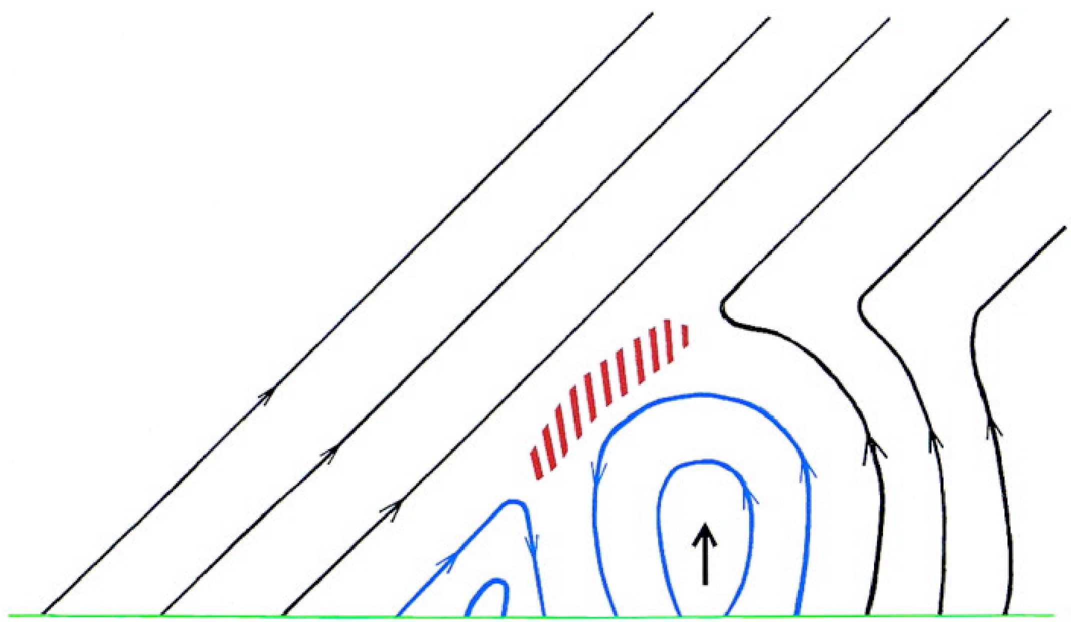
Impulsive SEP Events
Solar Sources and Magnetic Field Connection



Reames (2002)

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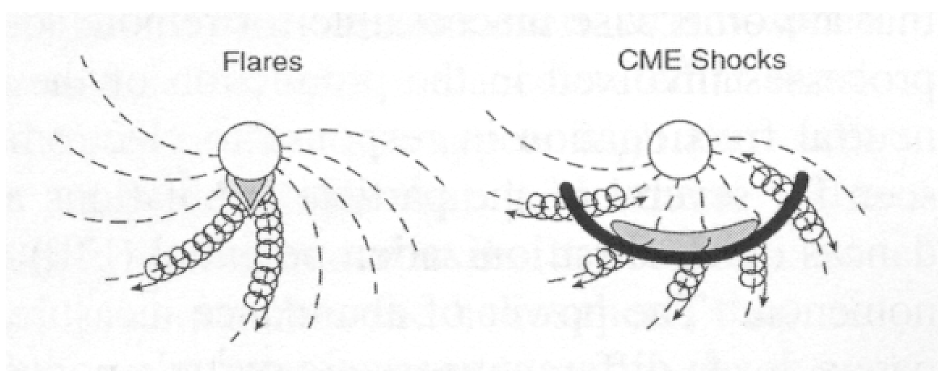
Two Types of SEP Events

	Impulsive	**Gradual**
Particles	Electron rich	Proton rich
$^3He/^4He$	~1	~0.0005
Fe mean charge state	~20	~14
Duration	Hours	Days
Origin	Impulsive Flares	CME Shocks
Longitude Cone	<30deg	~180 deg



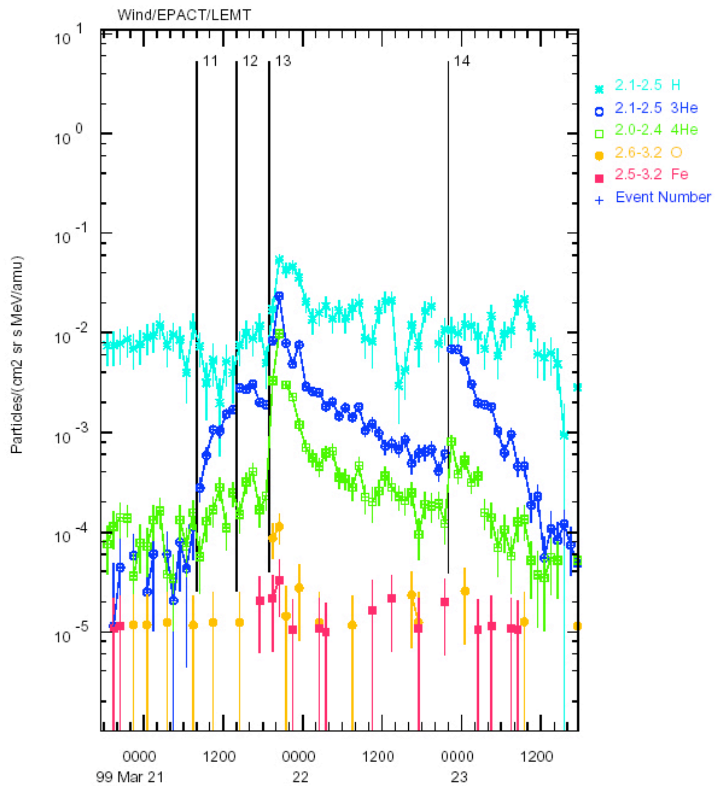
After Reames (1996, 1999)

Why do we want to know the origin of impulsive SEP events?

- Impulsive SEP events are thought to come from impulsive solar flares, but does anomalous composition of ions occur in every impulsive flares?
- Specifically, is there a special acceleration mechanism in open field configurations, since the presence of open field lines is essential for particles to get out?
- Why do the associated flares tend to be small?
- What is the role of CMEs in certain impulsive SEP events?
- Does enrichment in ^{3}He and heavy ions in certain gradual SEP events result from remnants of previously accelerated impulsive SEP events?

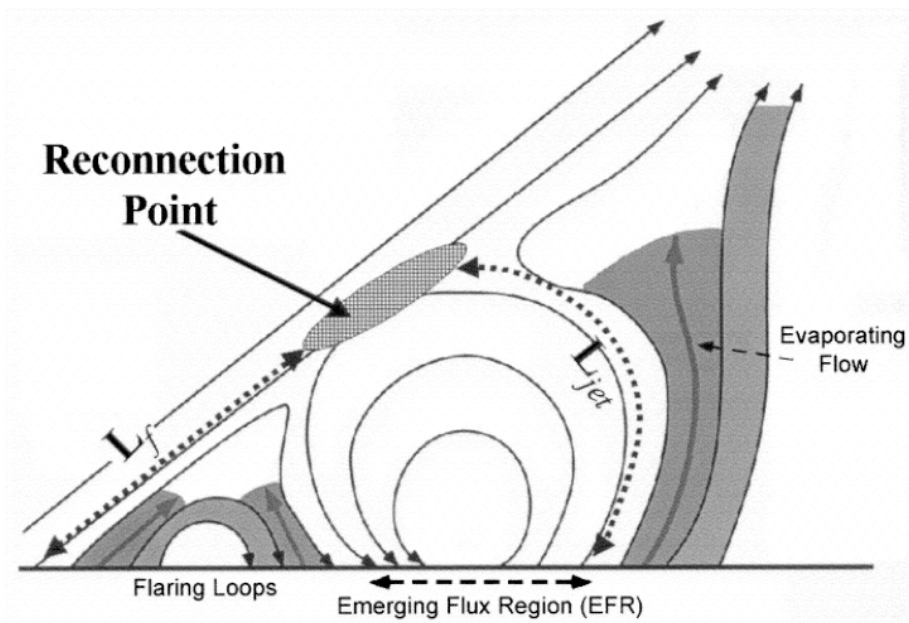
Challenges in source identification

- Long travel time of ~1 MeV ions [2.5 hours (0.5 hours) for 2 MeV/n (50 MeV/n) ions traveling 1.2 AU].
- How well are the onsets at different energies determined?
- Possible propagation effect due, e.g., to the irregularities of IMF.
- The associated coronal activity (e.g.,brightening) tends to be tiny. How can we distinguish the activity associated with the impulsive SEP event from similar ones?



