first SEP- Ground Level Event (GLE)
- 1963 Wild, Smerd, & Weiss
  - (A) type III radio bursts – electron acceleration
 - (B) type II bursts –shocks – proton acceleration

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(A) Type III

- 1970 ^{3}He-rich events (Hsieh & Simpson)
  - ^{3}He/^{4}He>0.1 *vs.* 4x10^{-4} solar wind
- 1975 Assoc. Fe/O enhancement (Hurford et al.)
- 1978 Selective heating mechanism (Fisk)
- 1985 Assoc. 10-100 keV electrons (Reames, von Rosenvinge, Lin)
- 1986 Assoc. type III bursts (Reames & Stone)
- 1988 Assoc. X-ray flares (Reames, Dennis, Stone, & Lin)
  - What is special? Nothing!
- 1992 Streaming electrons generated waves (Temerin & Roth)
- 1998 Reconnection cascade enhanced Fe (eg. Miller)
- 1999 γ-ray lines show ^{3}He/^{4}He>0.1, eg. ^{16}O(^{3}He, p) ^{18}F (.937…) (Mandzhavidze, Ramaty, Kozlovsky)

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(B) Type II

- 1961 CNO abundances (Fichtel & Guss)
- 1969 Fe (Bertsch, Fichtel, & Reames)
- 1973 CMEs discovered (Tousey 73; *Skylab* e.g. Gosling et al. 74)
- 1982 GLE protons accel. late by shock (Cliver, Kahler, Shea, Smart)
- 1983 IP shock theory –self-amplified waves (Lee)
- 1984 large SEP events 96% assoc. with CMEs (Kahler et al.)
- 1985 large-SEP abundances are coronal (Meyer)
- 1988 SEP longitude distribution explained by shock accel. (Cane, Reames, & von Rosenvinge)
- 1994 21 GeV protons accel. above 5 solar radii (Kahler)
- 2001 SEP intensities correlated with CME speed (Kahler)

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SEP Distribution in Space and Time

Cane et al. (1988)
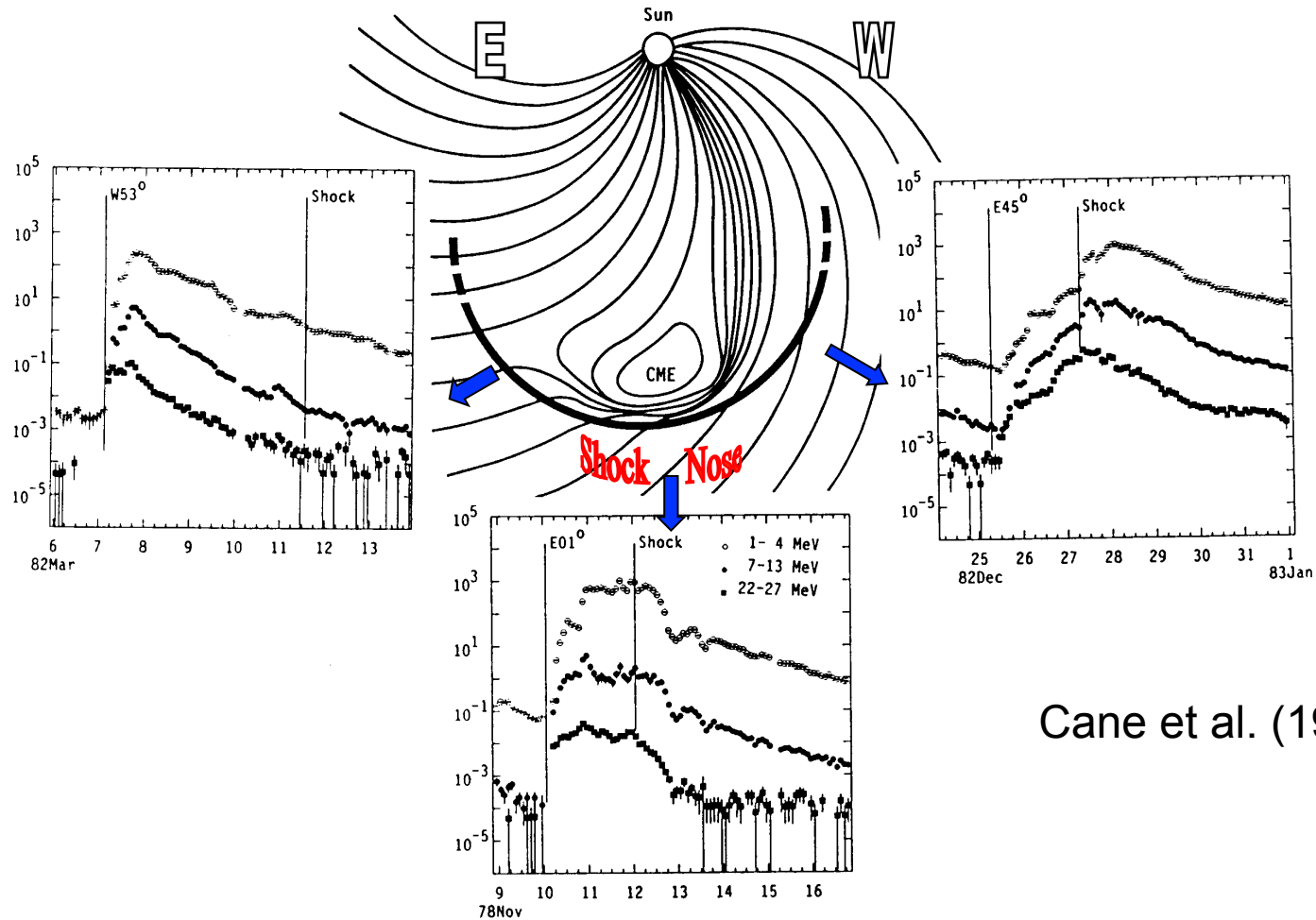
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Peak particle intensities are correlated with CME speed.
Only 1-2% of CMEs are fast enough to accelerate SEPs.
Kahler (2001)
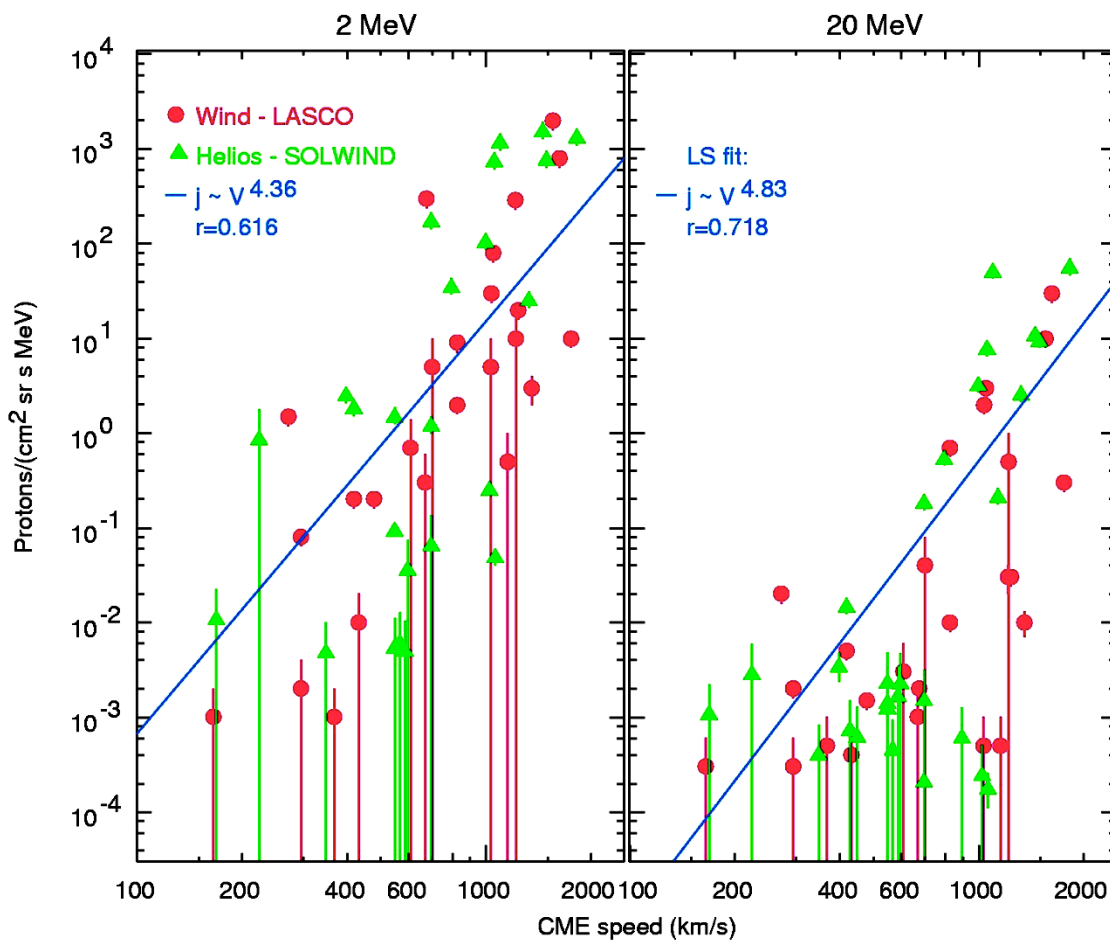
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Two Mechanisms of SEP Acceleration:

(A) Impulsive
Resonant stochastic accel.

flares or
jets

hours

type III

^{3}He-
hi-Z- &
electron
-rich

$Q_{Fe} \sim 20$

~1000/yr

(B) Gradual (long duration)
Shock accel.
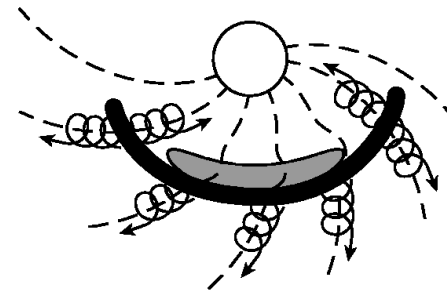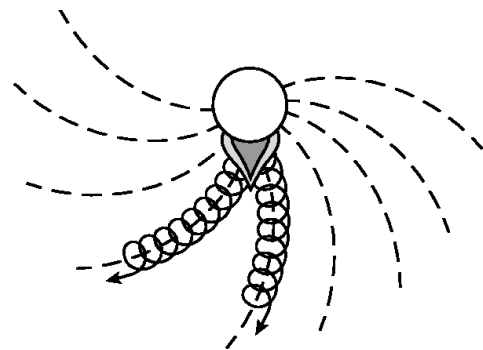
fast CME,
shock

days

type II, IV

coronal
abunds.

