

The Extreme Solar Event of 20 January 2005: Properties of the Flare and Origination of Energetic Particles

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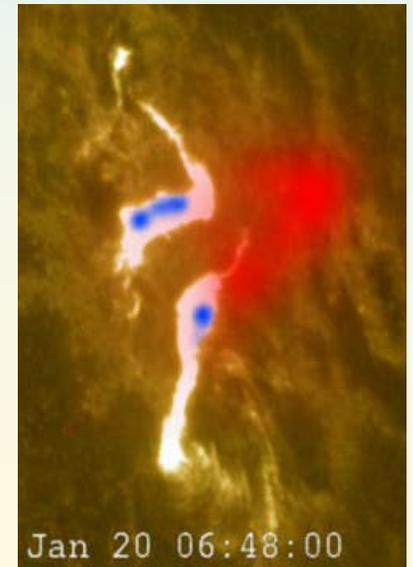
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***Deceased 17 May 2007**



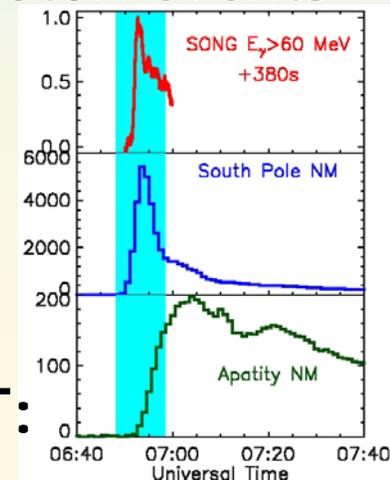
Outline

■ Contents

- Brief reminder of the 20 January 2005 event
- **Gamma-ray burst and GLE:** consistent timing and similarity
- **Flare**, its preparation and particularities
- **CME**, its speed, and comparison with other events
- Strong **high-frequency radio bursts** and proton events
- **Conclusion**

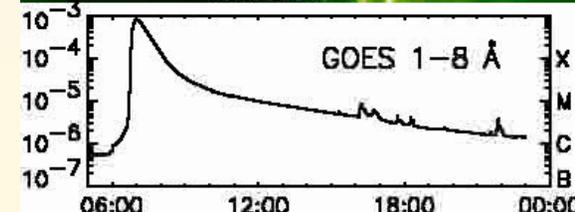
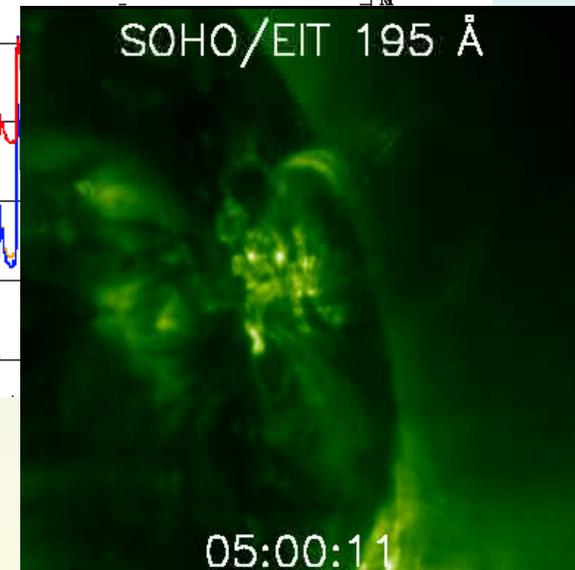
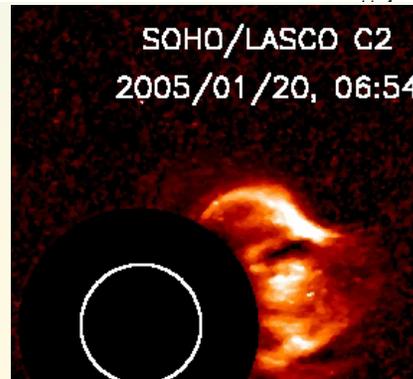
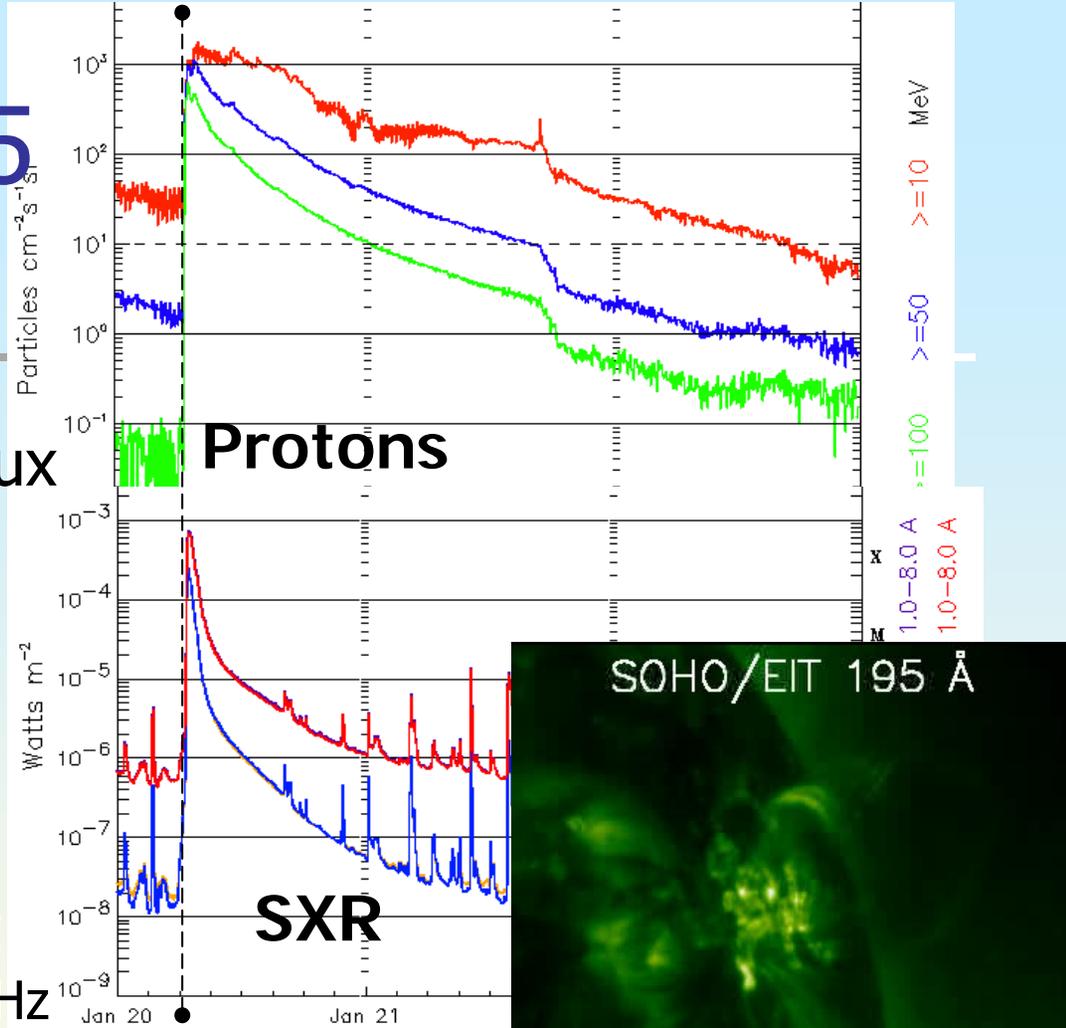
■ Methodology

- Joint analysis of **multi-spectral data**
- **Cross-check** using different methods
- Analysis of the **leading spike only, by 07 UT:**