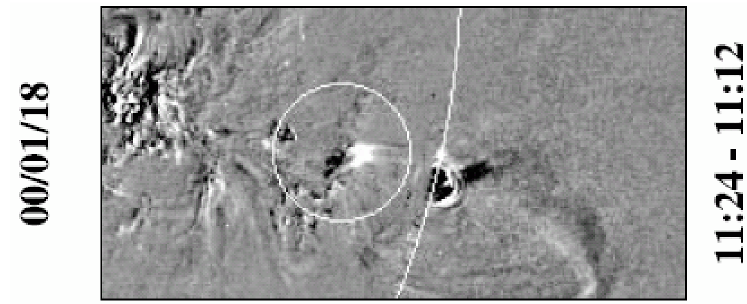
Impulsive SEP Events and Jets

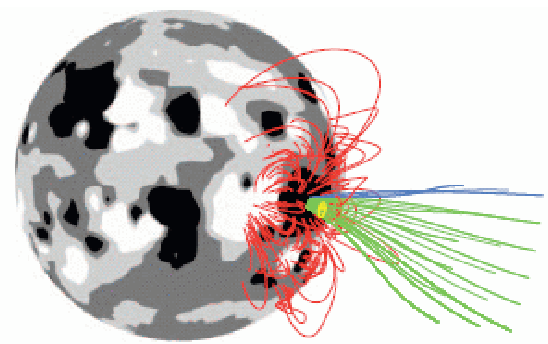
- This association is expected, because impulsive SEP events accompany type III bursts (Reames and Stone 1986), and type III bursts (metric) accompany X-ray jets (Kundu et al. 1995).
- Type III bursts signify ≤ 10 keV electrons along open field lines, and jets signify interaction of emerging bipoles (closed) with open flux (Shimojo and Shibata 2000).



Impulsive SEP Events and Jets

- Wang, Pick & Mason (2006) identified the source region by looking for an H_ flare or an EIT ejection/flare at W20-W90 within a few hours of the estimated ion injection time.
- The particle injection time is derived from the velocity dispersion. Some events do not show a clear velocity dispersion.
- Jets are found between W25 and W72 in EIT images, sometimes accompanied by white-light jets observed by LASCO.
- The source regions next to open field regions, as shown by the PFSS model.
- Jets tend to recur.





(a) 2000 JANUARY 18

Impulsive SEP Events and Jets

TABLE 1

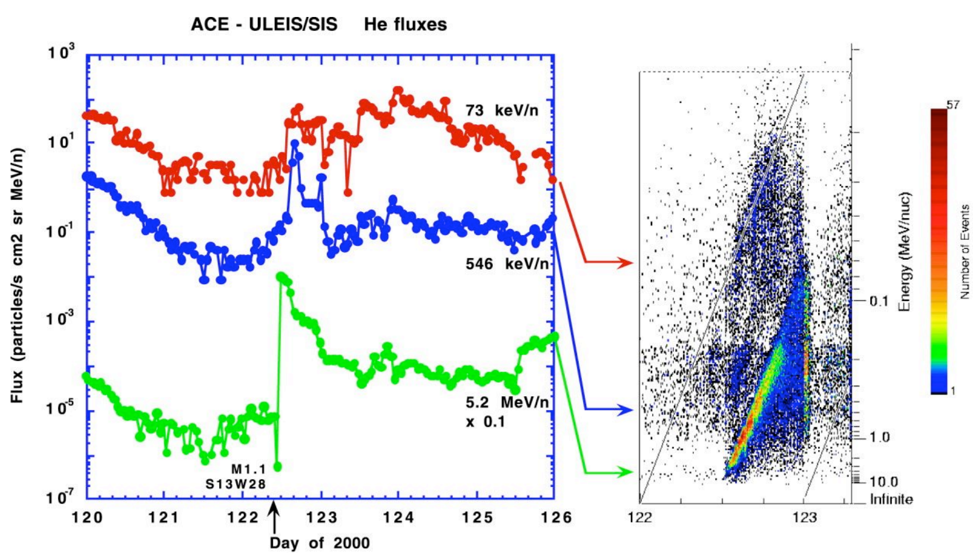
25 Impulsive SEP Events

		EIT Event[b]		LASCO CME[c]				
Date	Hα Flare[a] Location (UT)	Type	Location (UT)	Type	P.A. (UT)	$^3He/^4He$[d]	Fe/O[d]	Reference
1997 Nov 24...............	N21°W63° (12:53)	λ195 flare/ejection	N21°W63° (13:17)	Jet	281° (13:37)	~0.1	~1	1, 6
1998 Aug 18.17..........	N20°W56° (04:13)	...	...	...	...	6.2	1.19	2
1998 Sep 9.17.............	S22°W60° (00:10)	...	...	...	...	0.21	1.76	2, 3
1999 Mar 21.17..........	N25°W26° (04:03)	λ195 flare/jet	N19°W27° (04:36)	?	?	1.67	2.22	3
1999 Jun 18.33...........	?	λ195 flare/jet	N24°W56° (05:17)	...	...	0.115	1.20	3
1999 Jul 3.70..............	?	λ195 flare/jet	S14°W56° (16:48)	?	?	0.25	0.72	2
1999 Aug 7.76............	N18°W40° (17:28)	λ195 flare/jets	N19°W43° (18:00)	?	?	0.81	1.49	2, 3
1999 Sep 19.61...........	N20°W70° (14:35)	...	...	...	...	0.02	0.17	2
1999 Sep 30.22...........	?	λ304 flare/surge	N19°W60° (04:06)	...	...	0.87	1.06	2
1999 Oct 22.75...........	?	λ195 flare/jets	N09°W72° (16:48)	?	?	0.06	0.44	3
2000 Jan 6.20..............	?	λ195 flare/ejection	N15°W52° (02:36)	?	?	33.4	1.06	2
2000 Jan 17.13............	S18°W46° (04:57)	λ195 flare	S17°W43° (04:52)	?	?	15.9	0.64	2
2000 Jan 18.50............	?	λ195 flare/jets	S14°W63° (11:24)	?	?	0.09	0.55	3
2000 Mar 7.................	S12°W71° (12:31)	λ195 flare	S15°W69° (12:36)	Narrow	262° (12:54)	0.35	2.69	1, 6
2000 May 1.42............	?	λ195 flare	N20°W49° (10:24)	Narrow	307° (10:54)	0.06	2.22	1, 2, 3, 4
2000 Jun 4..................	?	λ195 flare/ejection	S07°W61° (07:13)	Narrow	292° (07:54)	0.31	1.49	1, 6
2000 Aug 22...............	?	λ195 flare/jet	N22°W40° (00:24)	Wide	301° (00:30)	~1	~1	1, 6
2000 Sep 27.17...........	N18°W56° (03:10)	λ195 flare/jet	N16°W54° (03:12)	Narrow	323° (03:26)	0.08	0.66	3
2000 Dec 28.00...........	N12°W38° (02:08)	λ195 flare/jet	N12°W37° (02:12)	?	?	0.16	1.62	3
2002 Aug 19...............	S11°W27° (10:34)	λ195 flare/ejection	S11°W27° (10:36)	Wide	225° (11:06)	0.05	0.60	6
2002 Oct 5.51.............	N09°W64° (11:52)	λ195 flare/jet	N09°W65° (12:12)	Jet	271° (12:30)	0.63	1.77	4, 5
2002 Oct 20................	S14°W53° (05:29)	λ195 flare/jet	S13°W52° (05:36)	Jet	241° (05:54)	0.17	0.85	6
2002 Dec 12.53...........	?	λ195 flare/jet	N14°W35° (12:48)	Jet	290° (13:31)	0.48	1.84	4, 5
2003 Mar 2.60............	?	λ195 flare/jet	S15°W25° (14:24)	Jet	252° (15:06)	0.65	0.87	5
2003 Mar 17.43..........	S16°W33° (10:14)	λ195 flare	S17°W35° (10:14)	Jet	254° (11:06)	0.18	0.56	5

From Wang, Pick & Mason (2006)

Injection Times

- Does velocity dispersion always give a reasonable injection time and path length?
- Is the delayed injection true?
- Does a longer path length jeopardize the scatter free assumption?