$Q_{Fe} \sim 14$

~10's /yr
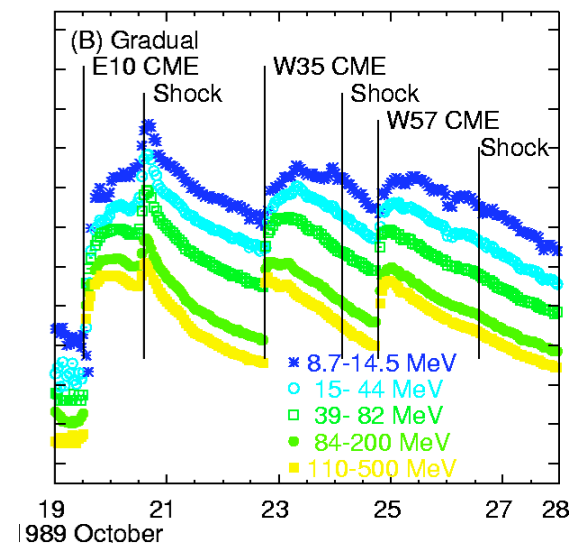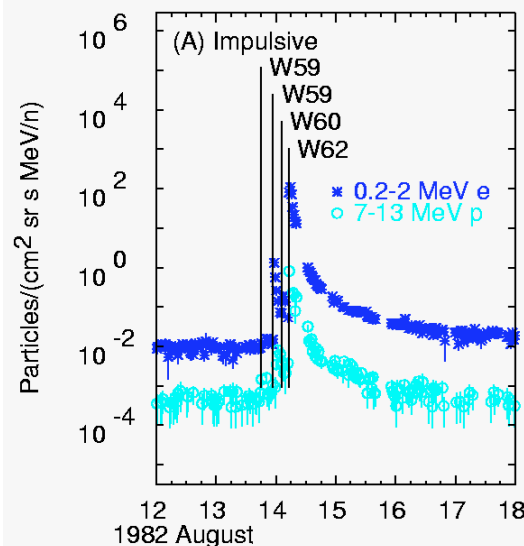
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Abundances - Gradual events
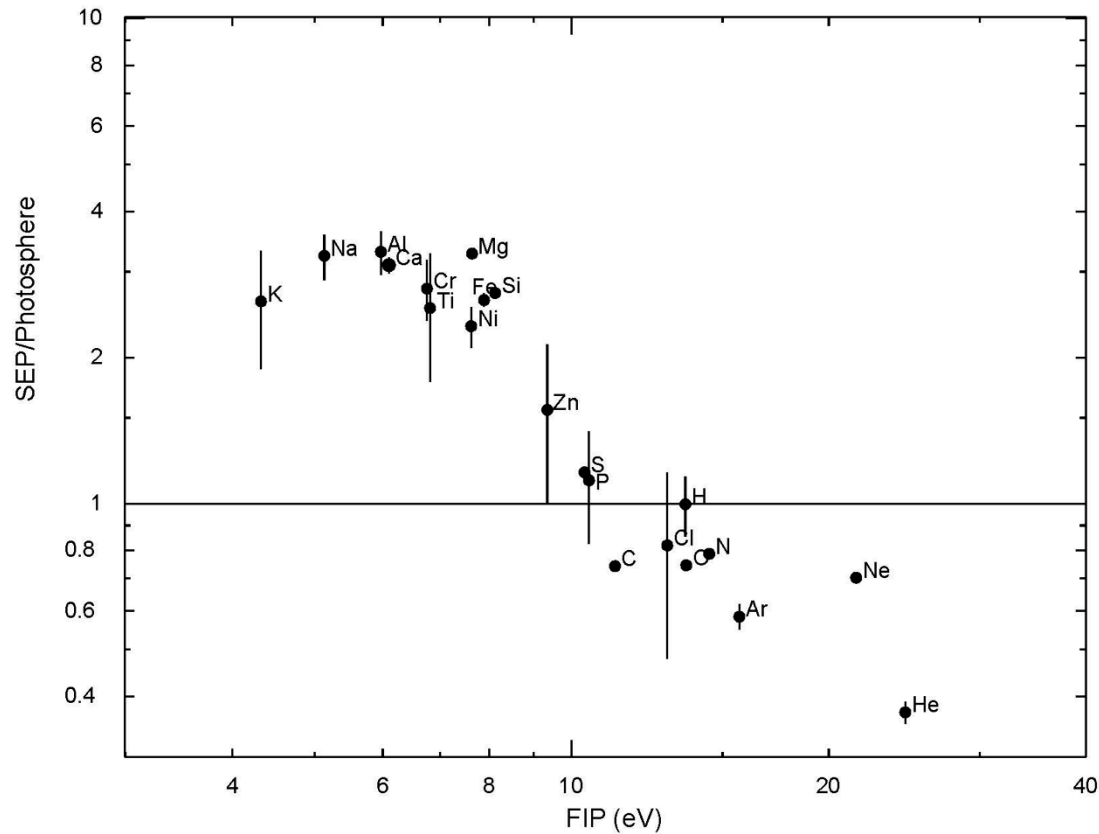
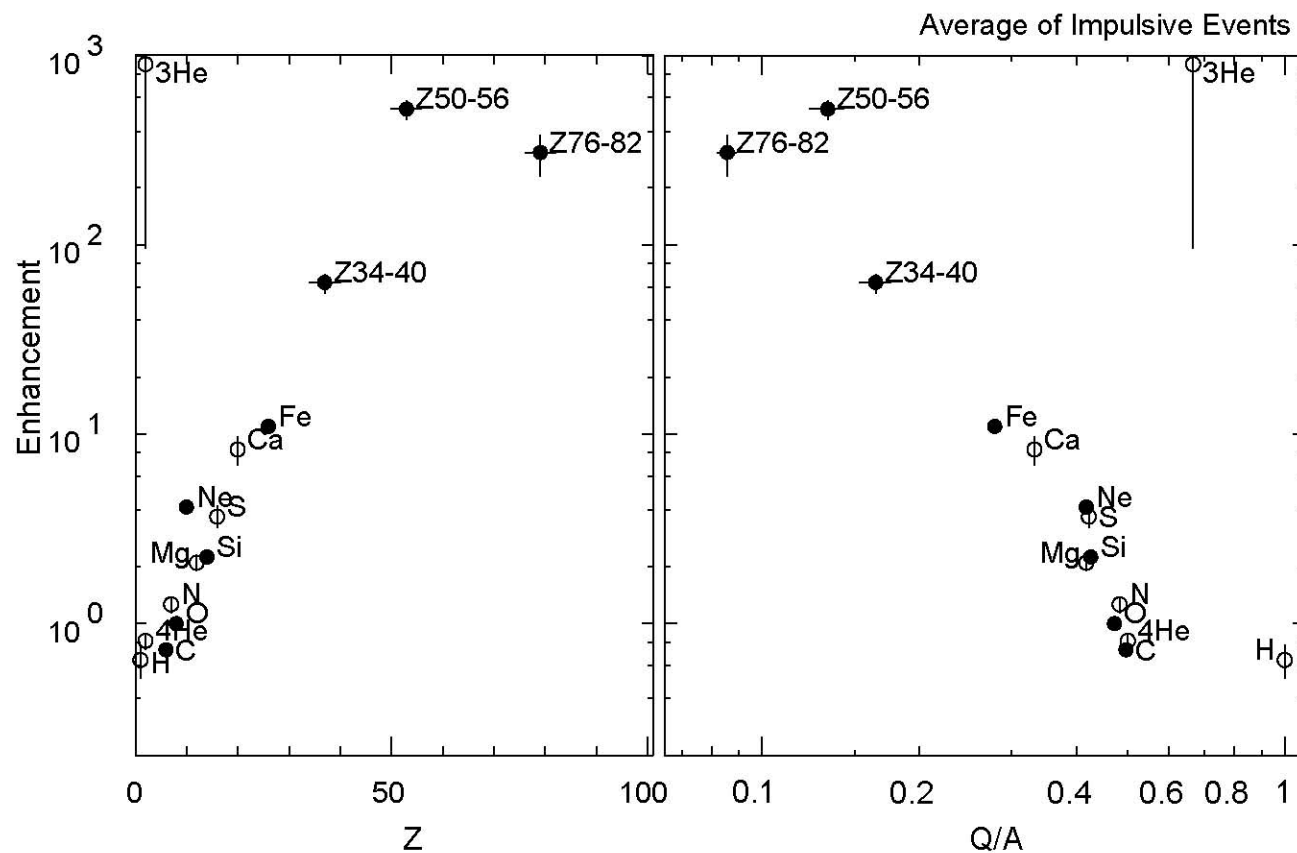Meyer (1985), Reames (1995, 1998, 1999)

Average levels – Schmelz (2012)

Lower energy – Desai et al. (2006), Isotopes – Leske et al. (2007)

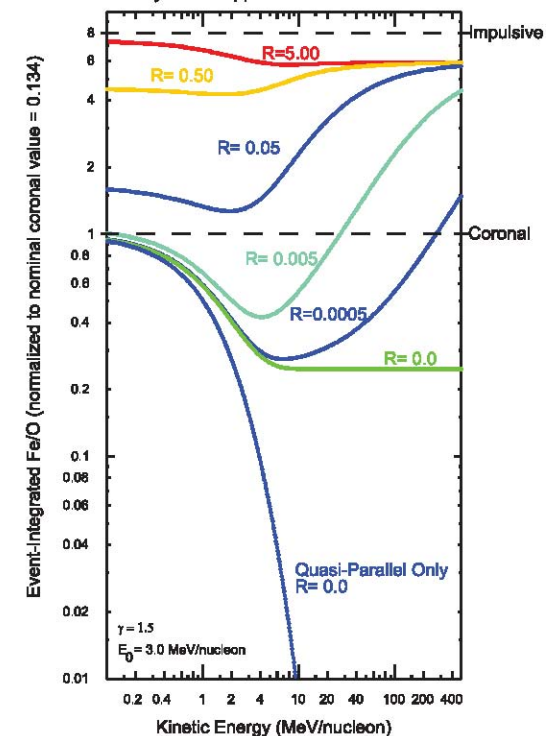Don Reames ... 2012 Hale lecture

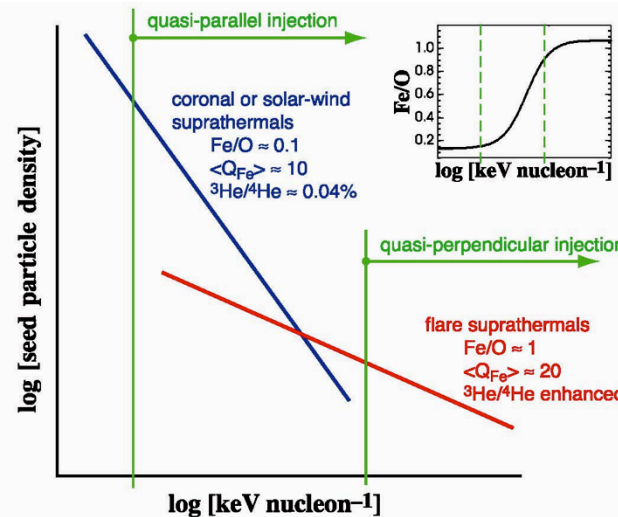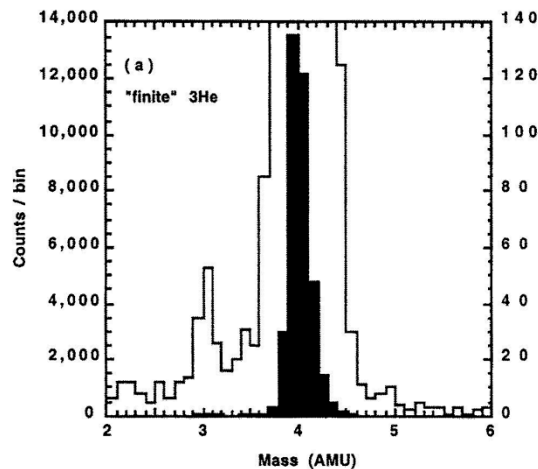# Abundances – Impulsive events

Reames & Ng (2004)

Reconnection theory (Drake et al 2009) – power-law in A/Q
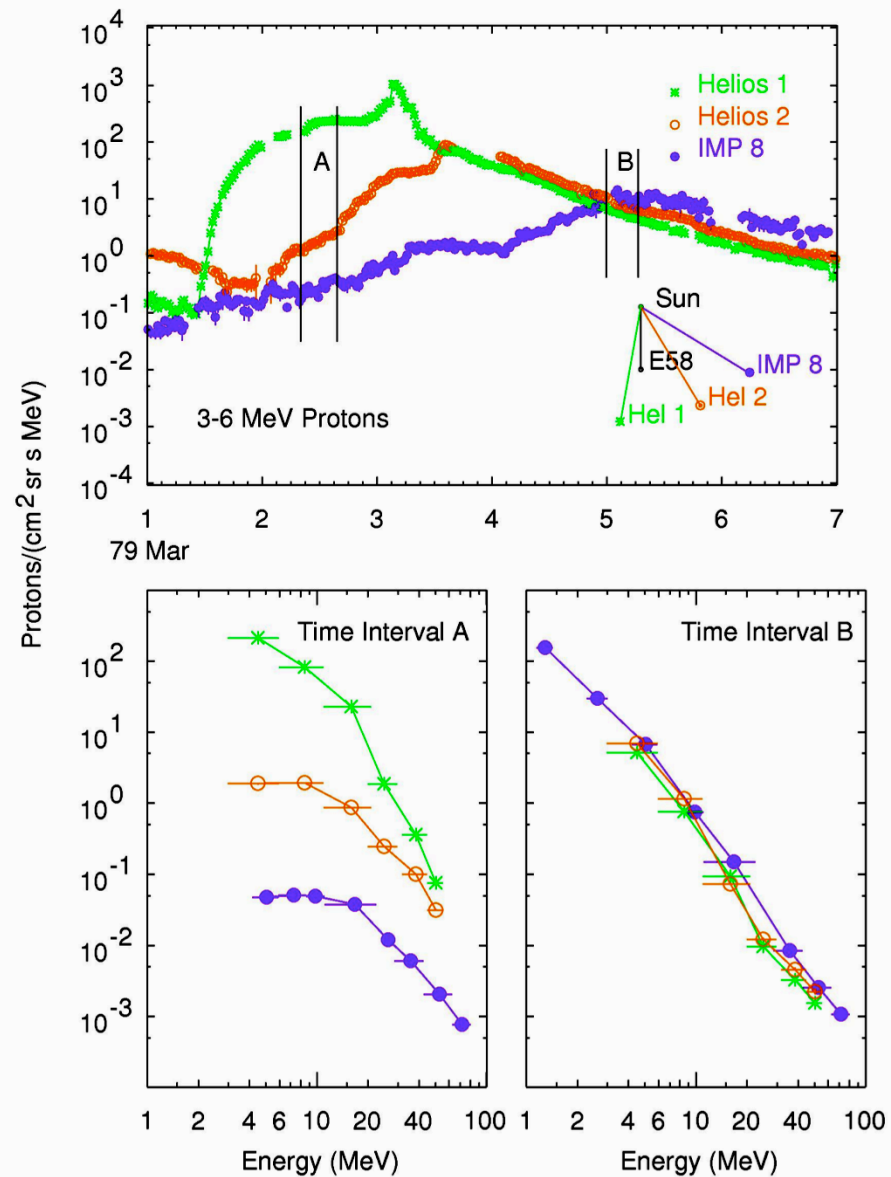
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Seed population – Impulsive suprathermal ions