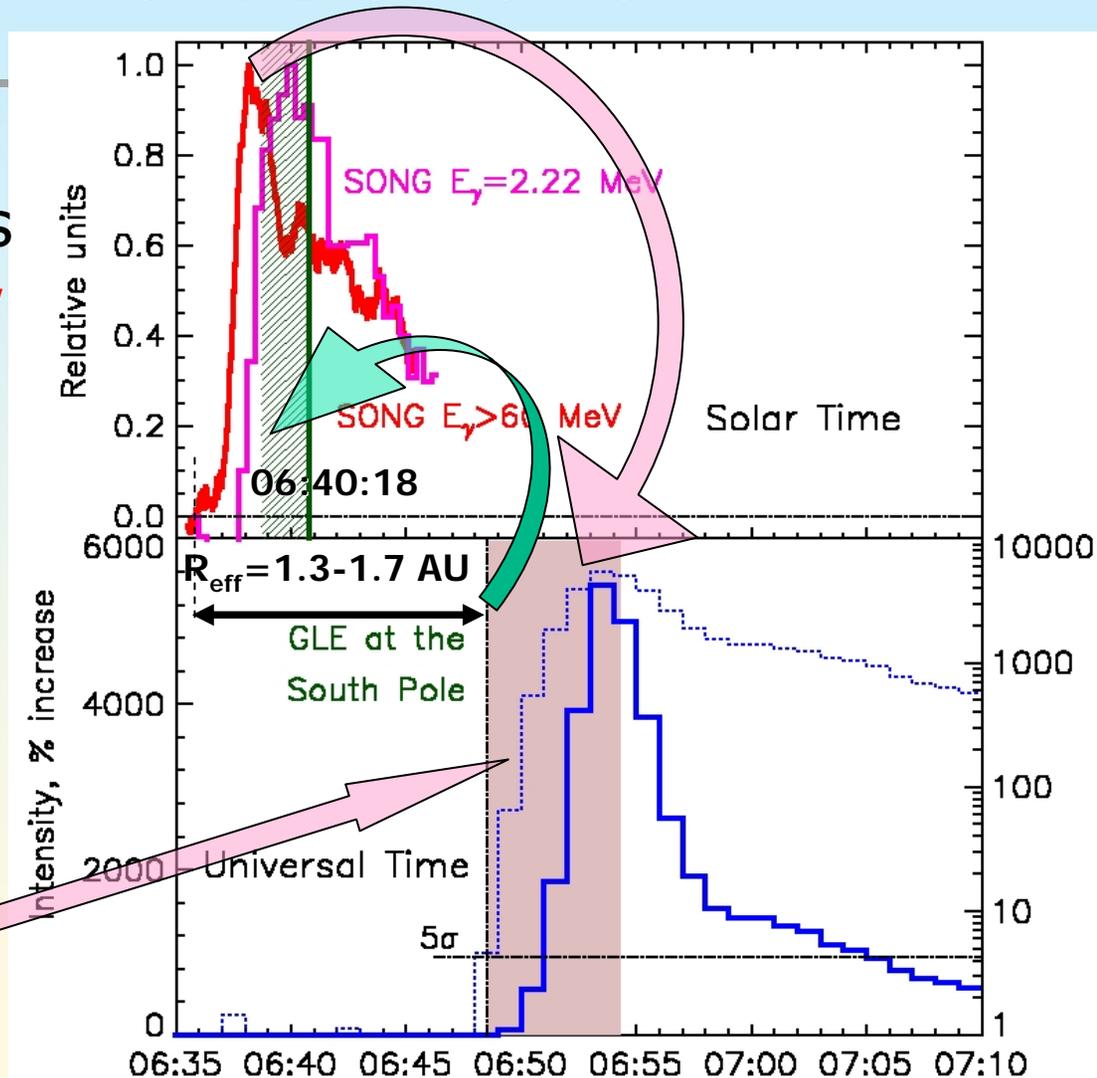
20 January 2005 event

- **Hard** near-Earth proton flux
 - $J_{E>100 \text{ MeV}} > 700 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- Largest in 23th cycle GLE up to **5500 %** (South Pole)
- **Gamma-ray burst** up to **200 MeV**
- **Huge microwave burst**
 - \sim **100,000 sfu** = $10^{-17} \text{ W/m}^2\text{Hz}$
- LDE Flare
 - X7.1/2B (N14W60)
- High-speed CME
 - $4.48R_{\odot}$ @ 06:54 UT



Gamma-Ray Burst and GLE

- To cause GLE at 06:48:30, 7 GeV protons must escape the Sun **by 06:40:18** (straight flight). ↻
- Common origin of protons responsible for gamma-rays and GLE
- Onsets: consistent with $R_{\text{eff}} = 1.3-1.7$ AU
- ⇒ Peaks: shading ↻



Consistent Timing and Similarity

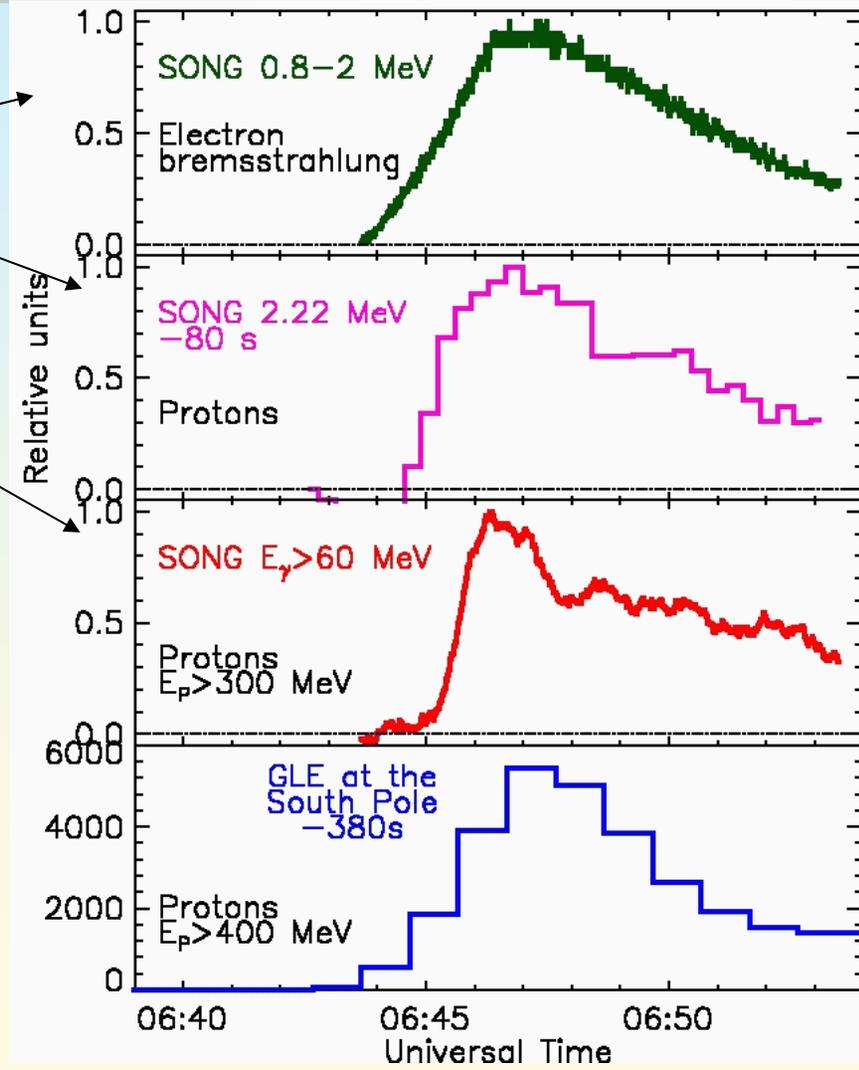
■ Similarity

1. Electron bremsstrahlung
2. 2.22 MeV, 80 s lag expected
3. $E_\gamma > 60$ MeV γ -rays
4. GLE leading spike

→ Acceleration mechanisms:

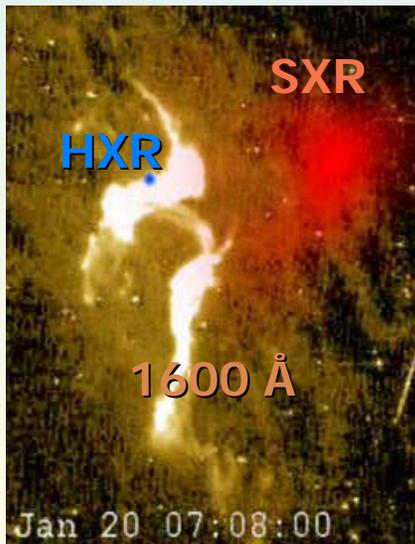
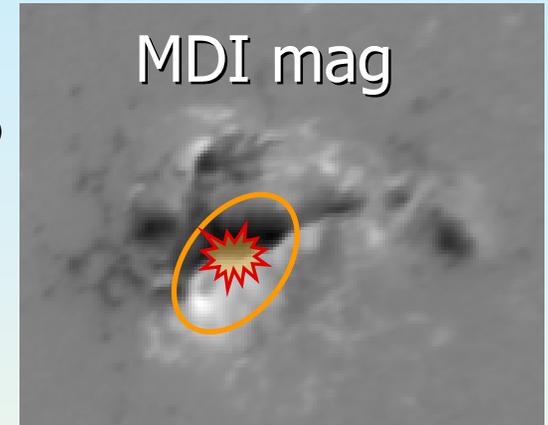
- Had close increments
- Operated during close times
- Similarly shifted from impulsive mode to a prolonged one
- Distant ($>1R_\odot$), operated with different populations, were controlled by different processes

- *Improbable* ⇒ same mechanism



Where and why Gamma-rays Originated?

- How the flare was prepared?



- What was unusual about the flare?

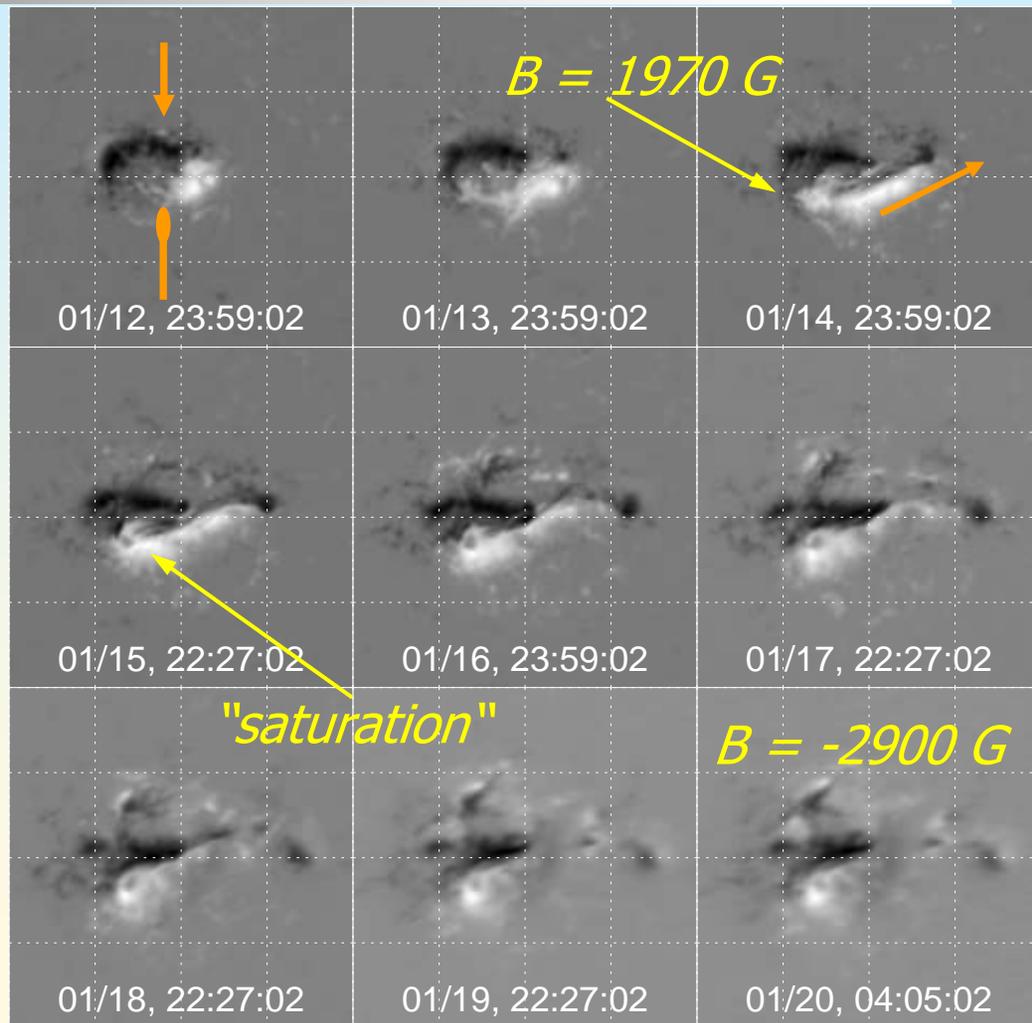
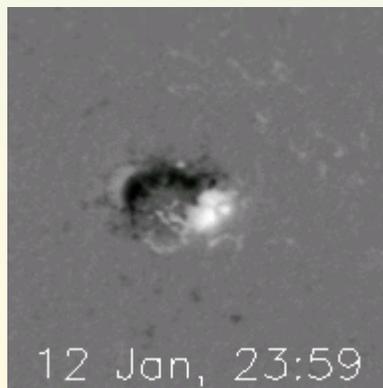
SOHO/MDI: Evolution of AR 720

- One-week magnetograms
 - All co-rotated to 15 Jan, 00 UT
 - Opposite-polarity domains approach
 - Strong shear motions