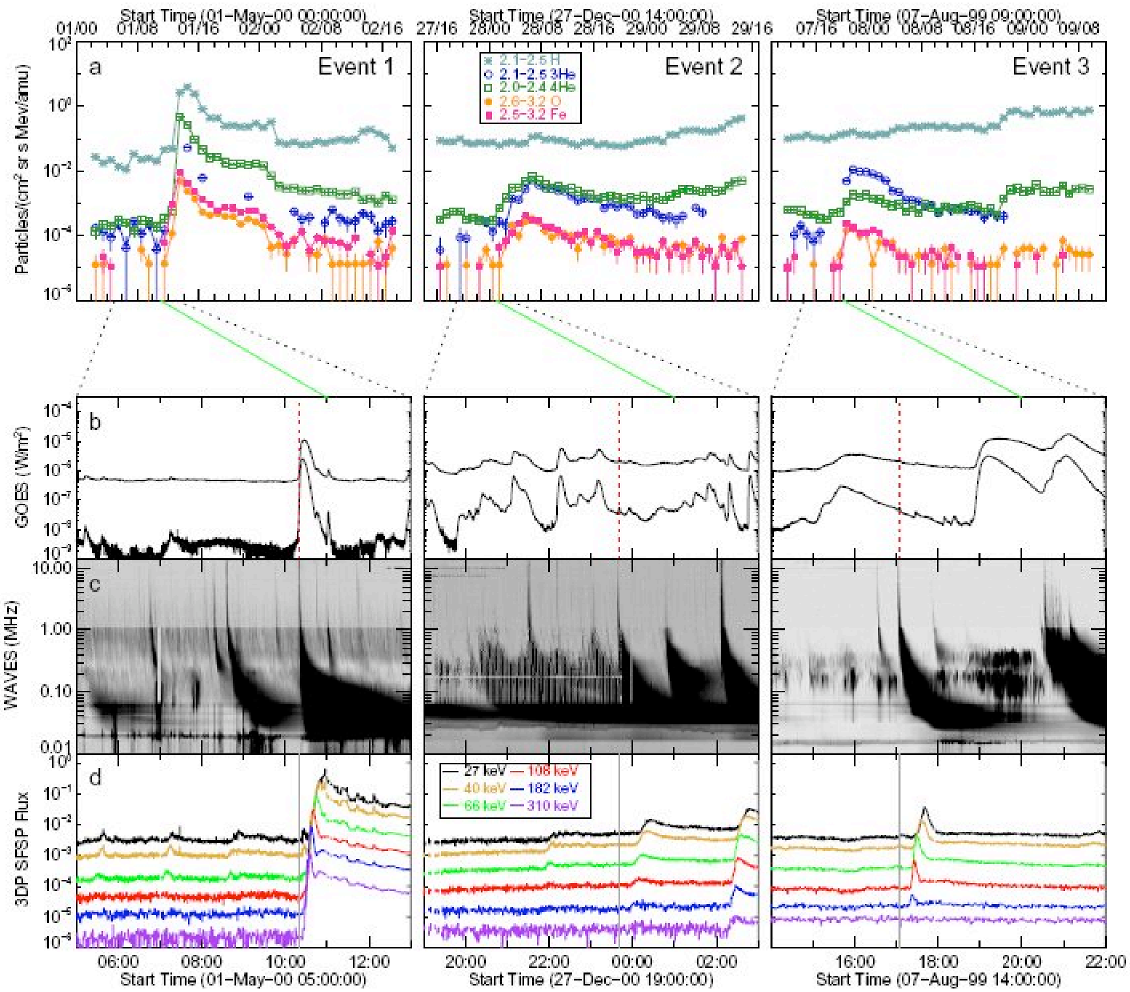


From Mason et al. (2002)

Use proxies of impulsive SEPs

- In order to mitigate the uncertainty of the injection time, we use type III bursts as proxies of impulsive SEP events (Reames & Stone 1986).
- Set the search window of 5 hours before the observed ion onset.
- Examine full-disk images to locate changes around the time of (or shortly after) the type III burst.
- In the case of multiple type IIIs, preference is given to those that accompany electron events (Reames, von Rosenvinge, & Lin 1985), and that extend to low frequencies.
- Images can help, because multiple type III bursts can occur in the interval from the same region (multiple injections?).