- 1999 ^{3}He in gradual events (Mason, Mazur, & Dwyer)
- 2001 ^{3}He/^{4}He, Fe/O, & Q(Fe) (Tylka et al.)
- 2003 *in situ* shocks (Desai et al.)
- 2005 Fe/O *vs.* E (Tylka et al.)
- 2006 shock model (Tylka & Lee)
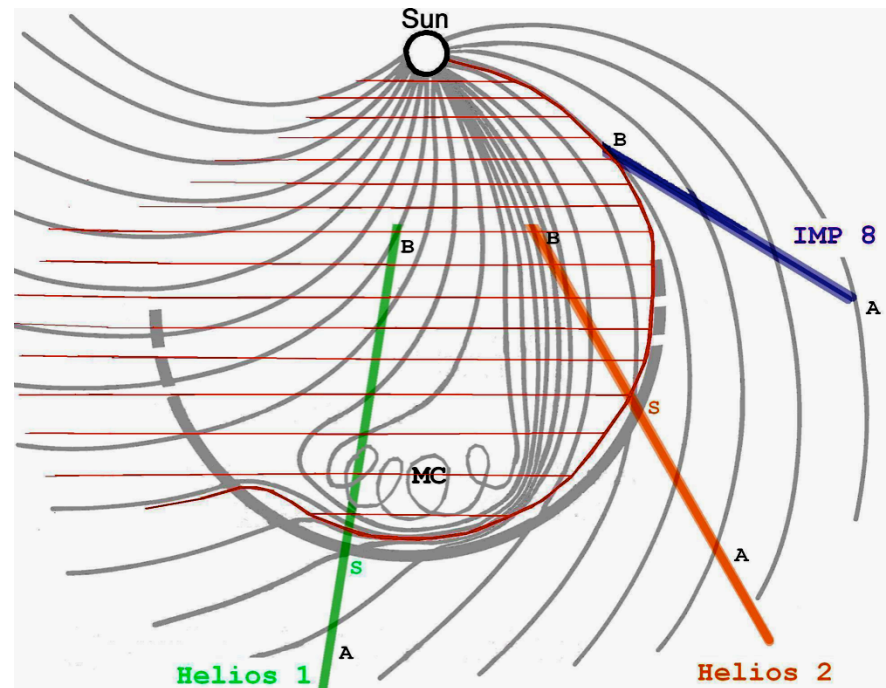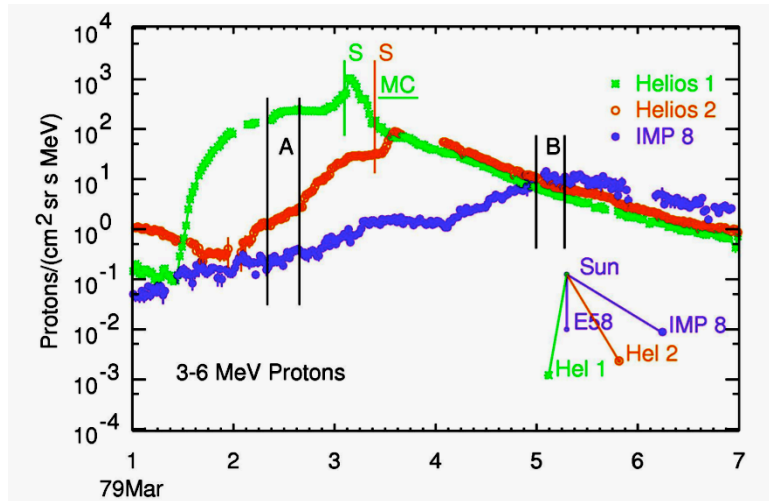

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The Multi-Spacecraft View
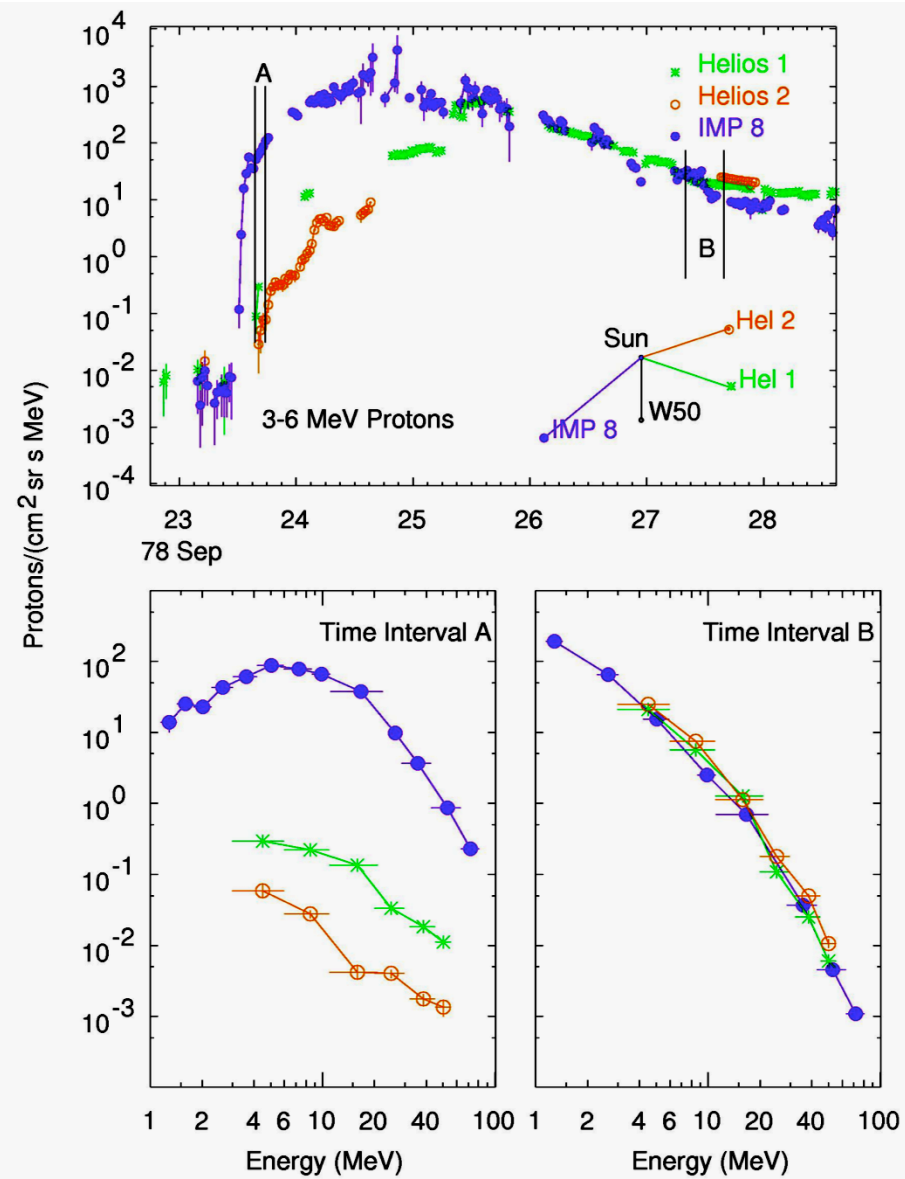

Reames, Kahler, & Ng 1997

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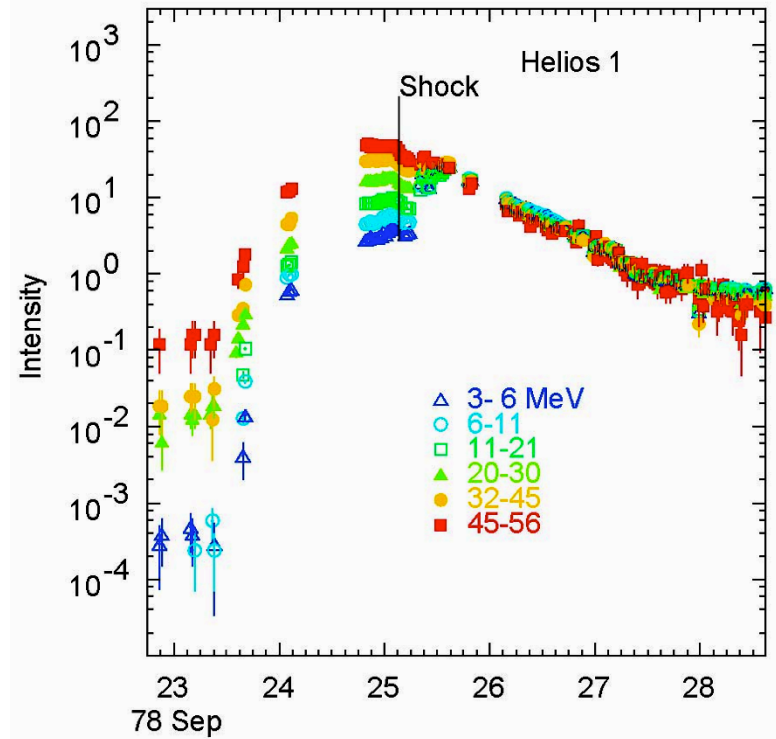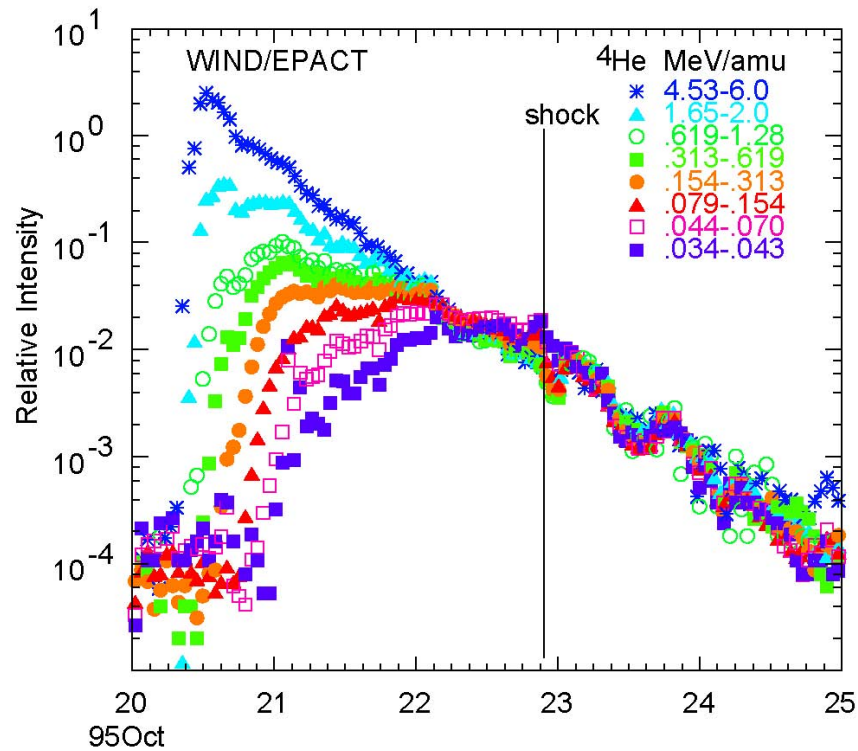# Quasi-trapped SEP "Reservoir" behind the shock expands adiabatically
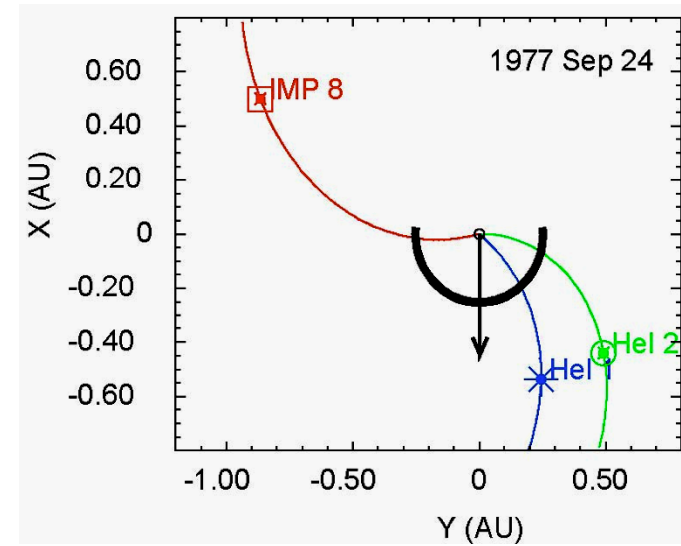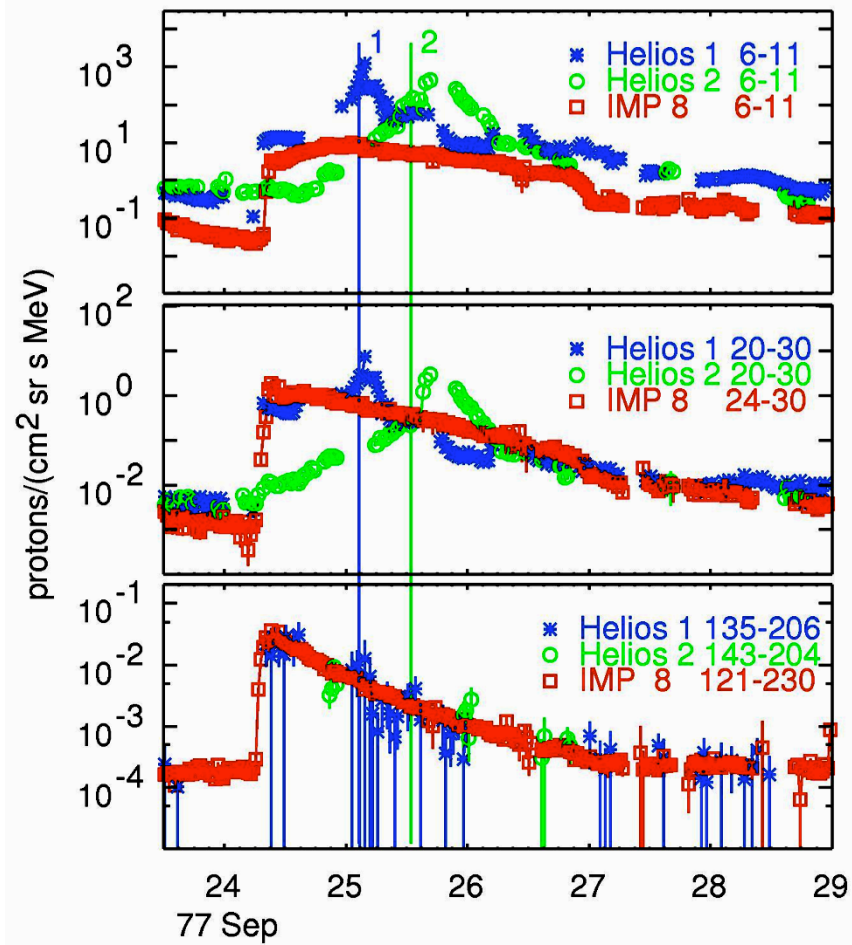