⇒ Flare productivity: **17 M**
and 5 X flares

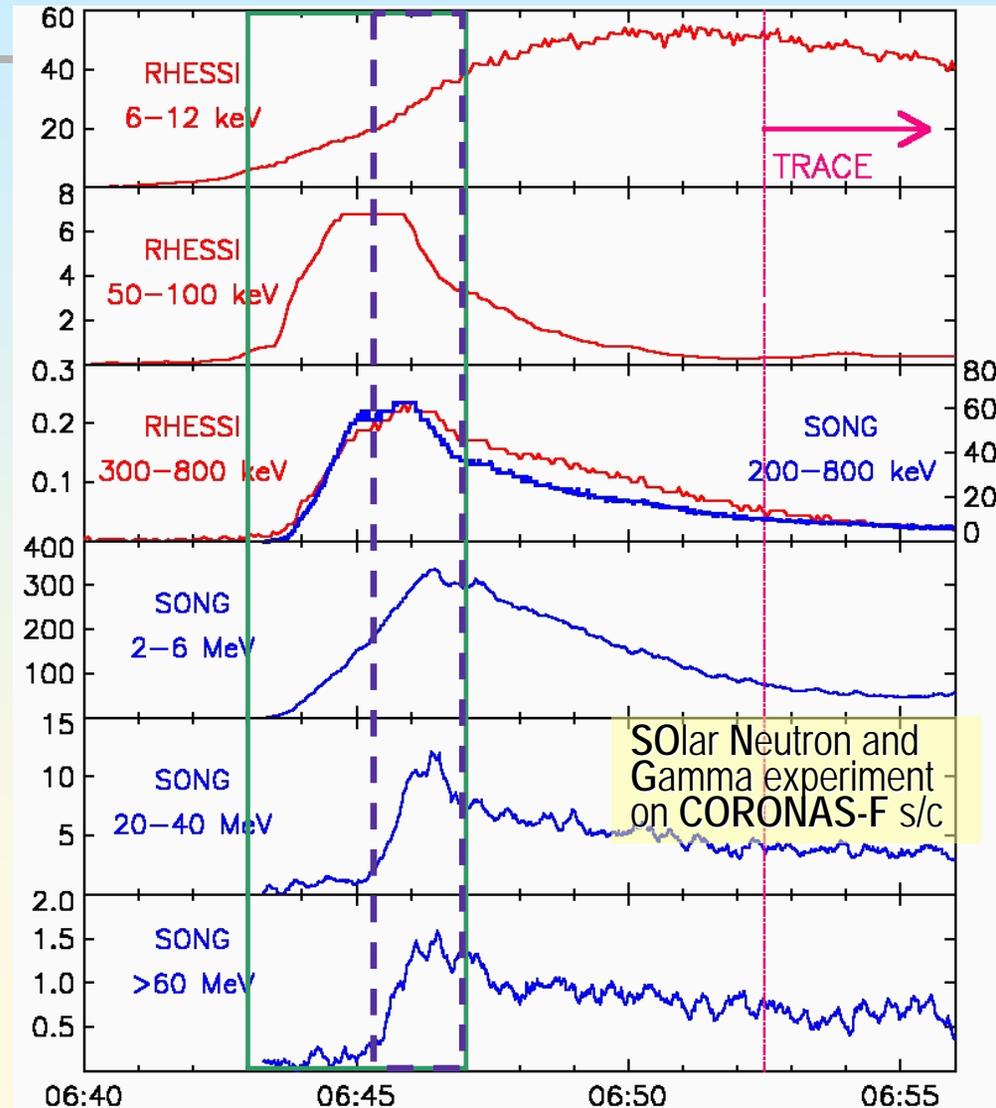
- $|B| \geq 2500 \text{ G}$ in umbrae

- Calculations:
 $|B| \geq 3800 \text{ G}$



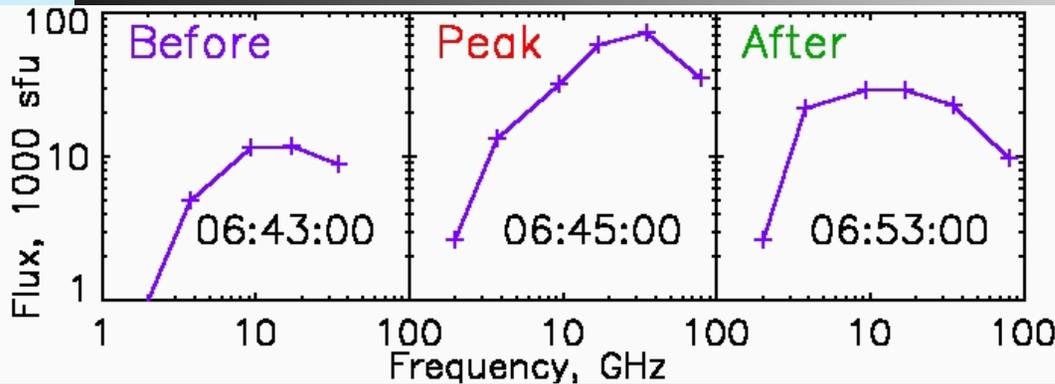
Flare: X-ray and γ -ray time profiles

- Major flaring
 - 06:43-06:47
- Time profiles similar, but harden:
 - Hardest emissions 06:45:20-06:47
- Gamma-rays up to 200 MeV (SONG)
- TRACE observations @ 1600 Å started later

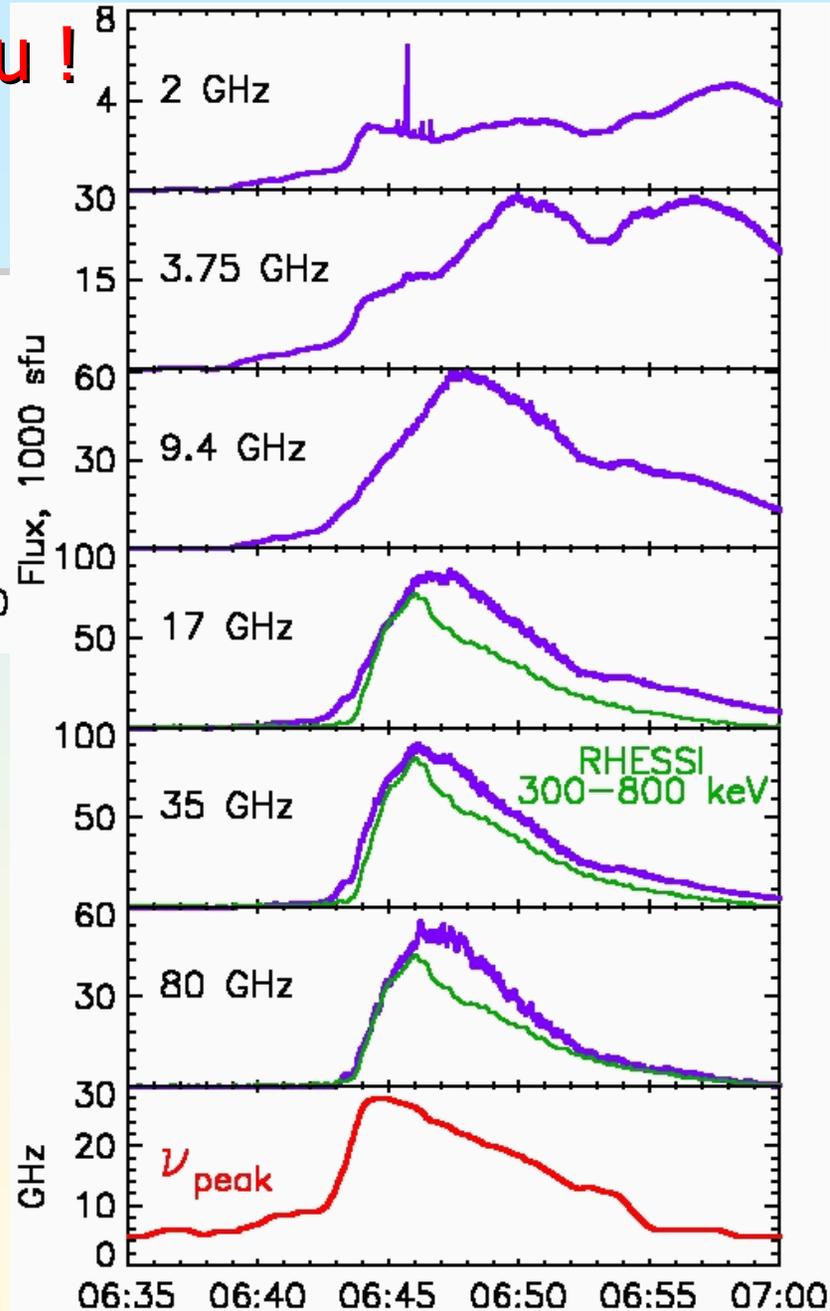


Max flux $\sim 10^5$ sfu !