Type III bursts as proxies



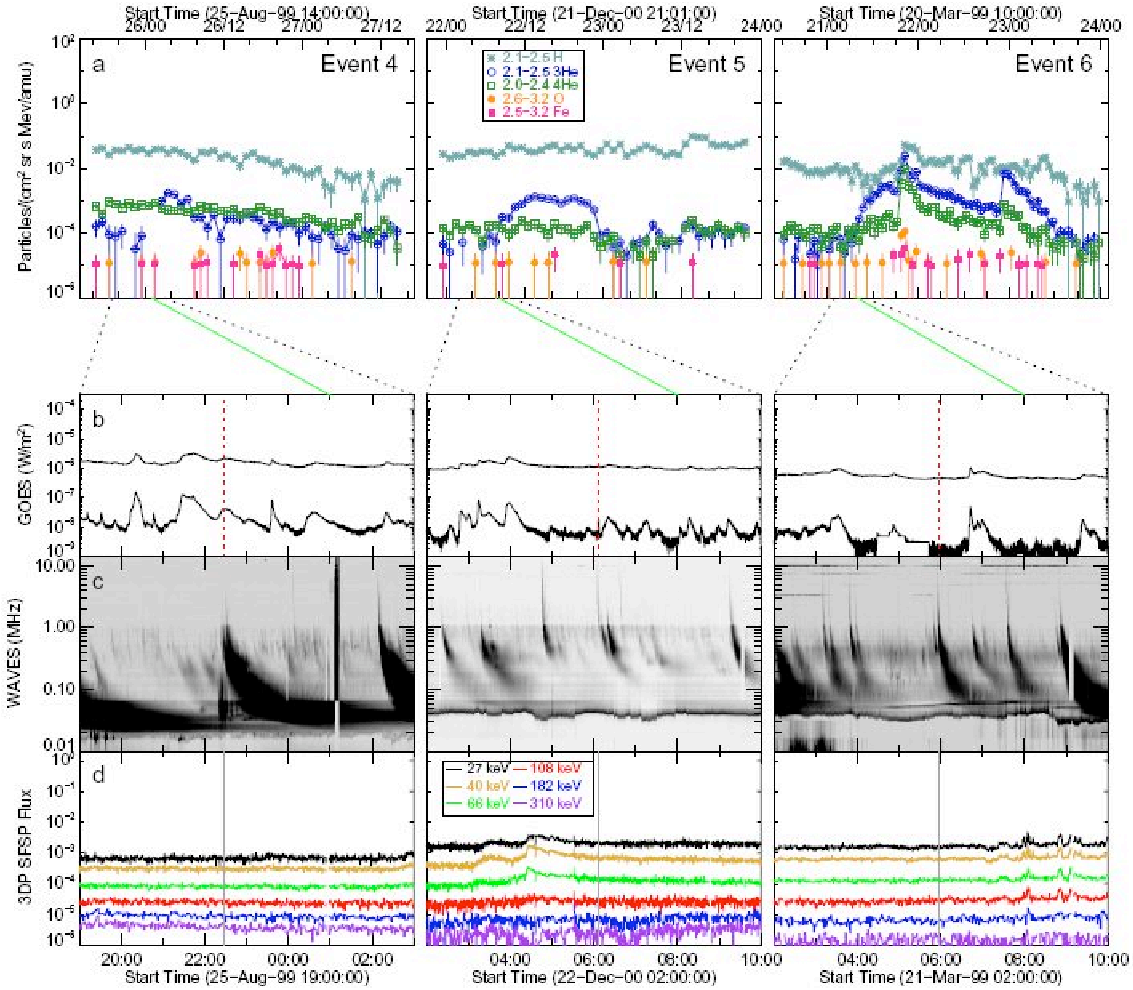
ions

GOES X-ray

Wind/WAVES
Radio spectrum

Wind/3DP
Electrons

Type III bursts as proxies



ions

GOES X-ray

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Radio spectrum

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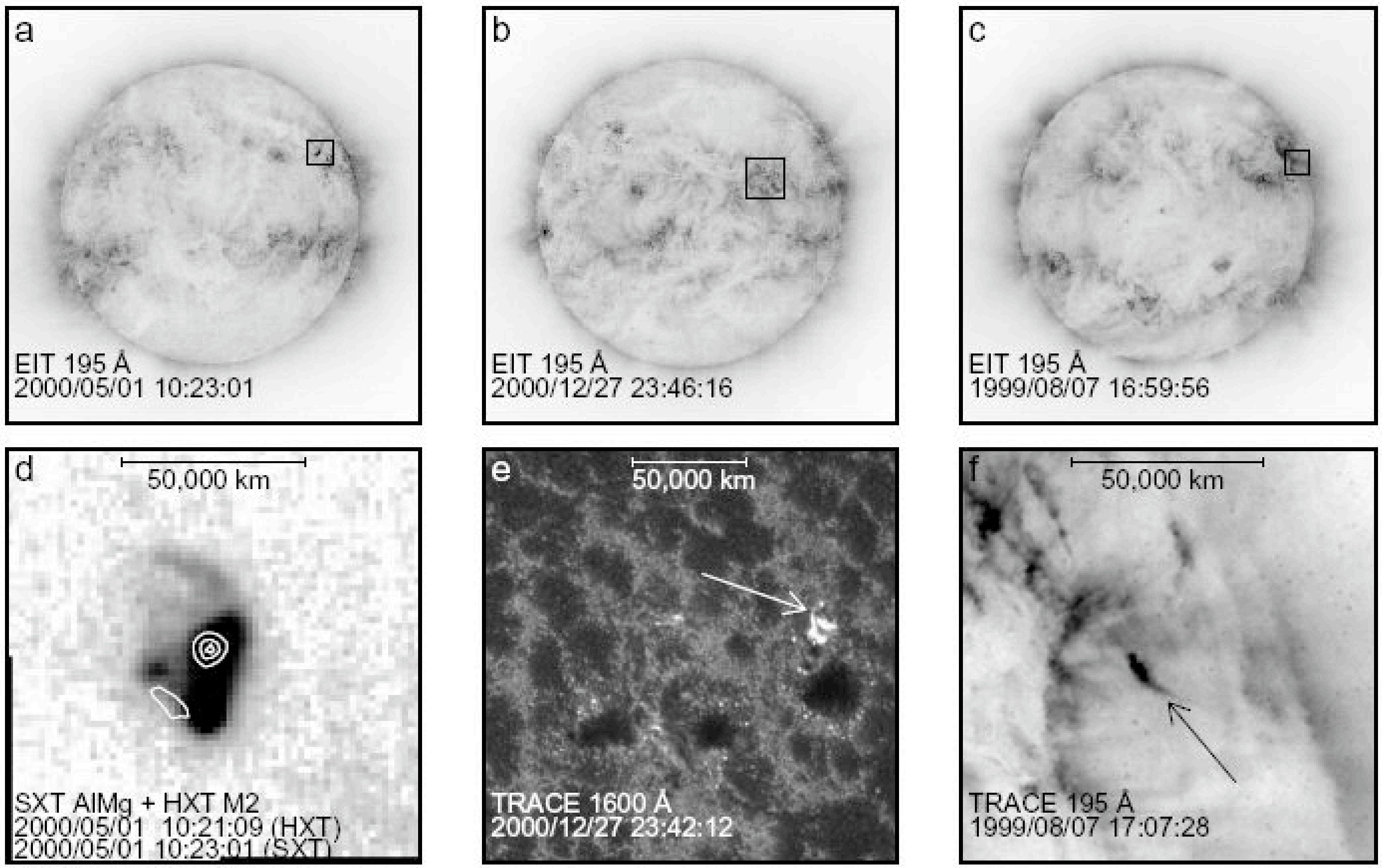
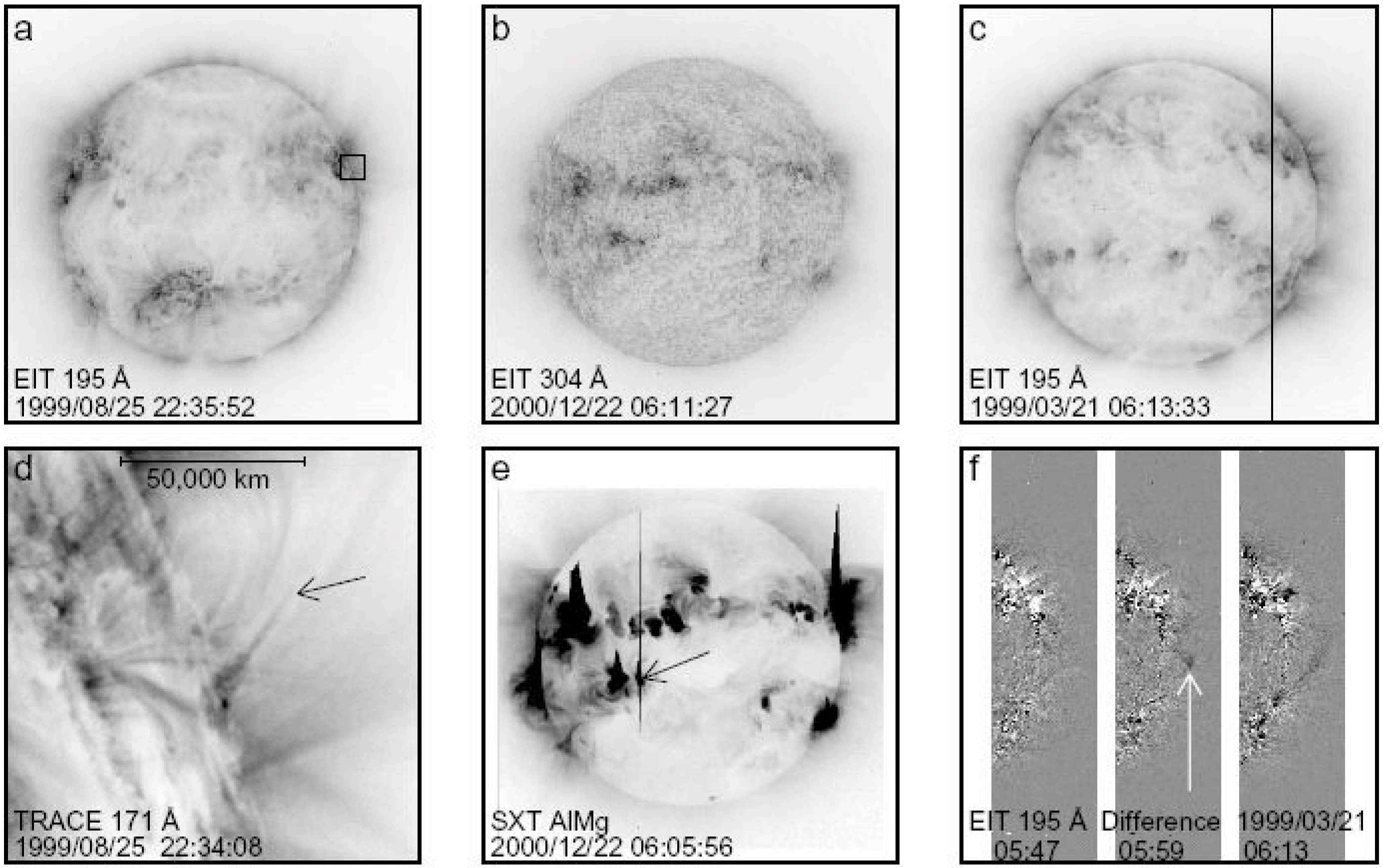
Electrons