Reserviors:
- McKibben (1972)
- Roelof et al (1992)
- Reames, Kahler, & Ng (1997)
- Reames (2010)

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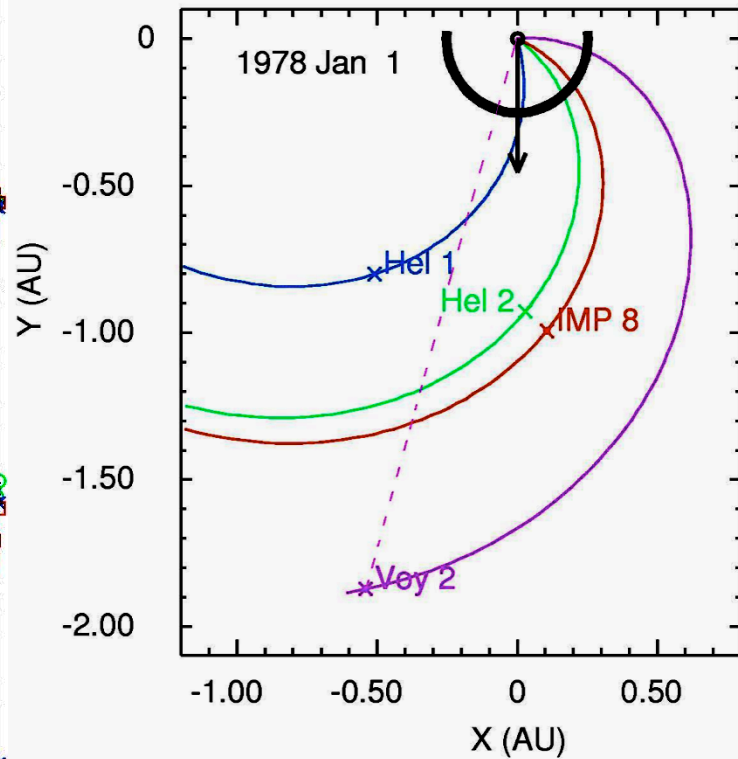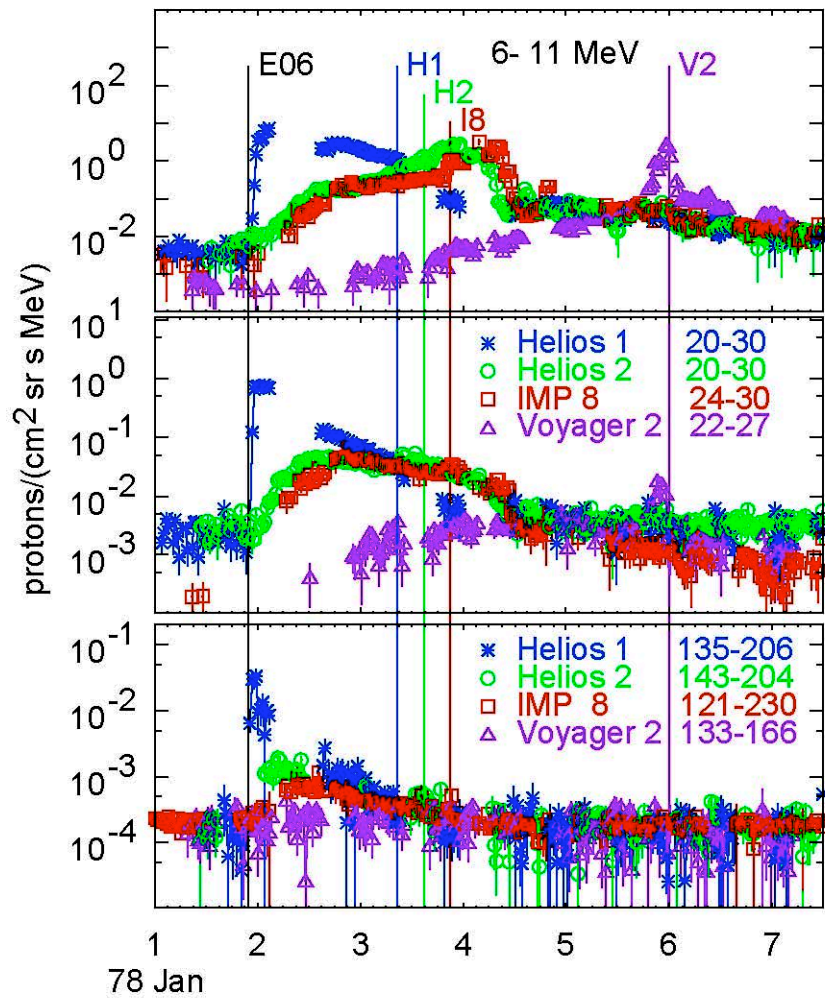Don Reames ... 2012 Hale lecture

Spectral shape remains constant with time in the reservoir

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Reames, Ng, & Tylka (2012)

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6- 11 MeV

	Helios 1	20-30
	Helios 2	20-30
	IMP 8	24-30
	Voyager 2	22-27

	Helios 1	135-206
	Helios 2	143-204
	IMP 8	121-230
	Voyager 2	133-166

1978 Jan 1
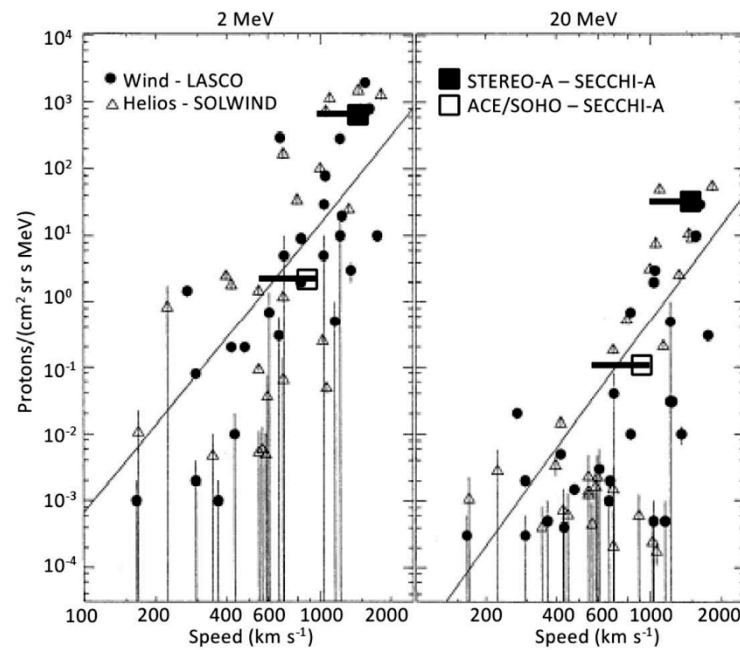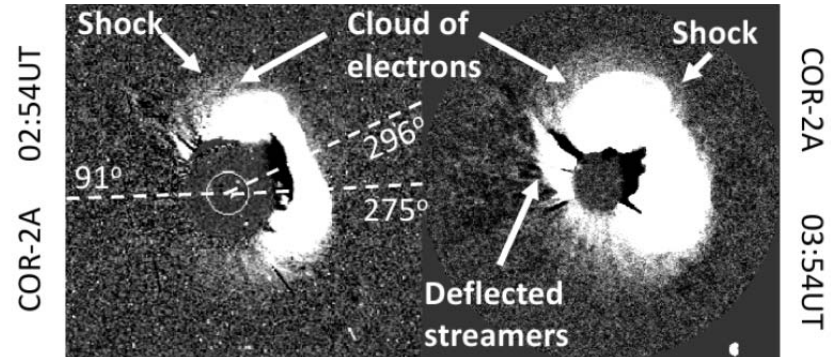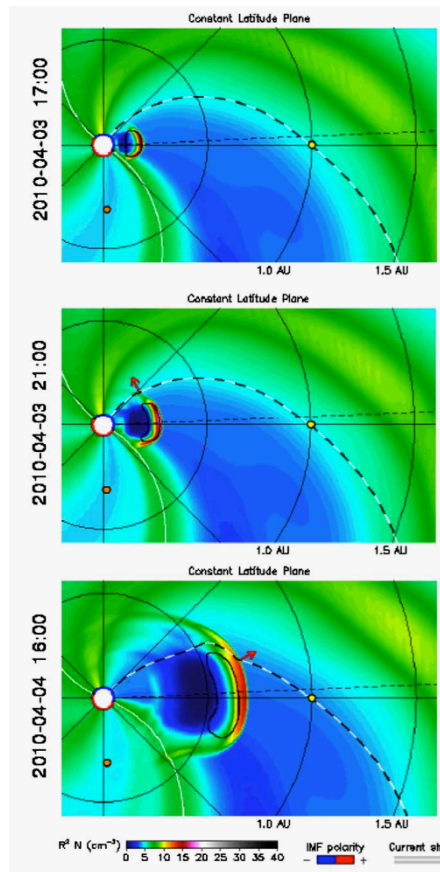
Berdichevsky et al (2008)
Reames, Ng, & Tylka (2012)