NoRP data

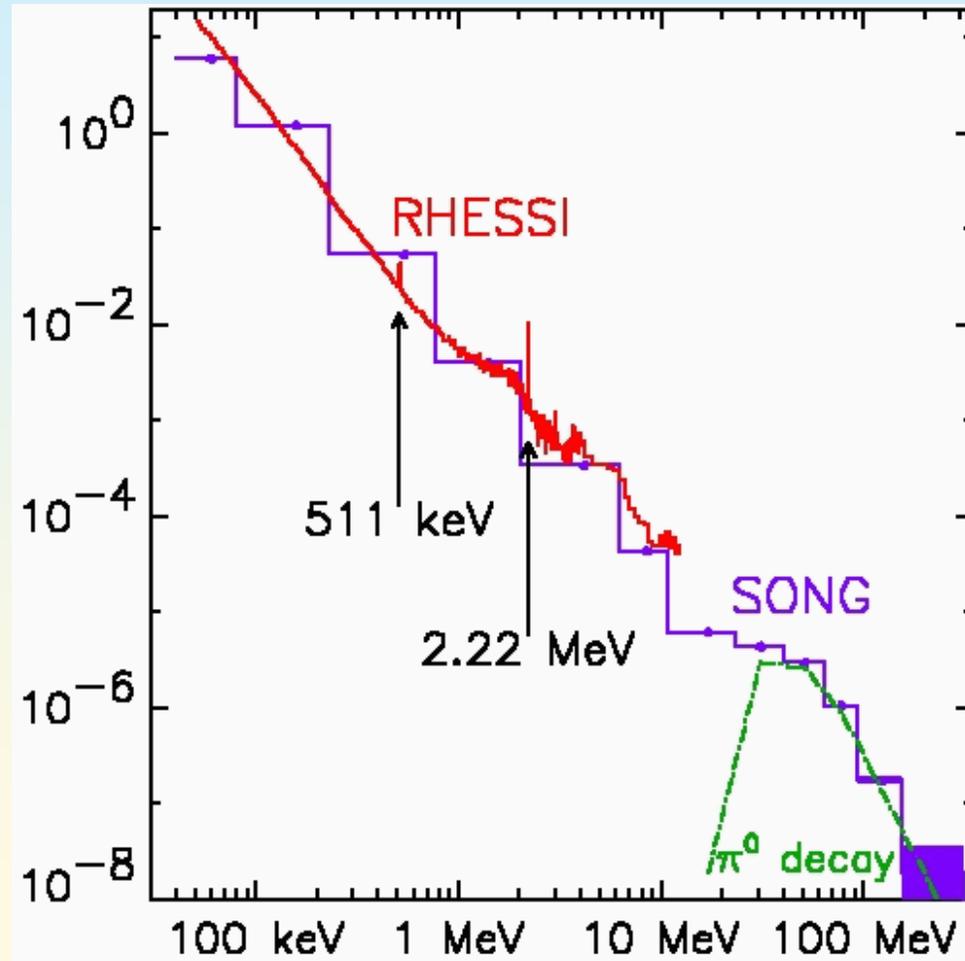


- Strongest burst since 1992
- $\nu_{\text{peak}} \approx 30$ GHz at 06:44-06:46 \Rightarrow microwaves came from **umbrae**
- Lots of emitting electrons
- Microwaves: $\alpha \approx -0.7 \rightarrow$ electrons: $\delta \approx 2.1$ – not optically thin limit & trapping \Rightarrow



HXR & gamma-ray spectrum

- Nuclear lines:
 - 0.51 & 2.22 MeV
- SONG: plateau $E_\gamma > 60 \text{ MeV} \rightarrow \pi^0 \text{ decay} \rightarrow E_p > 300 \text{ MeV}$
- $\gamma \approx 2.5 \rightarrow \delta \approx 4$
 - softer than microwaves suggest, as expected



Flare and sunspots

- Light curves over both umbrae

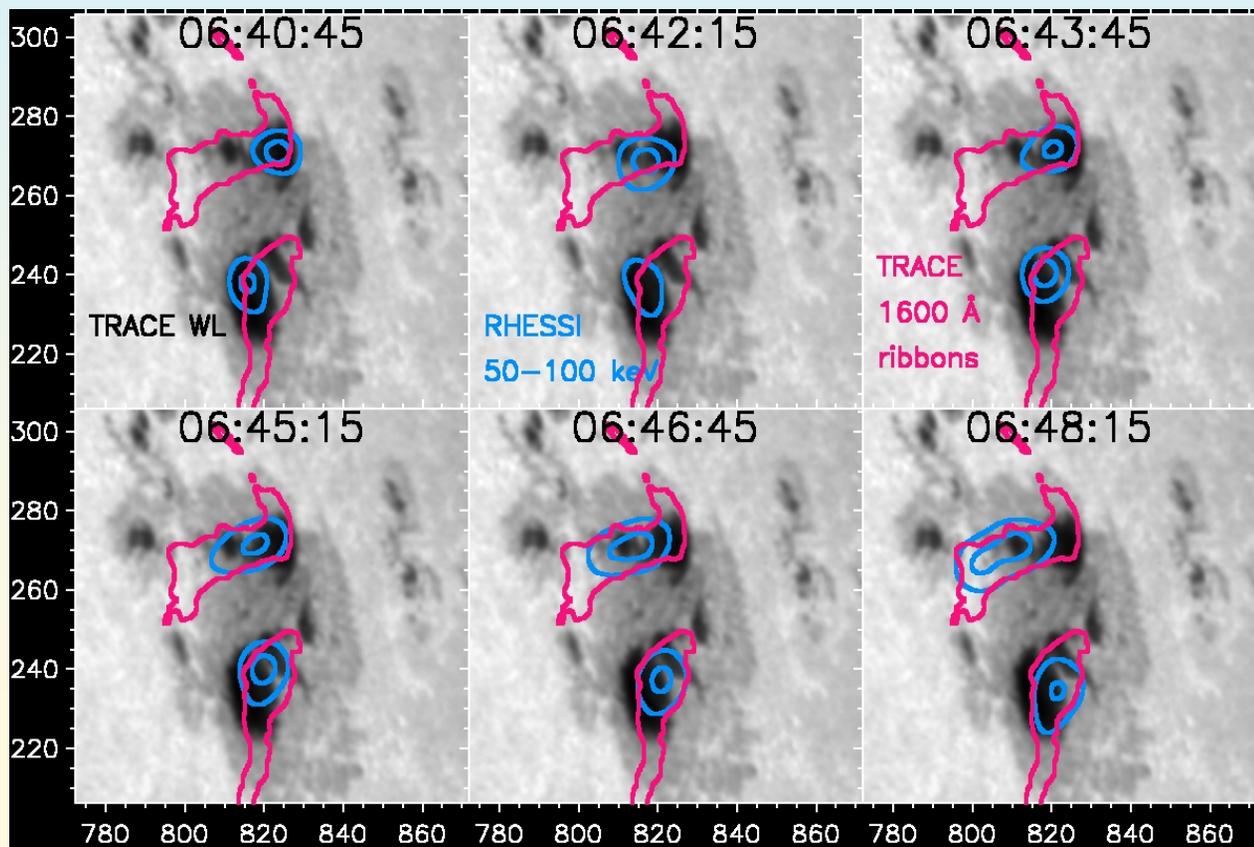
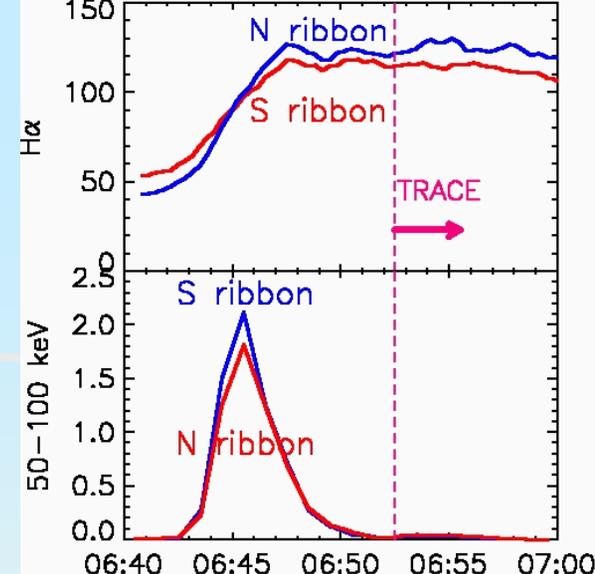
similar →

common source:

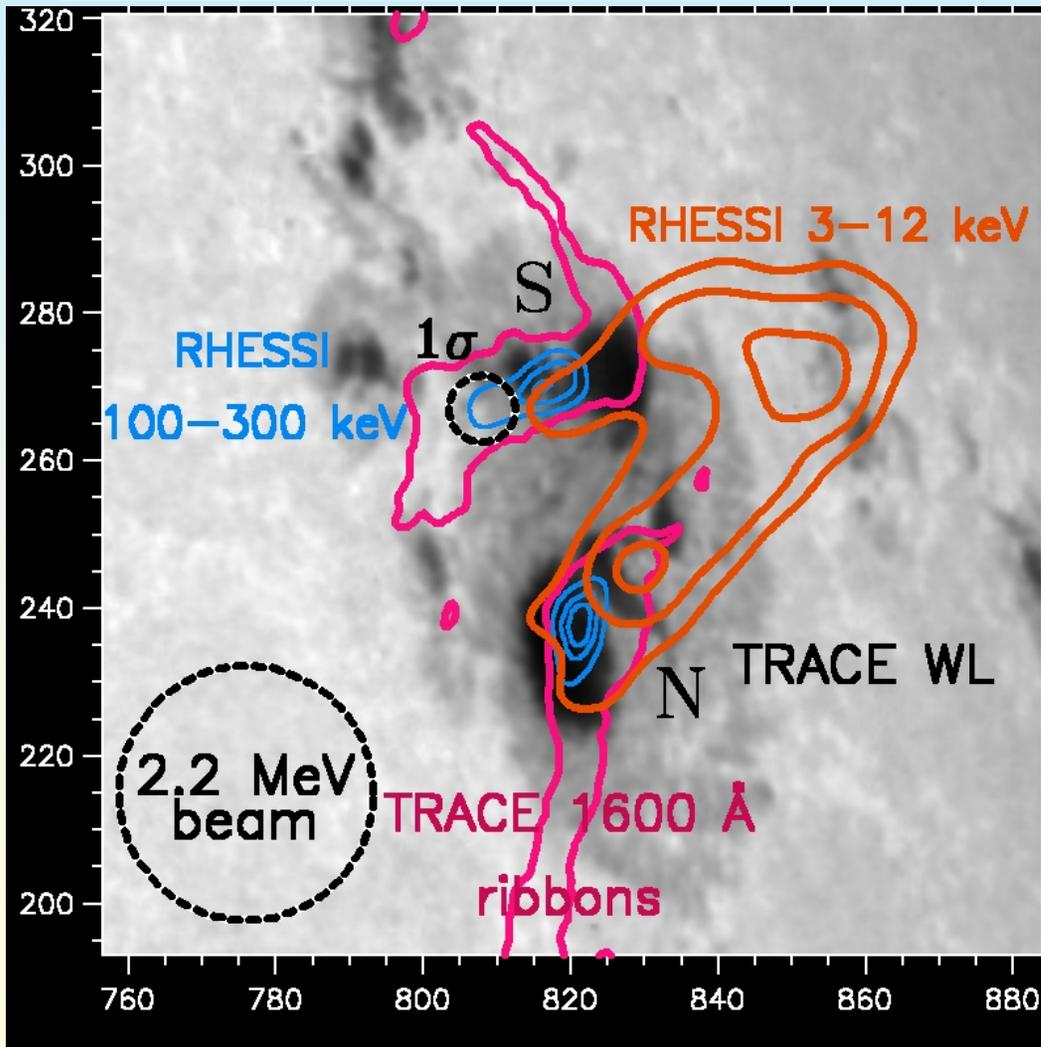
- Closed configuration

- Flare in HXR & $H\alpha$ above umbrae

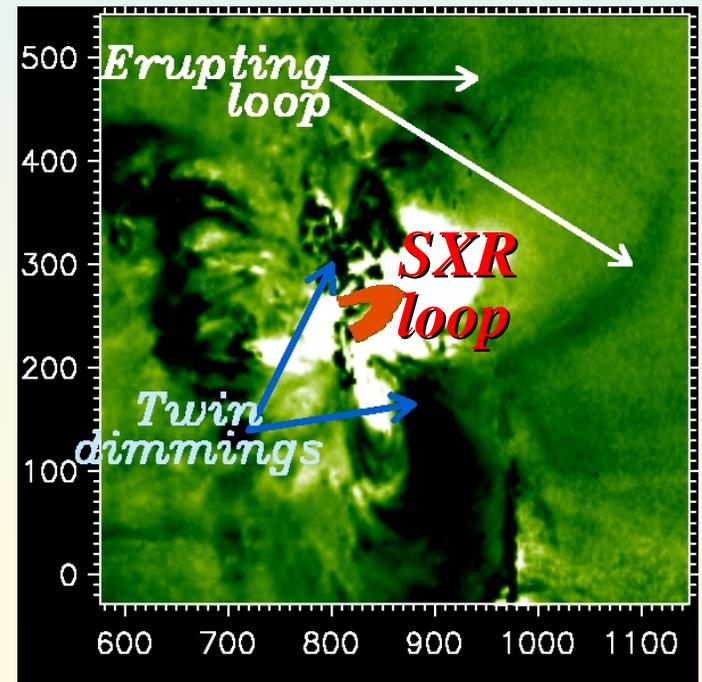
- Strongest magnetic fields
- Southern source more stable → larger magnetic flux



SXR, HXR, and γ -ray Sources

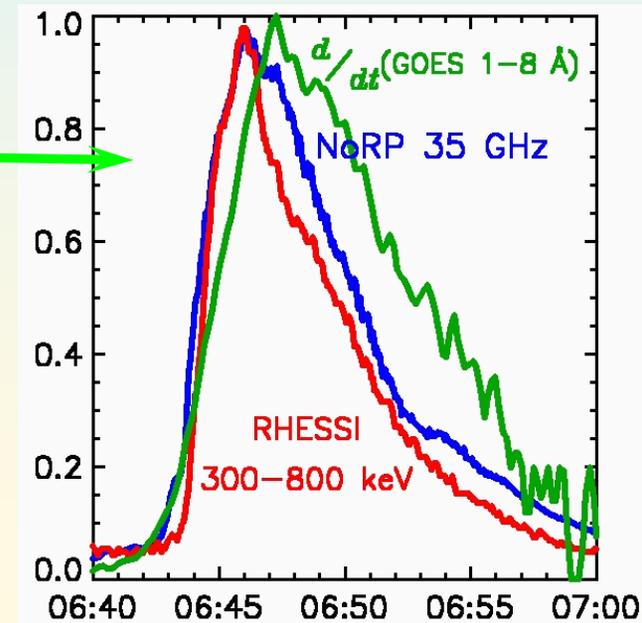
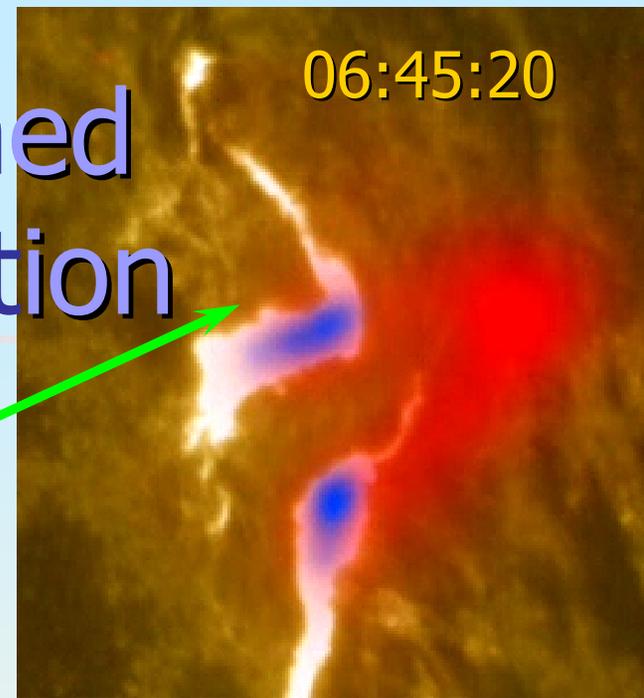