Images around type III times



Images around type III times

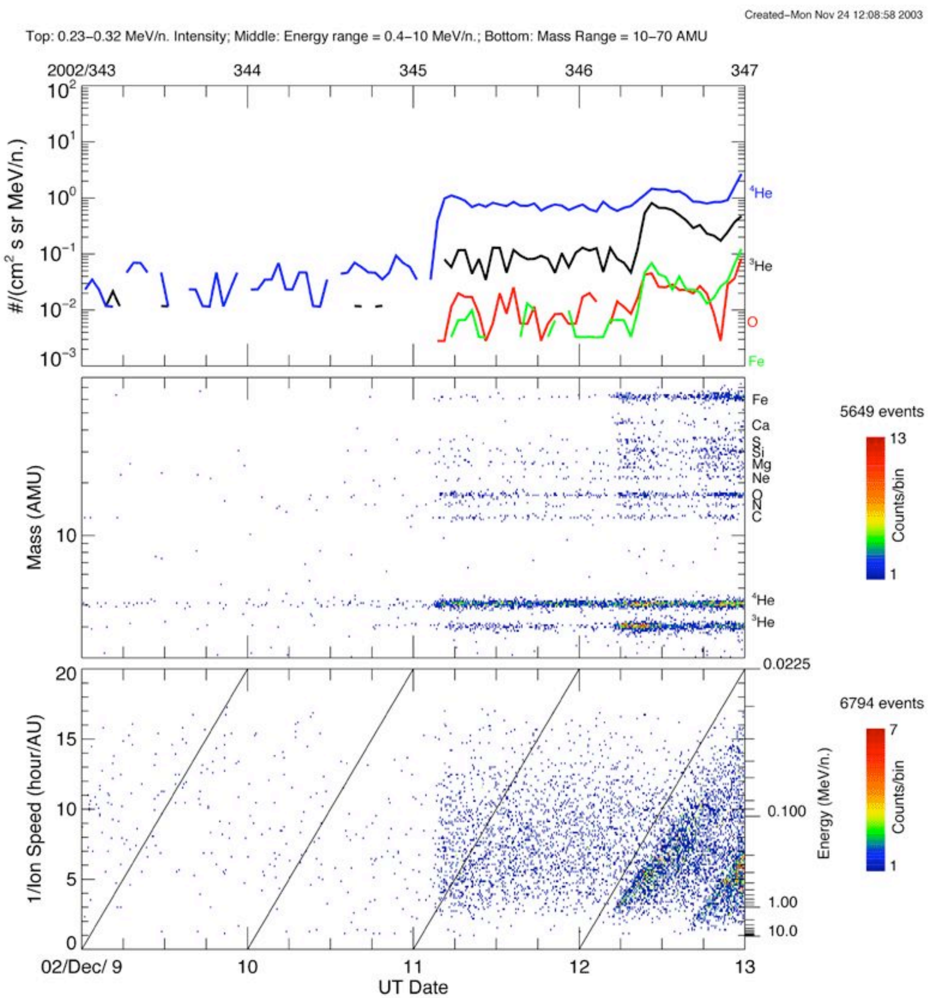


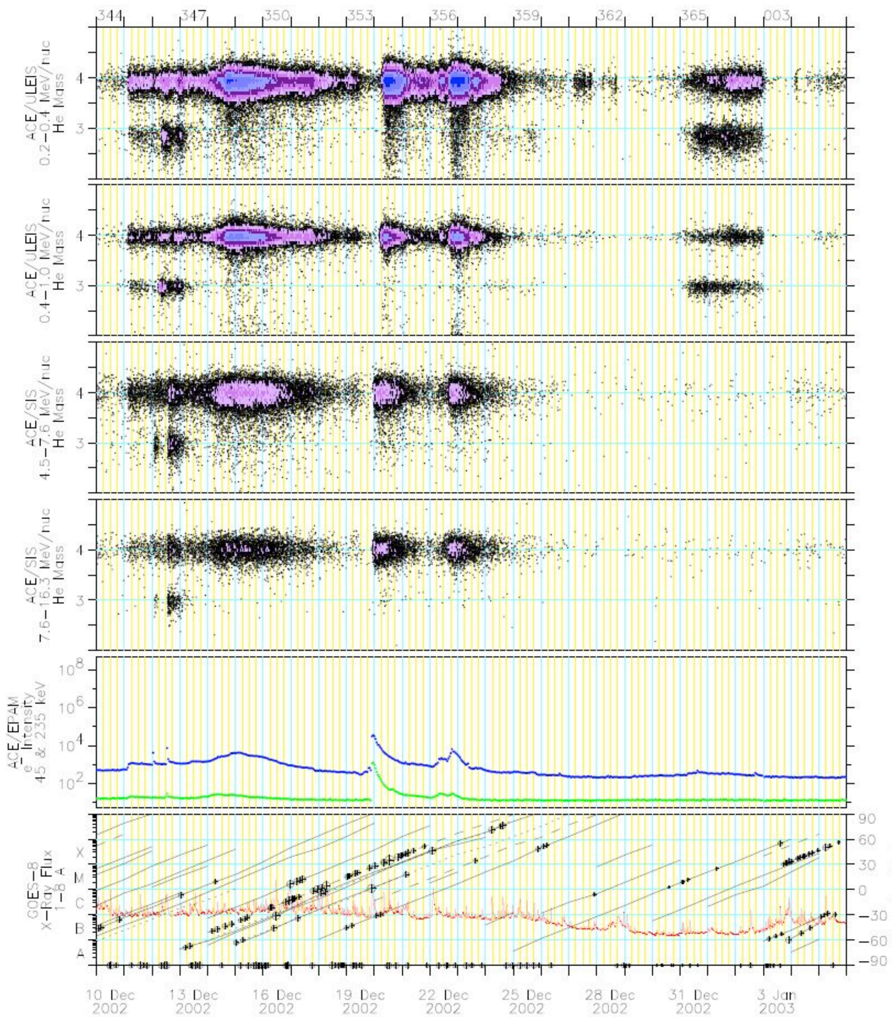
Identification – Events with different abundances

- 117 impulsive SEP events selected from Wind/LEMT data at 2-3 MeV/Nuc
  - Category 1: ^{3}He/^{4}He >0.5, Fe & O unobserved, 39 events
  - Category 2: Fe/O >0.5, ^{3}He/^{4}He <0.5 or ^{3}He below background ^{4}He, 31 events
  - Category 3: ^{3}He/^{4}He >0.5 and Fe/O >0.5, 47 events

Category	Type III	>30 keV electron	CME
1	35/38	11/38	7/20
2	30/31	21/30	19/26
3	45/47	36/42	20/29
Total	110/116	68/110	46/75

Quick check with ACE



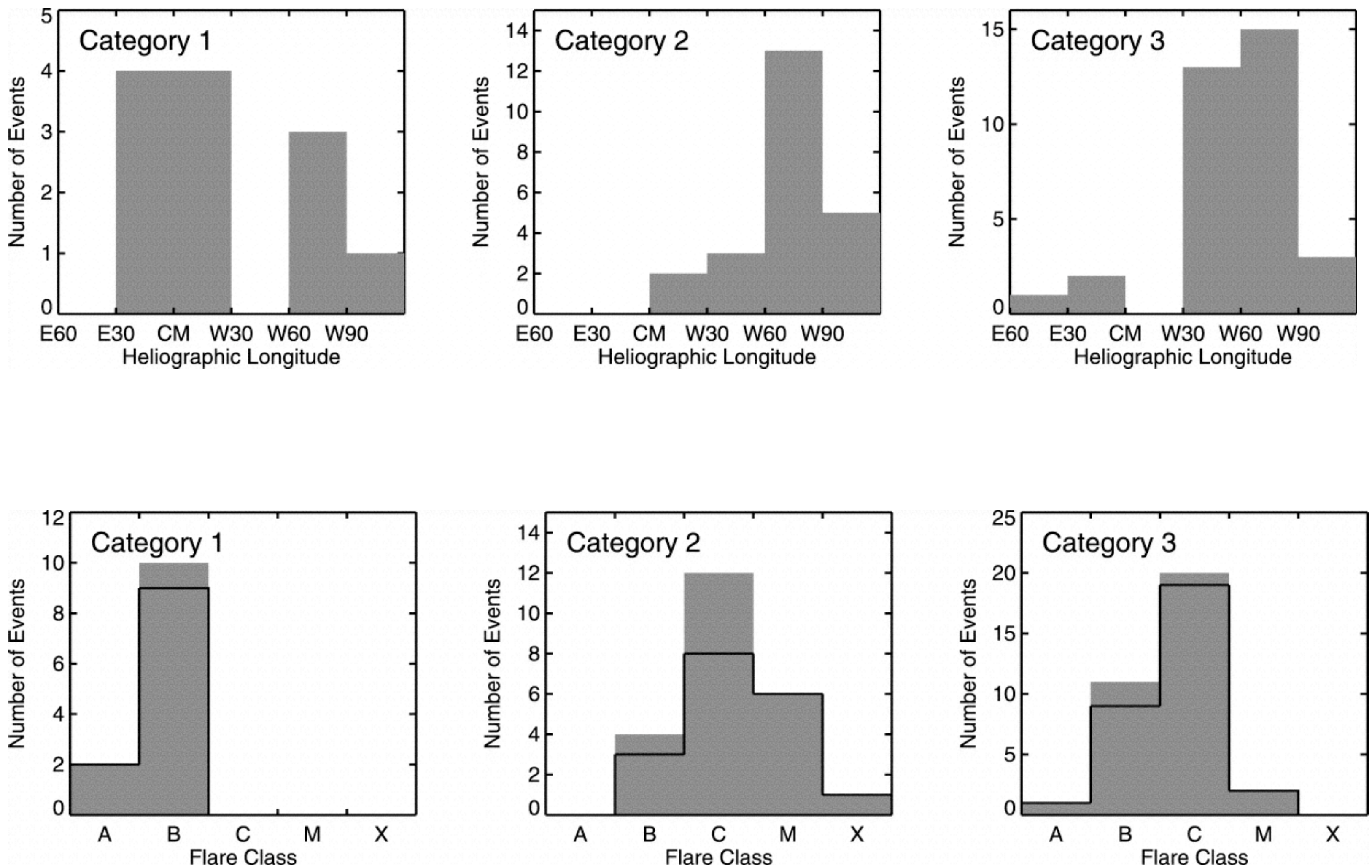


Identification

- In about 60% of the events, we can identify the solar source. The remaining 40% events are difficult, because of (1) no unique type III bursts, (2) no full-disk images around the type III time, (3) no compelling signatures in images.
- We identified the solar source of 10 of Wang et al. (2006)'s 25 events. In 8 of them, we picked up the same region.

Category	**Unique Type III**	**Coronal Images**	**Identified Source**
1	30/35	18/30	12/18
2	30/30	26/30	23/26
3	44/45	39/44	34/39
Total	104/110	83/104	69/83

Location and Flare Intensity



Associated Electrons and CMEs

- CME association is quite high.
- Some of them are fast and quite wide (partial halo CME).
- But none of them but one associated with DH type II bursts, so these CMEs appear to be different from those that accelerate gradual SEPs.

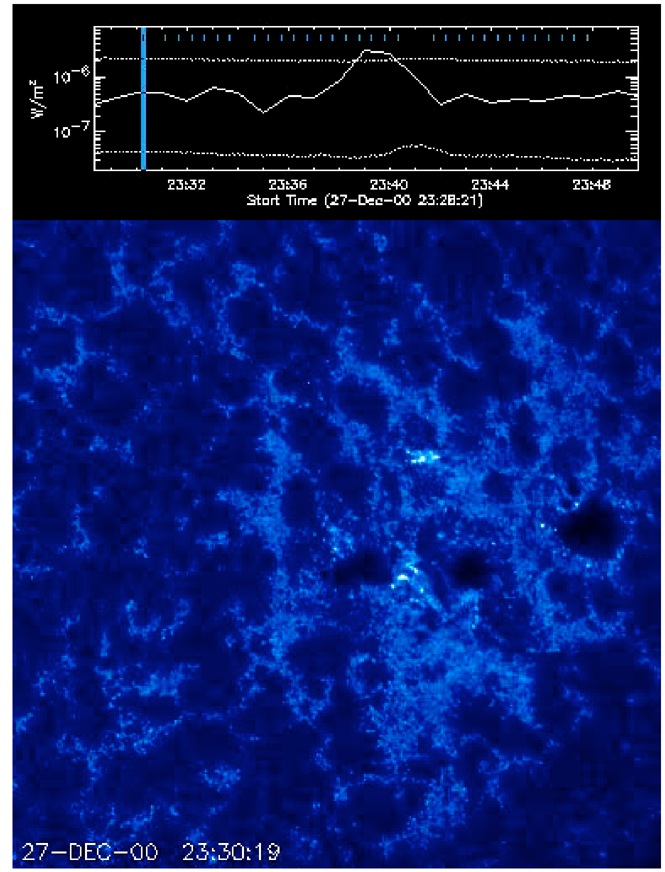
Category	>30 keV electrons	CME	CME v (km/s)	CME _ (degs)
1	1/12	3/12	570-613	13-46
2	17/19	16/20	293-1502	13-170
3	30/32	18/26	288-1360	5-113
Total	48/63	37/58	288-1502	5-170

^{3}He vs Fe

- These results suggest that ^{3}He-rich events may be different from Fe-rich events.
- Cliver & Kahler (1991)'s ad hoc scenario – ^{3}He high coronal, and Fe in flare region
- He/O~57 in the corona, so one needs more Fe ions to be observed at the same Fe/O ratio as ^{3}He/^{4}He.
- ^{3}He depleted as energy input increases → category 2 events?
- Instrument effects?