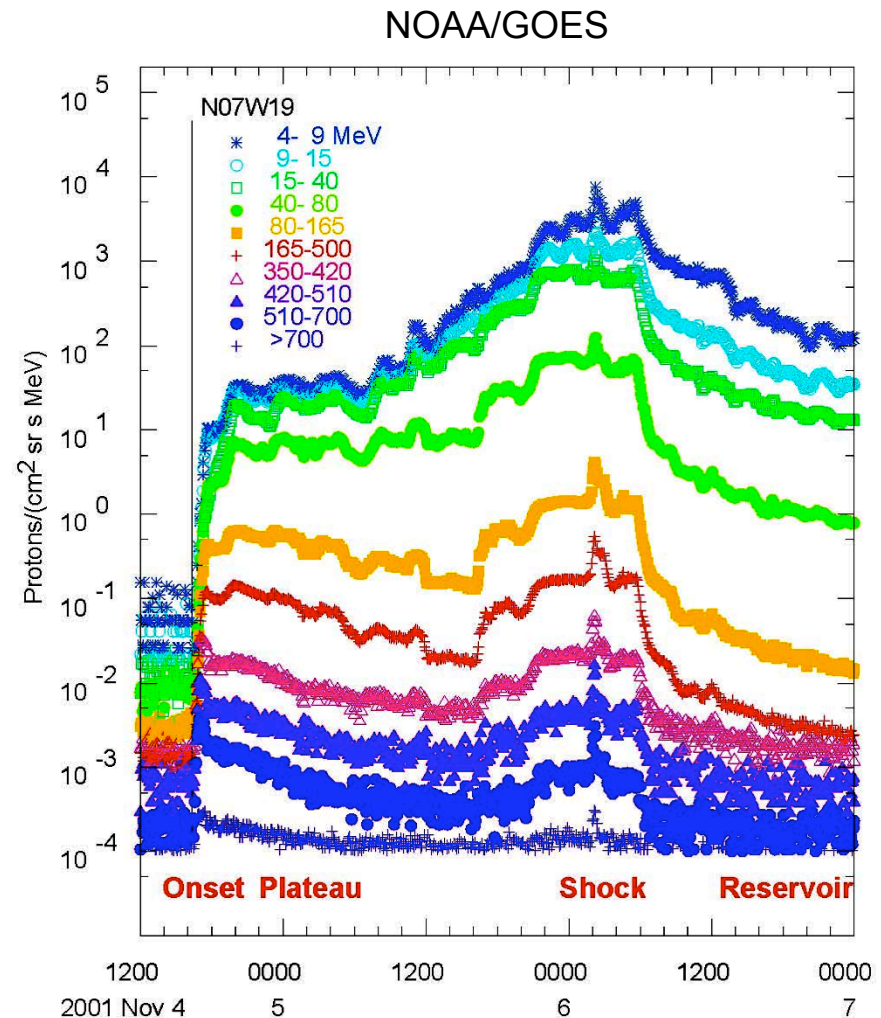Don Reames ... 2012 Hale lecture

STEREO

Rouillard et al. (2011, 2012) SEP onset times and intensities correspond to shock arrival times and speeds at connection to STA and Earth

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Phases of a large SEP event (at the right longitude):

1) Onset (velocity dispersion)

2) Plateau

3) Shock peak

4) Adiabatic decay

NOAA/GOES

N07W19

* 4- 9 MeV
○ 9- 15
□ 15- 40
● 40- 80
■ 80-165
+ 165-500
△ 350-420
▲ 420-510
● 510-700
+ >700

Protons/(cm^2 sr s MeV)

Onset Plateau   Shock   Reservoir

1200   0000   1200   0000   1200   0000
2001 Nov 4   5   6   7

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Onsets:

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1998 May 6 GLE 57

Reames 2009a, ApJ 693, 812

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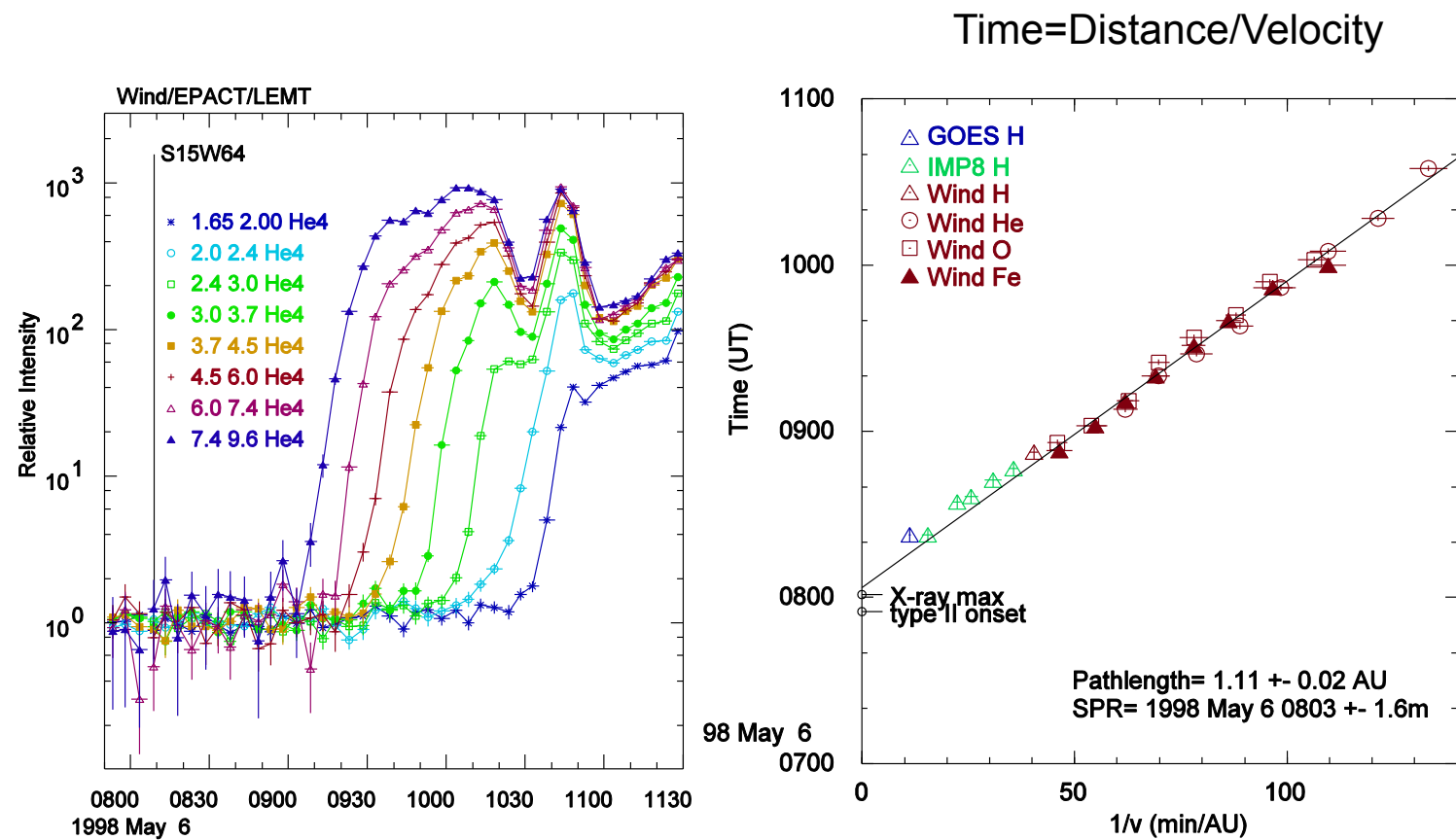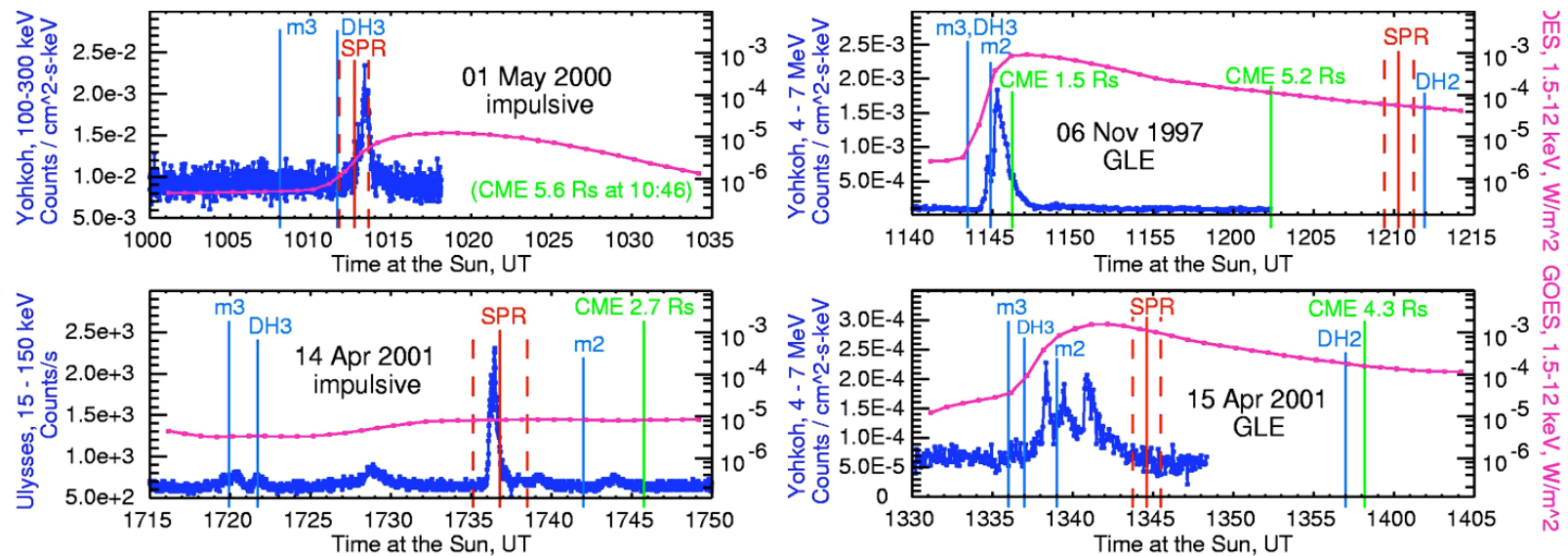
Tylka et al. (2003, 28th ICRC, 3305)
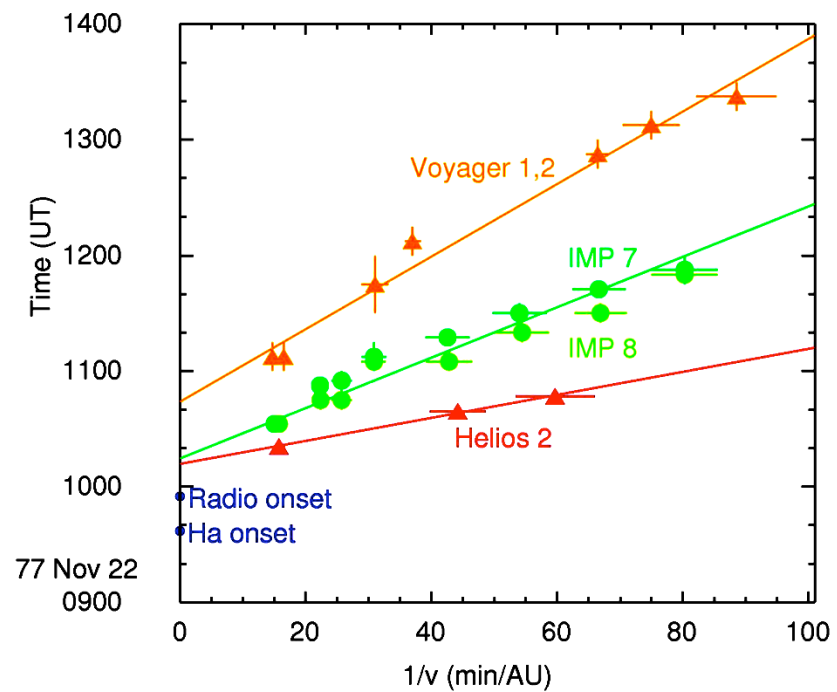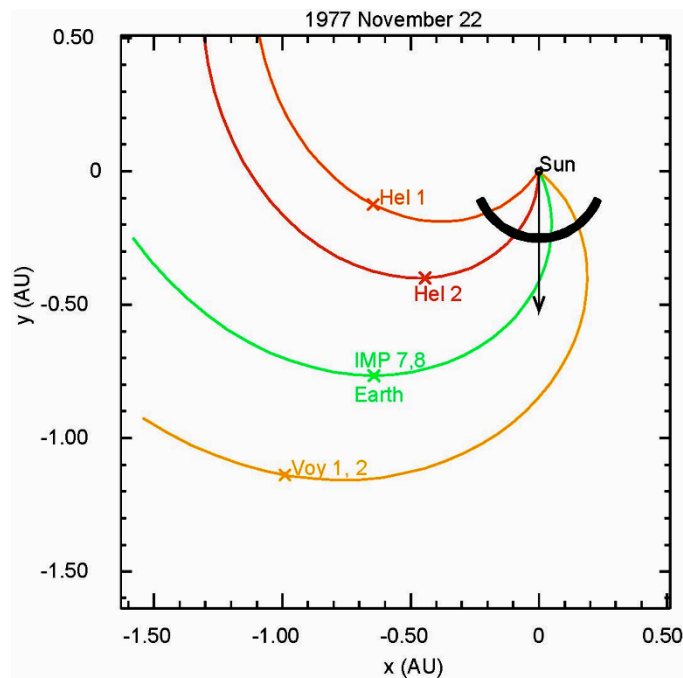For impulsive SEP events, SPR time coincides with hard X-ray peak.
For GLEs, SPR usually falls well after hard X-ray peaks.