- Compact, closed configuration
- 2.22 MeV line also
- Dimmings aside \Downarrow



All emissions are confined to the closed configuration

- All images confined to the active region, where magnetic structures are closed
- Magnetic fields very strong
- Neupert effect connects HXR emissions with electrons in closed SXR structure
- 2.2 MeV line γ -ray source due to collisions of accelerated nuclei with dense layers is on a ribbon



Outcome from Flare Analysis

- 2.22 MeV line emission is due to collisions of **accelerated nuclei** with dense layers. Its source is located at bases of **closed** magnetic structures.
 - Accelerated particles from remote outer source have **no access** into **closed** structures in/above AR.
 - If they precipitated from outside, then into **twin-dimming** regions (footprints of ejected flux rope) **that was not the case**.
 - Remote ($>1R_{\odot}$) **CME hardly could control** detailed course of the flare.
- *Protons responsible for leading GLE spike could be accelerated only in magnetosphere of AR.*
- **Protons** accelerated in diffusion region injected **both down and up**. The latter could reach Earth to produce **GLE**.

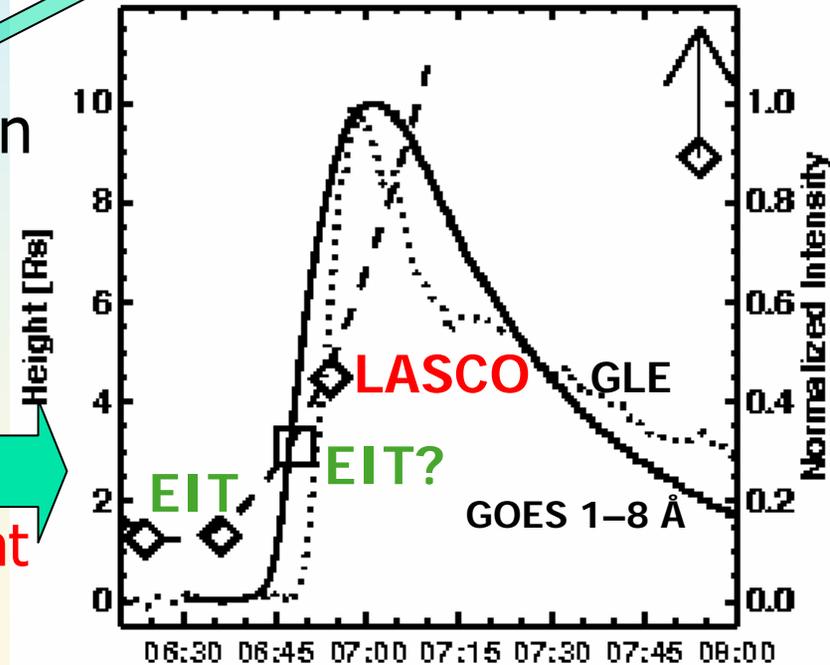
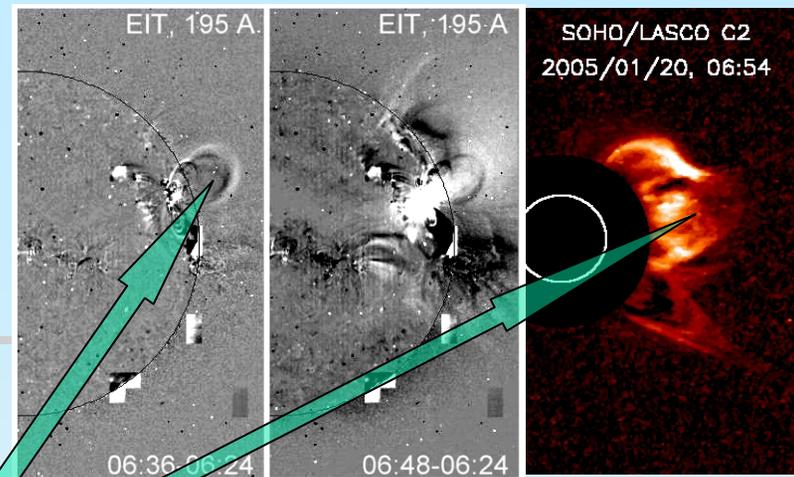
⇒ An Old Contest:

- Gopalswamy et al. (2005, 29th ICRC, 101): “common **shock** origin for type II radio bursts and GLEs” (> **3200 km/s** on 20 Jan)
- Simnett (2006, A&A 445, 715): “CME was **not** responsible for the relativistic ion acceleration”

How about the CME?

CME and its speed

- CME visible in **only one C2 frame** at 06:54 because of 'snowstorm'
- **Simnett (2006)** estimated CME speed by including **erupting loop** in EIT image at 06:36 \Rightarrow 2500 km/s
- Gopalswamy et al. (2005), **2st order fit**: **3242 km/s**. However:
 - Acceleration **not constant**
 - Identification FS \Leftrightarrow EIT loop **might not be justified**
- **Other ways possible** \Rightarrow