Jets

- An important solar source of impulsive SEP events
- Usually 2-5 min after the onset of a type III burst
- 13-17 jets out of 25 events observed by TRACE
- Not all of them are LASCO jets. Sensitivity issues?

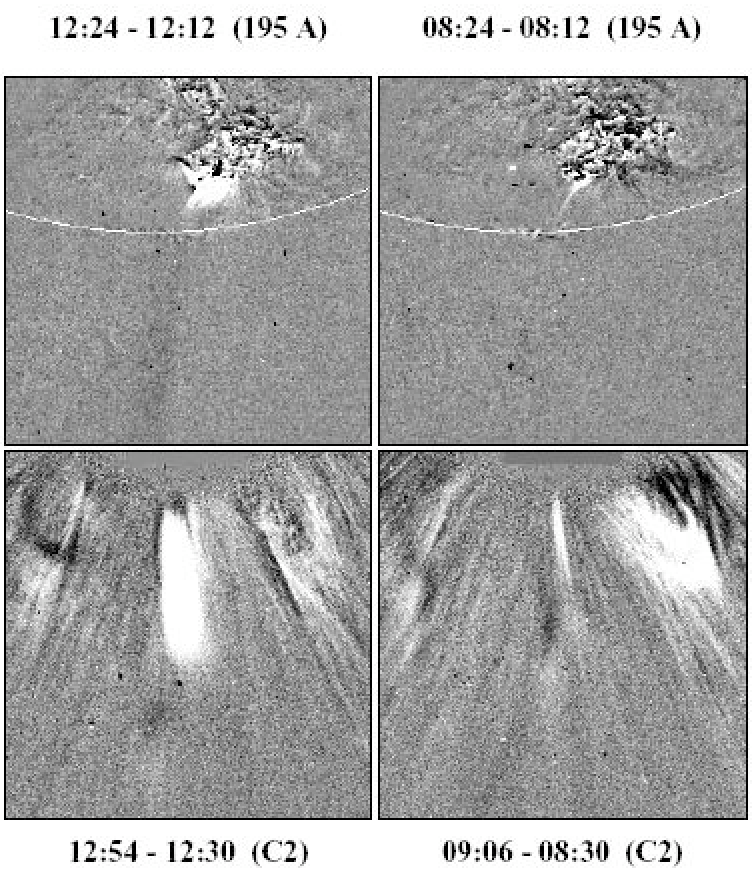


TRACE 1600 A (10^5K) movie

Comments on EIT Jets

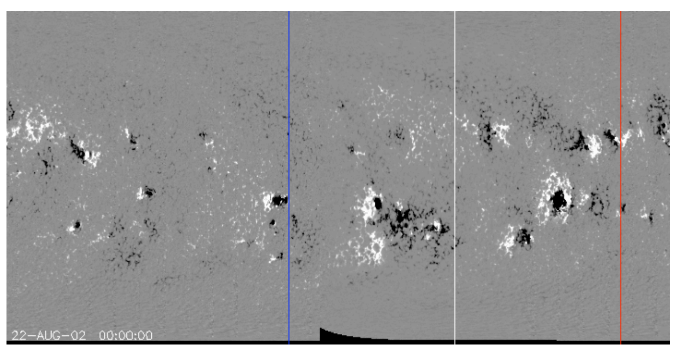
- How can jets be observed in EIT images with ~12 min cadence? Are many of them missed?
- Can LASCO observe accompanying jets even from regions far from the limb (e.g., W30)?
- What is the relation between jets and type III bursts? Which provides a better diagnosis of open fields, less affected by sensitivities of instruments?

2002 OCTOBER 5



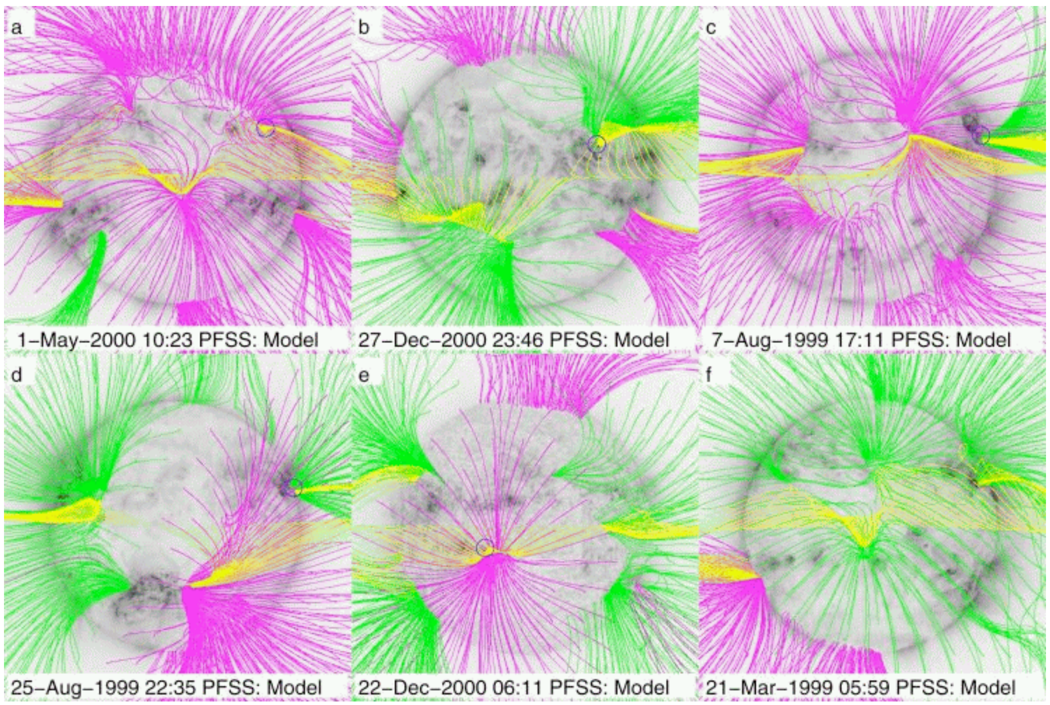
Potential field source surface model

- Assumes current-free corona (therefore not representing flare-productive active regions).
- Once arriving at the magic surface, called the source surface, they are deemed to be radial.
- Other field lines are closed.
- The source surface is usually set as a sphere at 2.5 R_{sun} from Sun center.
- Use the photospheric synoptic map as a lower boundary condition.



Magnetic field connection

- PFSS model is the only operational extrapolation that can handle global magnetic field
- We use the MDI data assimilated to the flux dispersal model (Schrijver 2001), which is updated every 6 hours.



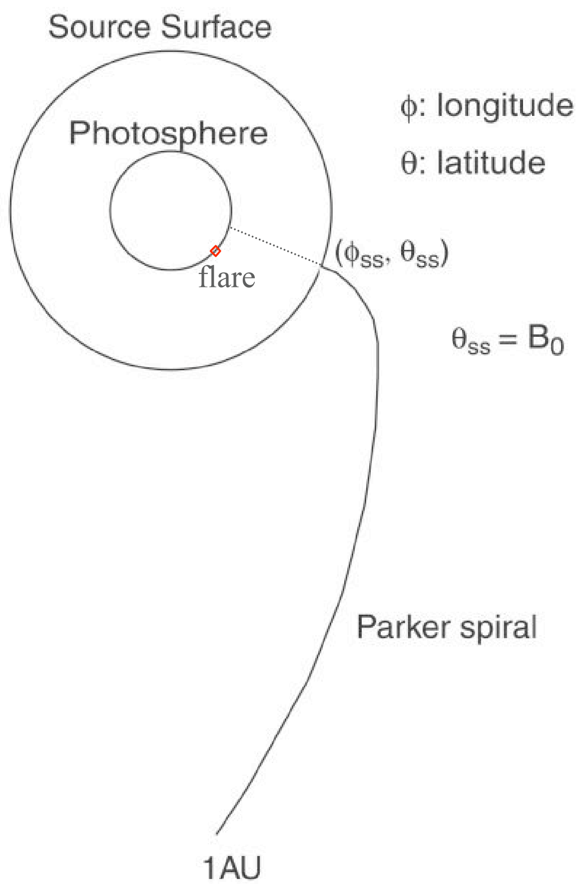
Open field lines are plotted.

pink: anchored in negative polarity regions,

green: anchored in positive polarity regions,

yellow: ecliptic.

Field line tracing



- Trace field lines from 1 AU. The source surface longitude is a function of the solar wind speed.
- "Well-connected longitudes" reflect straight extrapolation of the Parker spiral to the photosphere.
- The PFSS extrapolation redistributes the field between the photosphere and the source surface.