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Multi-Spacecraft View of Onsets

Reames & Lal (2010, ApJ 773, 550)
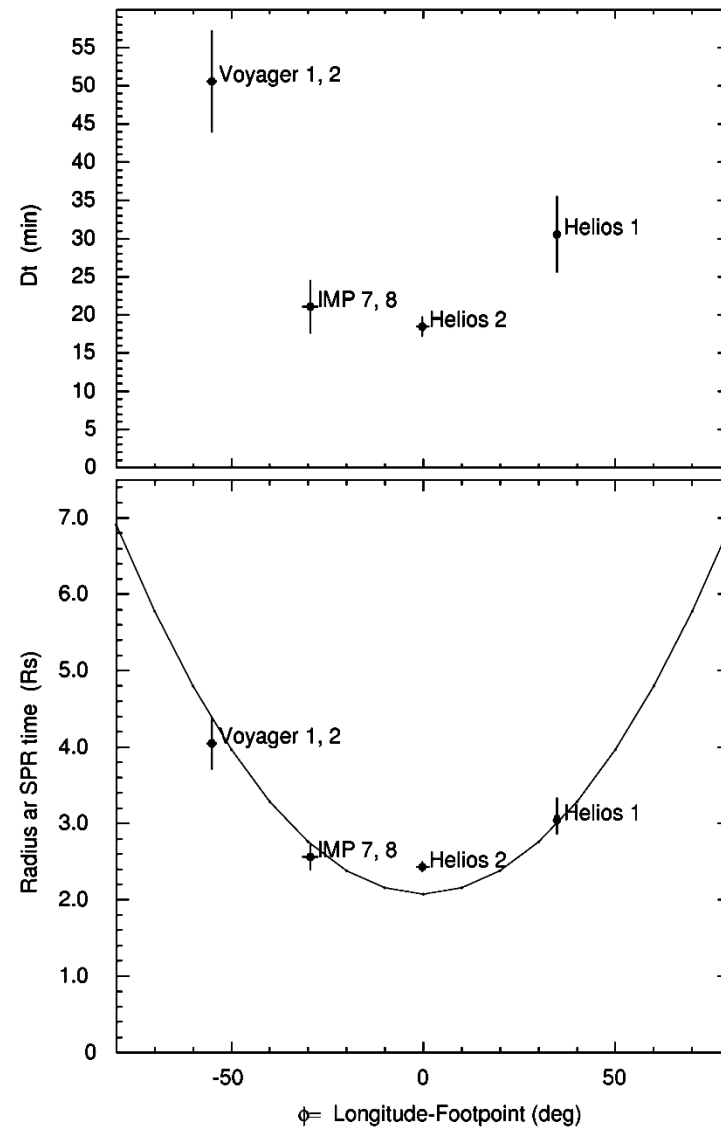

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Similar behavior for a single GLE, either:

1) SEPs begin at higher altitudes on the flanks of the shock, or

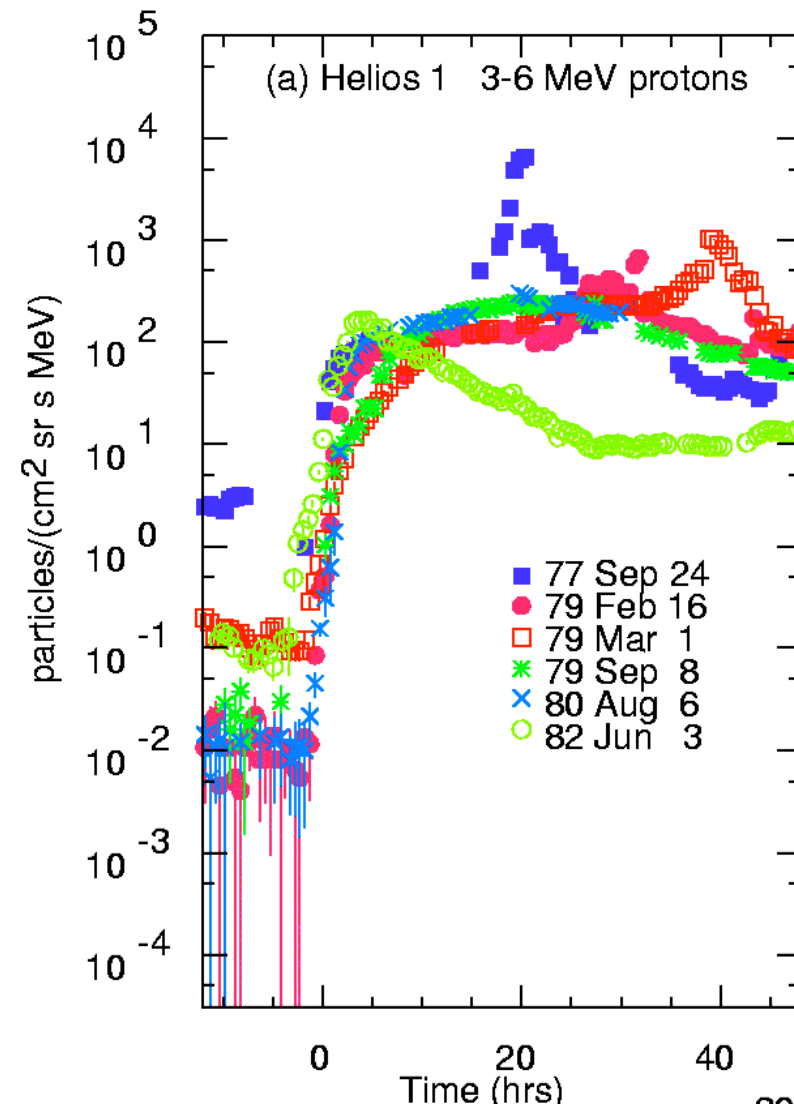2) The shock speed decreases on the flanks

Reames & Lal (2010, ApJ 773, 550)

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Plateaus:

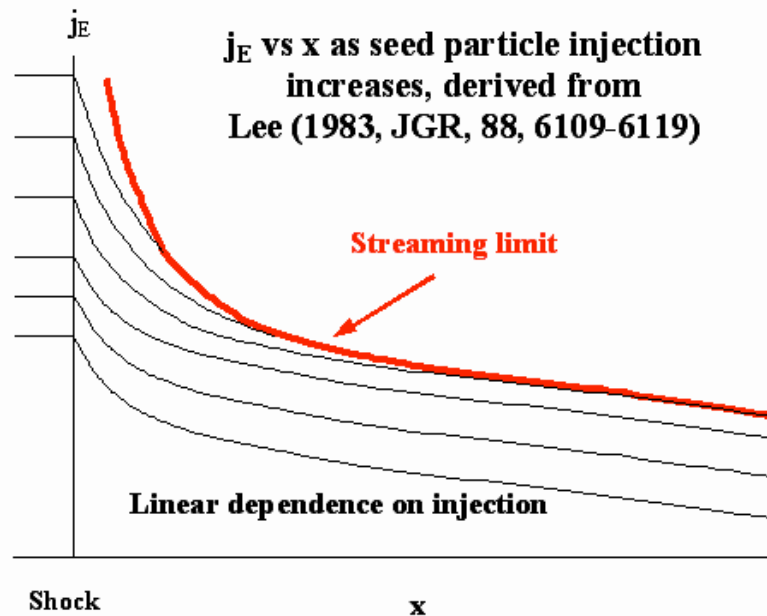Don Reames ... 2012 Hale lecture

The Streaming Limit

In large SEP events, intensities of protons of a few MeV never seemed to exceed ~200 protons/(cm^2 sr s MeV) early in the events.

Reames, 1990, ApJ 358, L63

(a) Helios 1   3-6 MeV protons

- ■ 77 Sep 24
- ● 79 Feb 16
- □ 79 Mar 1
- ✳ 79 Sep 8
- ✕ 80 Aug 6
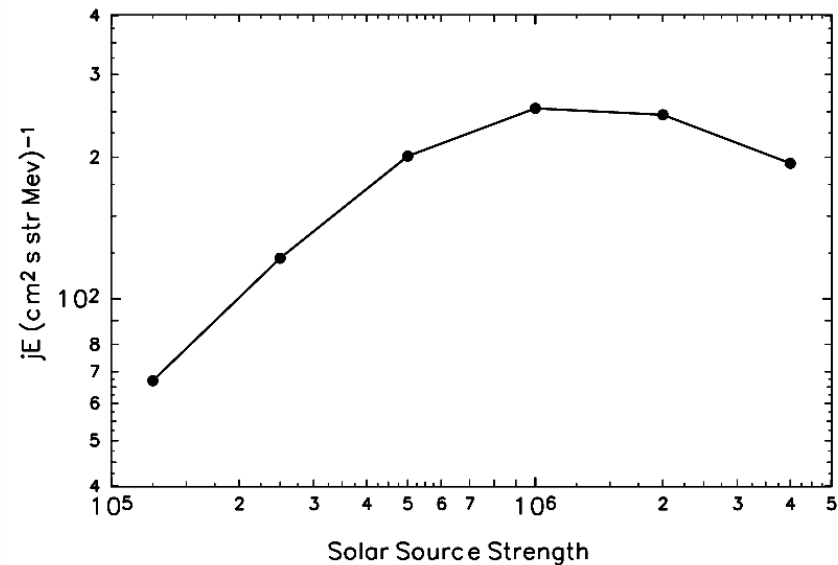- ○ 82 Jun 3

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Self-amplified waves throttle SEP transport

More injected particles $\Rightarrow$ more self-amplified waves

Ng & Reames (1994 ApJ 424, 1032)
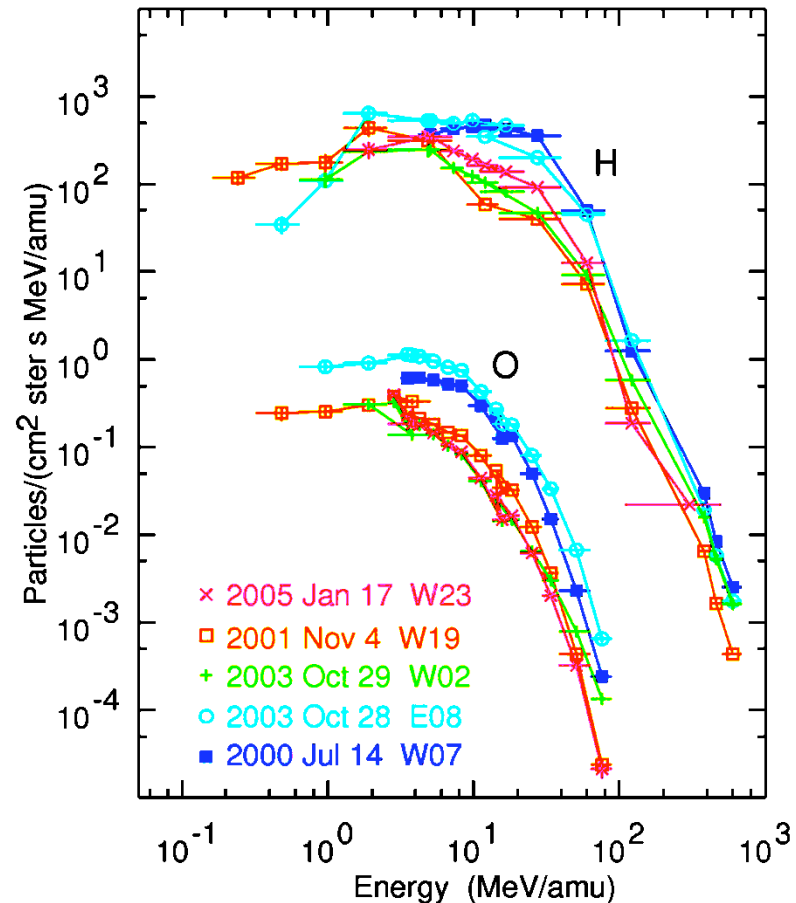
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H and O Spectra of 5 largest GLEs

Resonance condition:

The wave number $k \approx B/P\mu$, where $P = pc/Qe$ is the magnetic rigidity of a particle of momentum p and μ is the cosine of its pitch angle with respect to the field, $\mathbf{B}$.
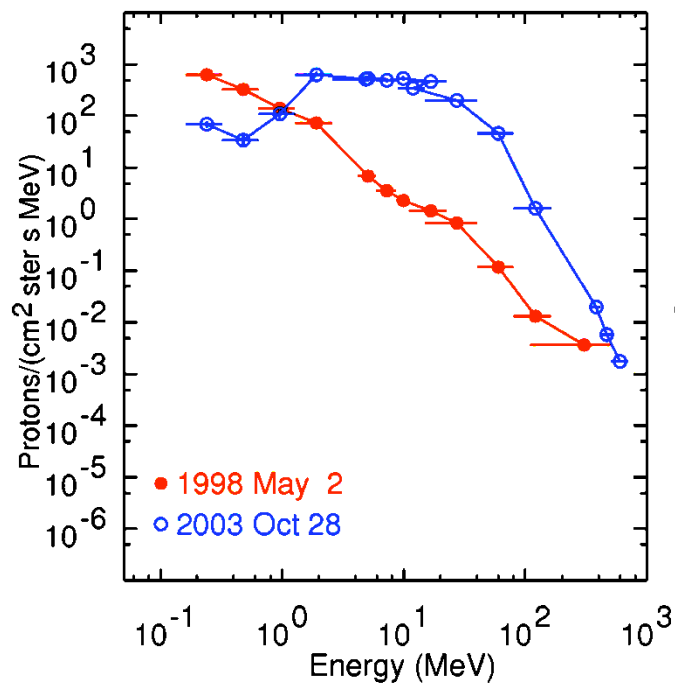
High-energy protons with small μ amplify waves that scatter low-energy ions with $\mu\sim1$

Reames & Ng (2010 ApJ 723, 1286)

H

O

× 2005 Jan 17 W23
□ 2001 Nov 4 W19
+ 2003 Oct 29 W02
○ 2003 Oct 28 E08
■ 2000 Jul 14 W07

Particles/(cm^2 ster s MeV/amu)

Energy (MeV/amu)
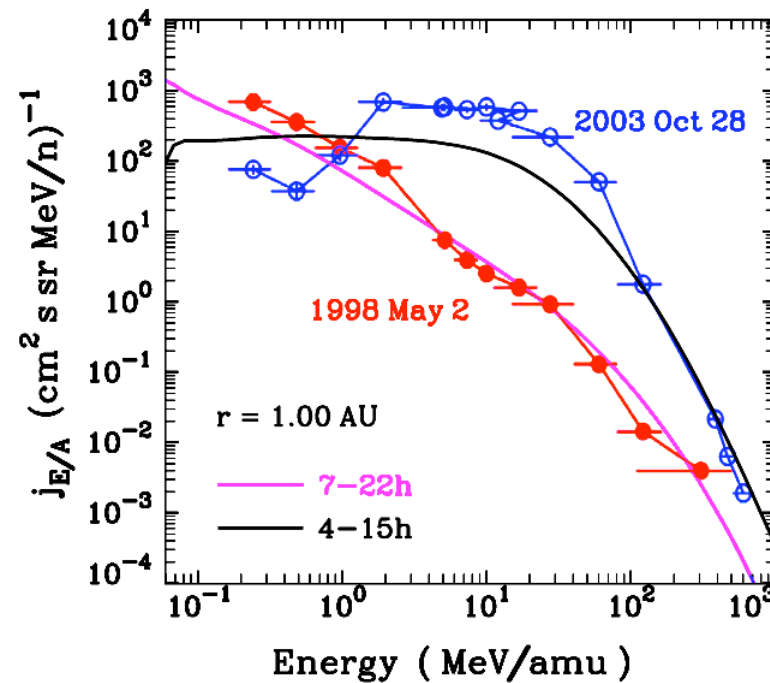
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98 May 2 Proton Spectrum

When the ~10MeV protons are rare, the ~1 MeV intensities can rise

Reames & Ng (2010)

Ng, Reames, & Tylka (2011)

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Shocks:
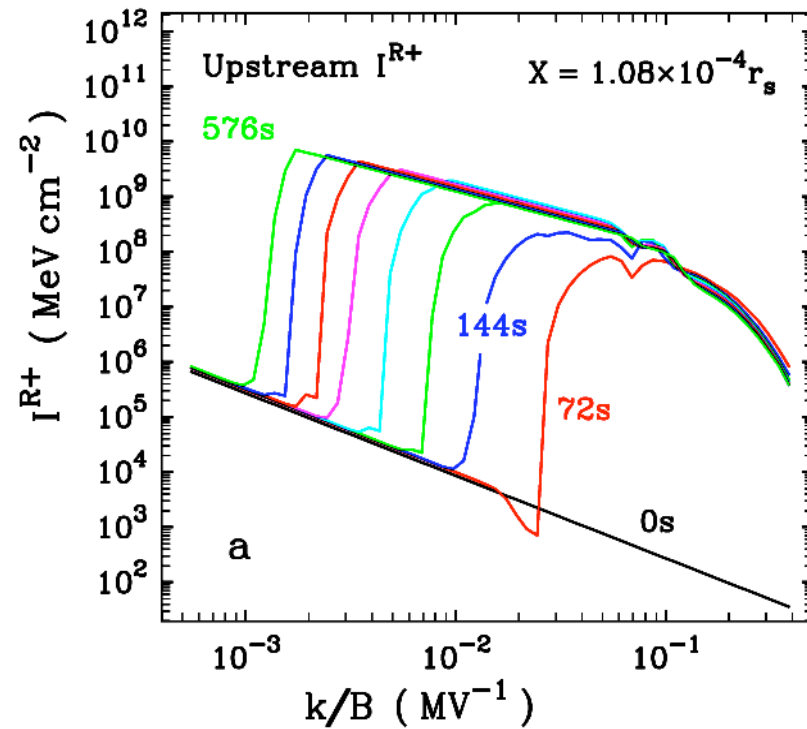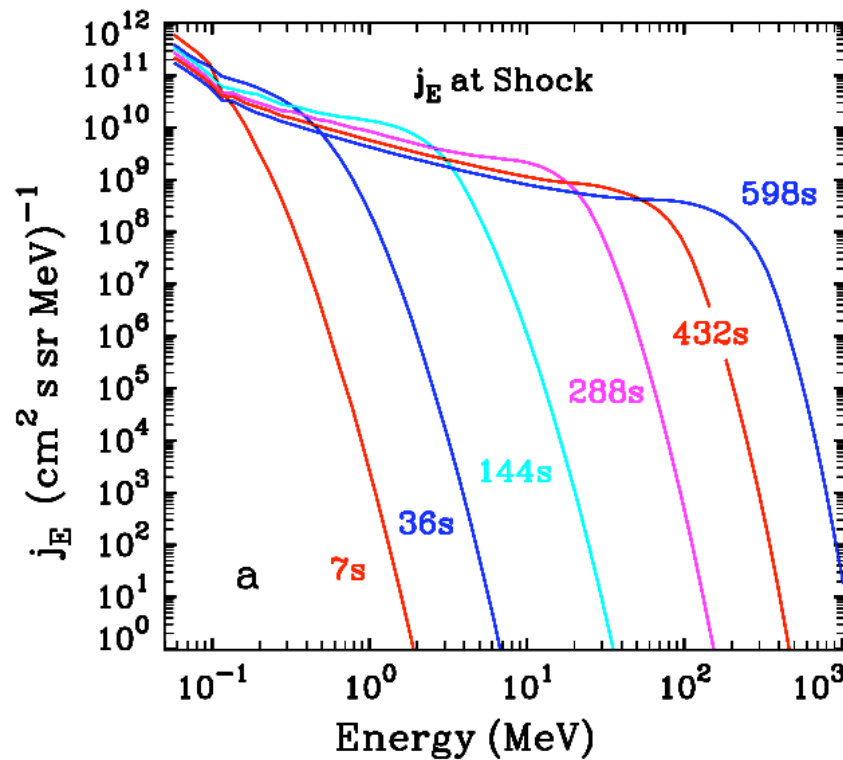
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Shock acceleration

Ng & Reames (2008)

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Reservoirs -
particle transport:

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Slow Parallel Diffusion?

The slow decrease of gradual event profiles was once attributed to slow diffusion.

Why would the event on Oct. 20 decrease slowly while that on the 23rd is rapid?

The slow decrease Oct. 22-26 defines a **reservoir**, **not diffusion!**

Particles from the impulsive injection on the 23rd are unscattered as they propagate outward.

(Mason, Ng, Klecker, & Green 1989)

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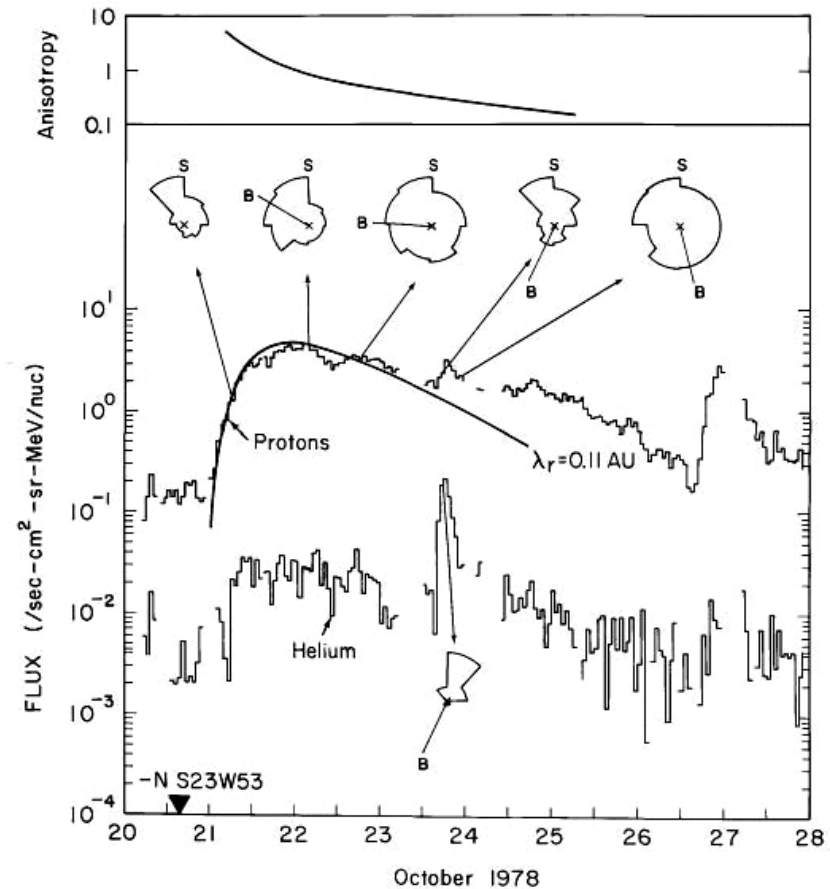
Mazur et al. (2000, ApJ 532, L79): Impulsive sources are modulated as flux tubes occasionally intercept the compact flare source. Gradual events, from spatially extended shock sources, populate all flux tubes. Chollet &Giacalone (2011). Flux tube edges are very sharp.