SEPs: tracers of magnetic field

(Hudson: "Tracing SEPs from Sun to Earth")

How to use the SEPs

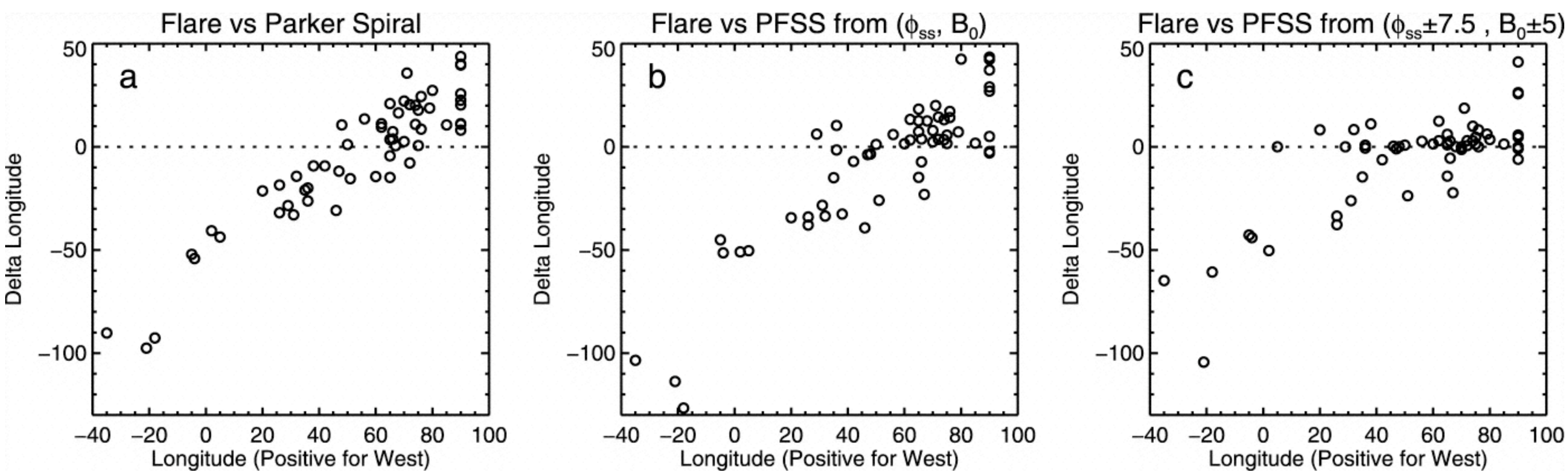
- We have many SEP events, now with RHESSI identification of solar sources. From each we get some knowledge of the connectivity to a probe in the heliosphere
- Magnetic models based on PFSS theory are now readily available
- The heliospheric part of the propagation can be approached now from ballistic or better solar-wind models

Solar MURI, June 2003
H.S. Hudson

Does the model give well-connected field lines in the source region of the SEP event?

Magnetic field connection

- What are the well-connected longitudes? Do all the flares in those longitude range produce impulsive SEP events?
- Does the PFSS model improve the magnetic connection of the Parker spiral?



Includes field lines from
[$_{ss}$ ± 7.5°, $_{ss}$ ± 5.0°]

More on Field Line Tracing

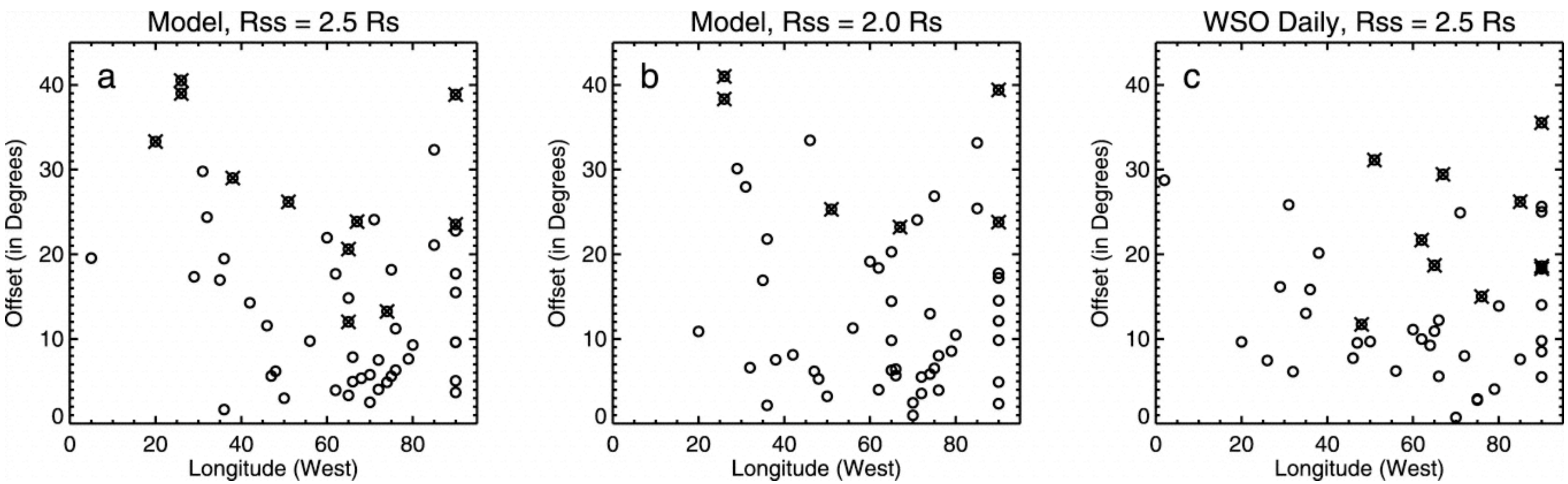
- Given various uncertainties of IMF, we need to allow for a range of field lines we trace.
- We trace field lines from [_ss ± 7.5°, _ss ± 5.0°] to the photosphere, as well as from [${\_}_{flare}$±10°, ${\_}_{flare}$±10°] to the source surface.
- Let the coordinates of the field line at the photosphere and the source surface be (${\_}_0$, ${\_}_0$) and (${\_}_1$, ${\_}_1$), then the offset at the photosphere and at the surface is written as

  $d_{phot}^2 = ({\_}_0 - {\_}_{flare})^2 + ({\_}_0 - {\_}_{flare})^2$ and

  $d_{ss}^2 = ({\_}_1 - {\_}_{ss})^2 + ({\_}_1 - B_0)^2$, respectively.
- We look for the field line that minimizes the combined offset

  $d = \mathrm{sqrt}(d_{phot}^2 + d_{ss}^2)$ [latitudinal effect small]

What the PFSS + Parker Spiral Model Tells Us



For the 58 events we traced field lines,

23 events show d < 10,

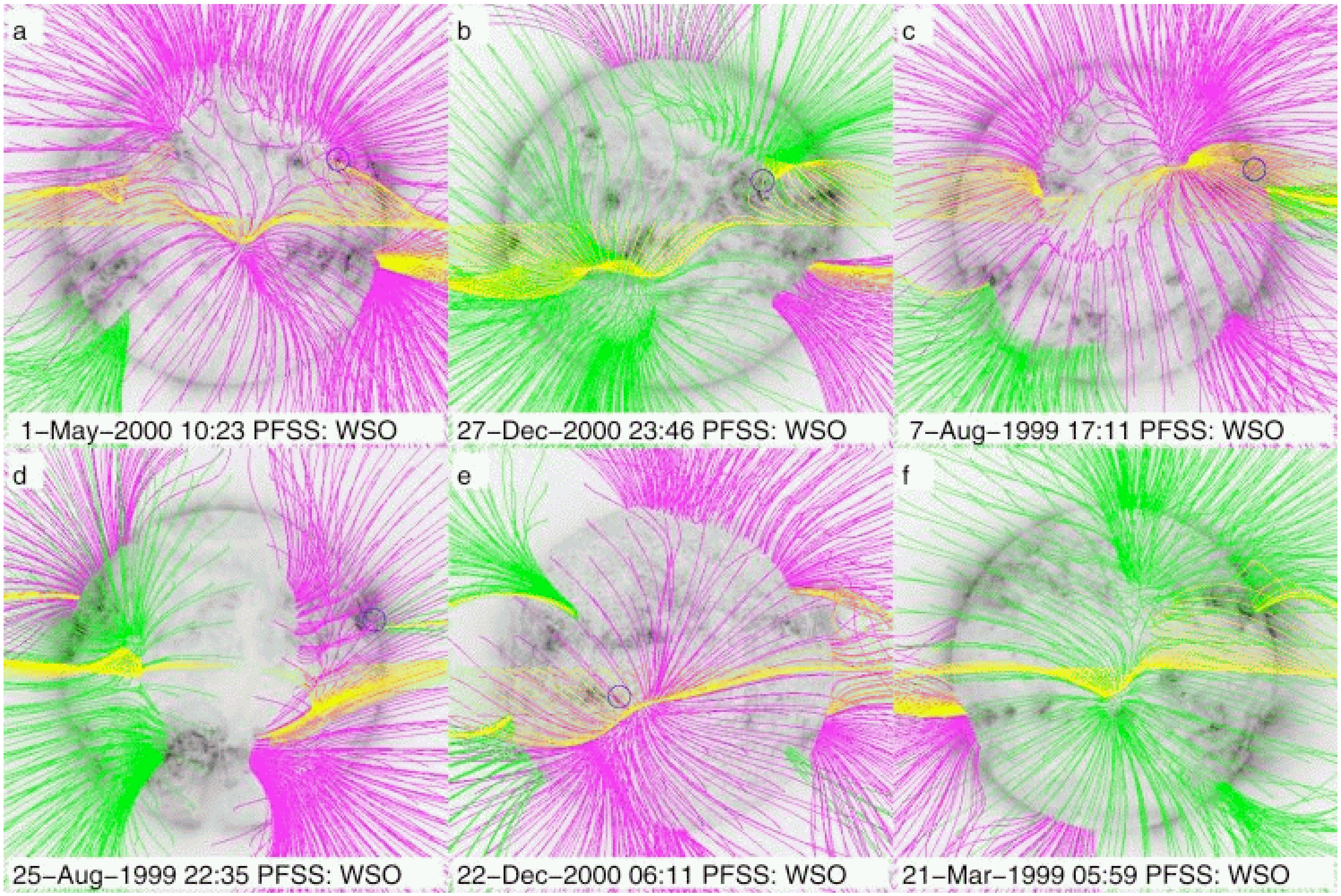
15 events show 10 < d <20,

9 events show d > 20, and

11 events show no open field lines from [$_{flare}$±10°, $_{flare}$±10°]