impulsive   gradual

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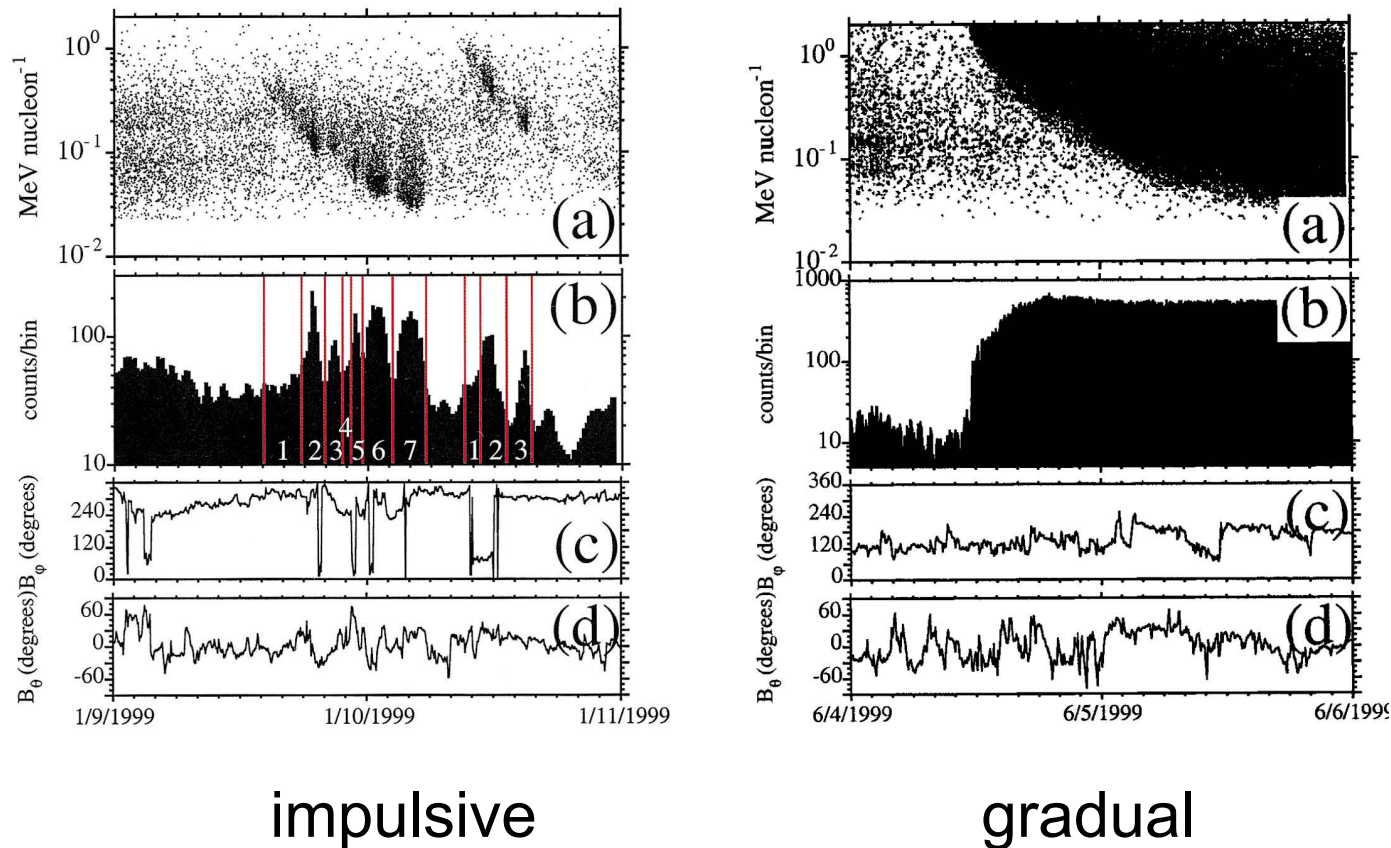
Magnetic Clouds:

Counter-streaming electrons in magnetic clouds (MCs) are taken as evidence that footpoints of the field lines are connected to the corona on both ends (Shodhan et al. 2000).

However, MCs during solar minimum, listed as 100% closed, are completely full of anomalous cosmic rays from the outer heliosphere as identified by their unique element abundances, He/O ~ 1 & O/C~ 20
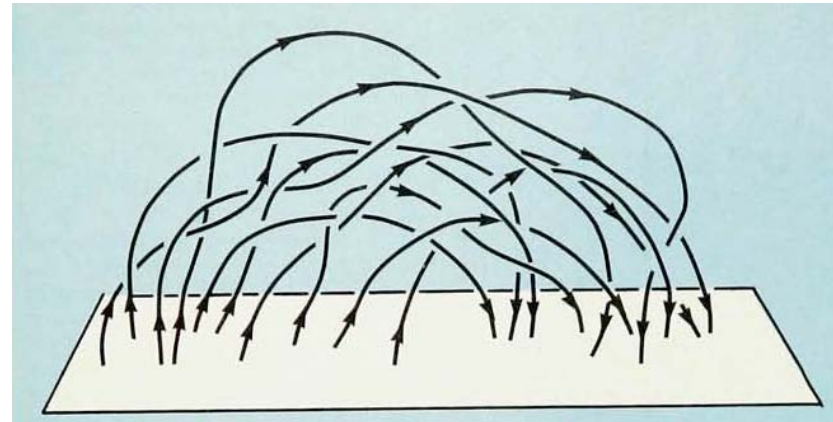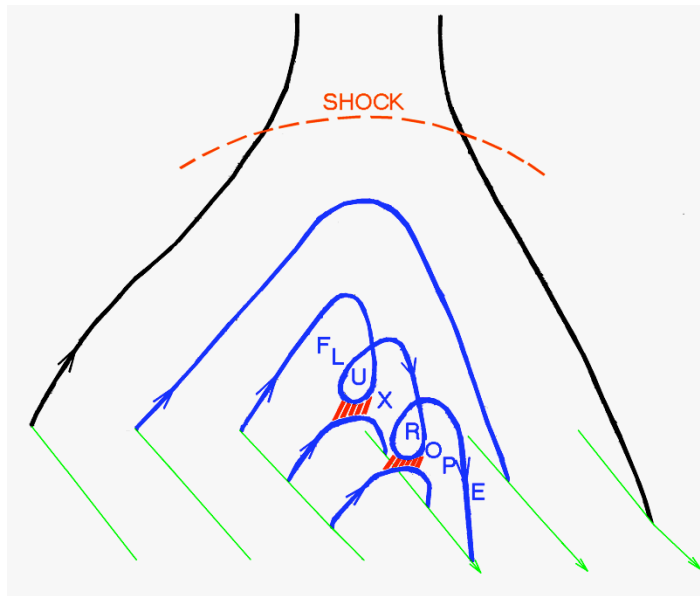
(Reames, Kahler, & Tylka 2009)

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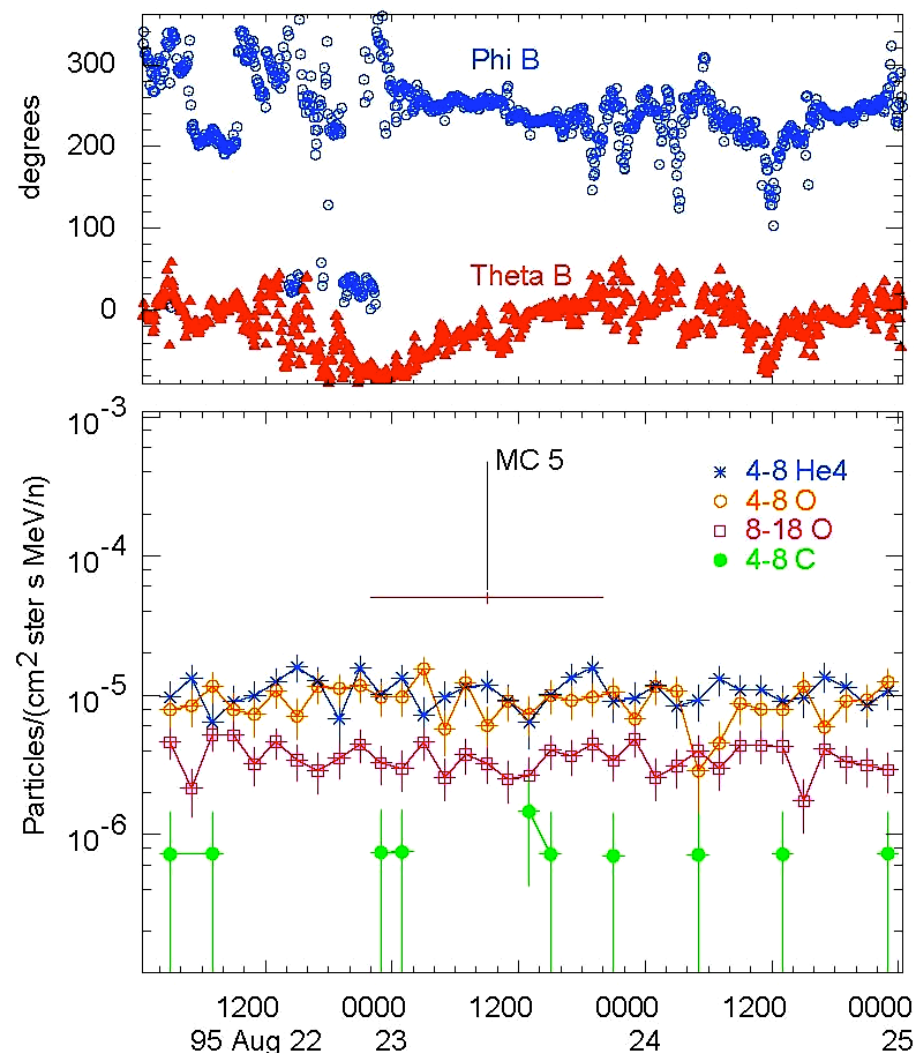
Random walk of magnetic field lines
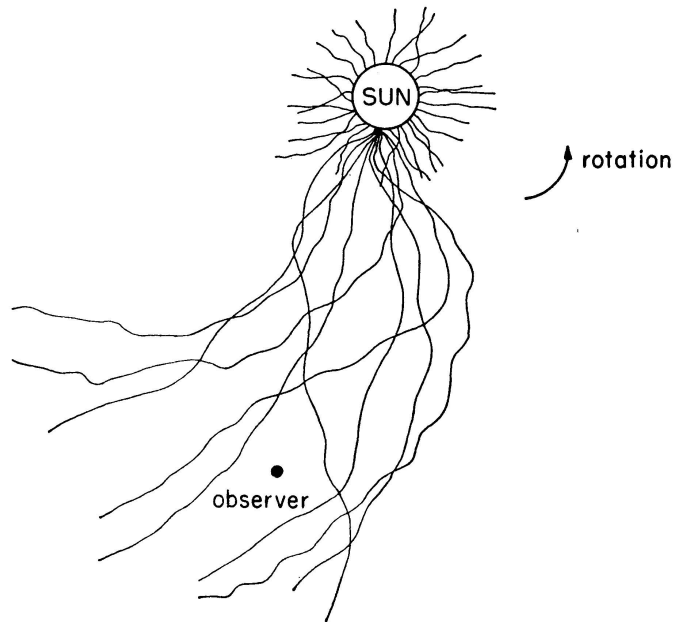
Jokipii & Parker (1969)

Parker (1987)

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Flares, Shocks, and Jets

Big shock events

Small ³He-rich events

Reames 2002
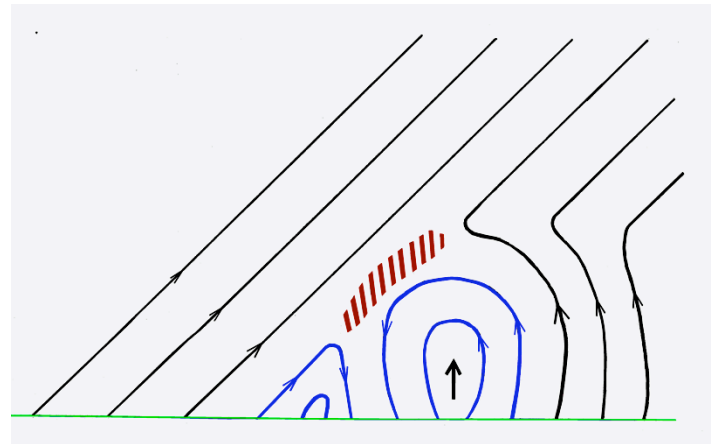
Jets (Shimojo & Shibata 2000)

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Conclusion

Next year will be the 50th anniversary of the simple model suggested by Wild, Smerd, and Weiss. With appropriate corrections for ion abundances, it seems to be holding up quite well.

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Thank you!

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