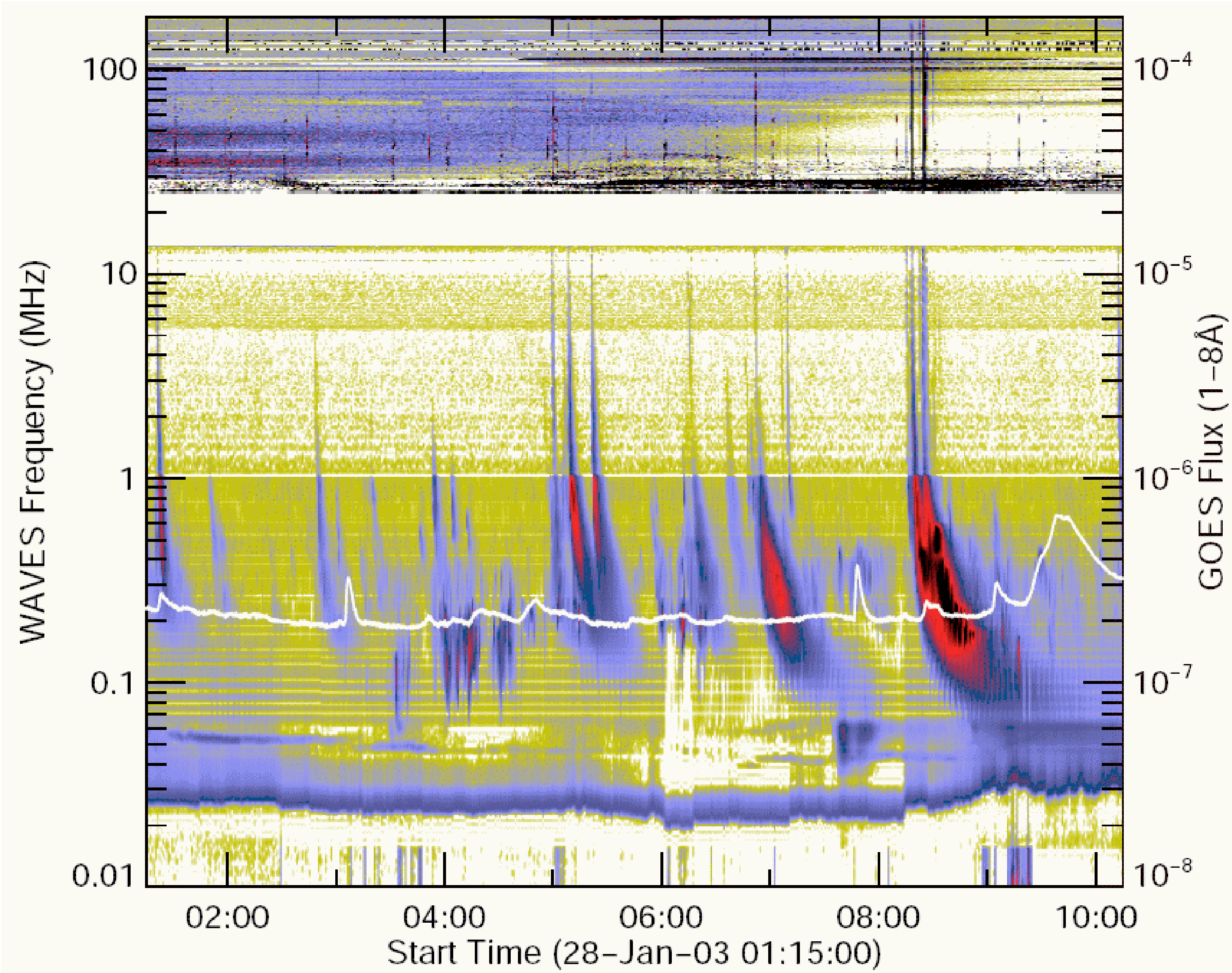
Results from PFSS extrapolations using different boundary conditions (R_{ss}=2.0 R_{sun} and the Wilcox Observatory magnetograms) are more or less similar, but in detail, locations of open field lines are somewhat different.

Comparison of Different Versions of PFSS



More on the PFSS + Parker Spiral

- It is not accurate enough to answer the question as to whether the impulsive flares associated with 3He-rich SEP events are nothing special, just close to open field lines.
- The paper by Wang, Pick & Mason (2006) sounds more optimistic, largely because they call ecliptic open field lines all the field lines that intersect the source surface in the range of [W35, W65], and [B_0 ± 15°].
- It is necessary to test the PFSS model alone using solar observations.
- Different PFSS workers should calibrate their results.



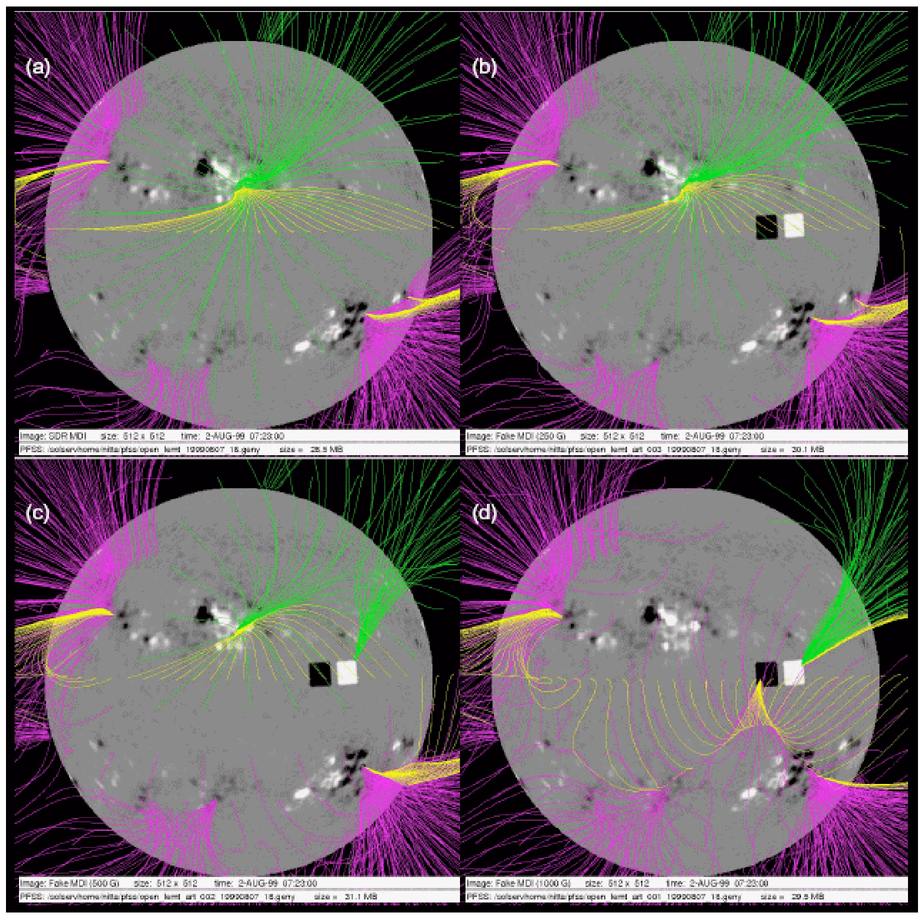
Metric spectra

RSTN: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/SPECTRAL_RSTN/

IHY: Ask Gopal.

Play with artificial flux emergence

Suppose the region near CM with open field lines is located at W 75, and see how the emergence of an AR at W 105 affects the distribution of open field lines.



250 G

500 G

1000 G

Summary

• We have worked on a large list of impulsive SEP events and tried to identify their solar sources, using image data.

• Our assumption is that impulsive SEP events should be associated with type III bursts.

• Even with the present array of spacecraft monitoring the Sun, about 30 % of events do not have image data at right times.

• The source characteristics (flare intensity, association of electron events, etc.) suggest differences between ^{3}He-rich and Fe-rich events, but this may be an instrument effects, which are not limited to SEP measurement, but also to coronagraphs, EUV/X-ray telescopes, and radio instruments.

Summary

- These results need to be confirmed with ACE data that produce particle spectra in wider energy ranges and have better mass resolution.
- We confirmed what is said about the PFSS model, pretty good in many cases, but not quite useful for studies that need accuracy.
- One of the reasons the magnetic extrapolation fails is that we do not have synoptic magnetograms in a strict sense. This continues with STEREO….
- The CMEs associated with impulsive SEP events may be fundamentally different from those that accompany large gradual SEP events.