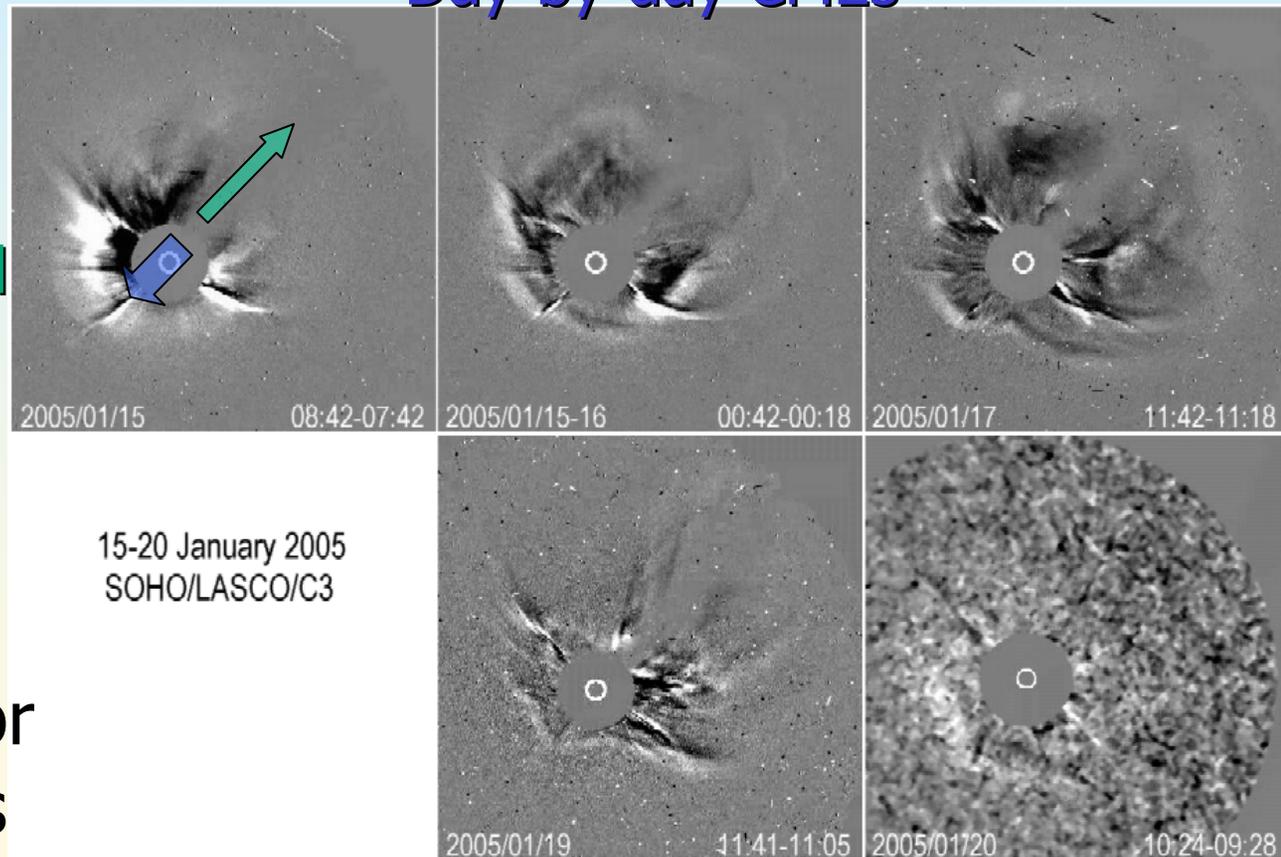


From Gopalswamy et al. 2005

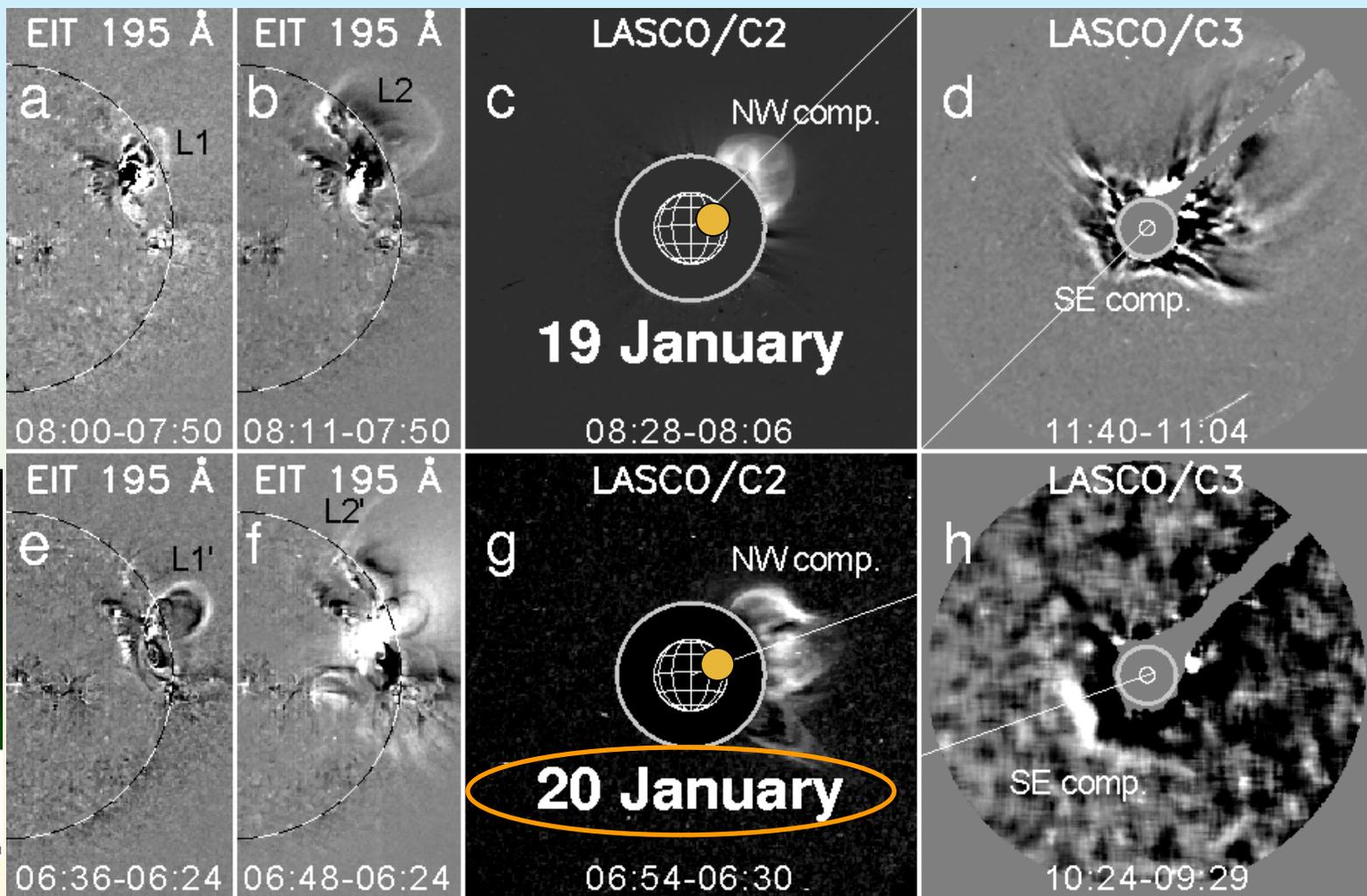
Homology of 15-20 January CMEs

- All CMEs:
 - Faster NW components, rapidly faded
 - Slower SE components
- Homology \Rightarrow persistence of speed ratios for SE & NW parts

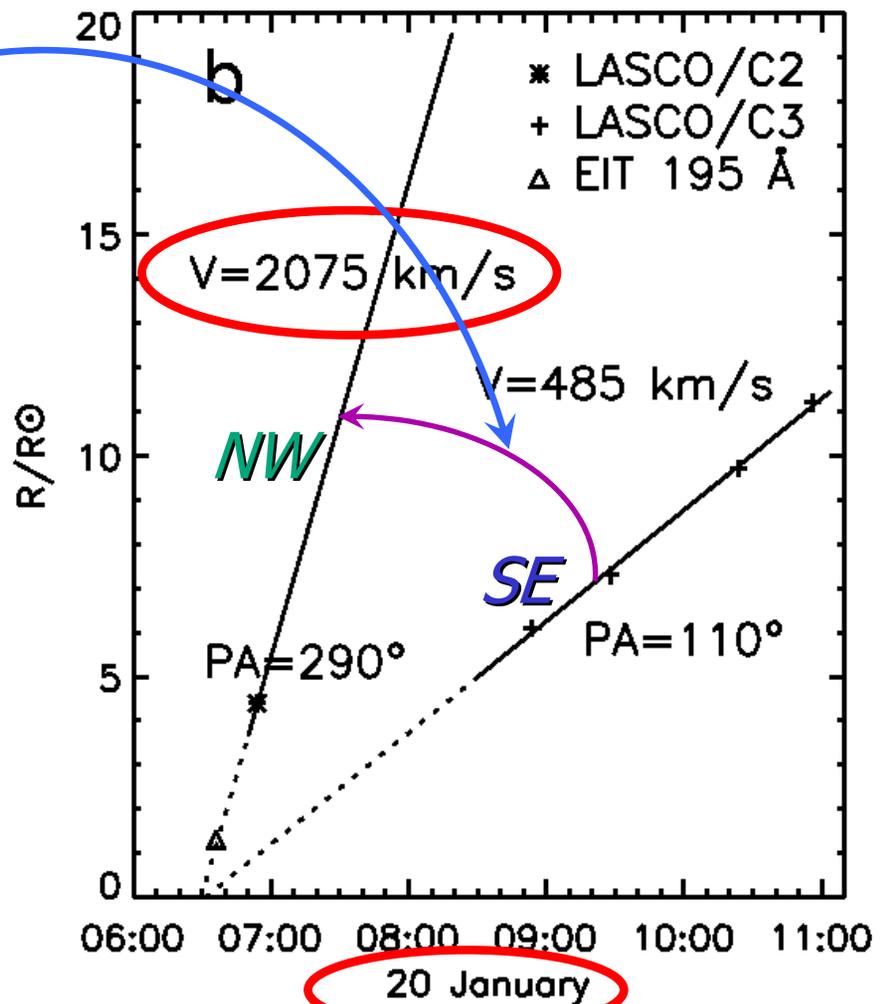
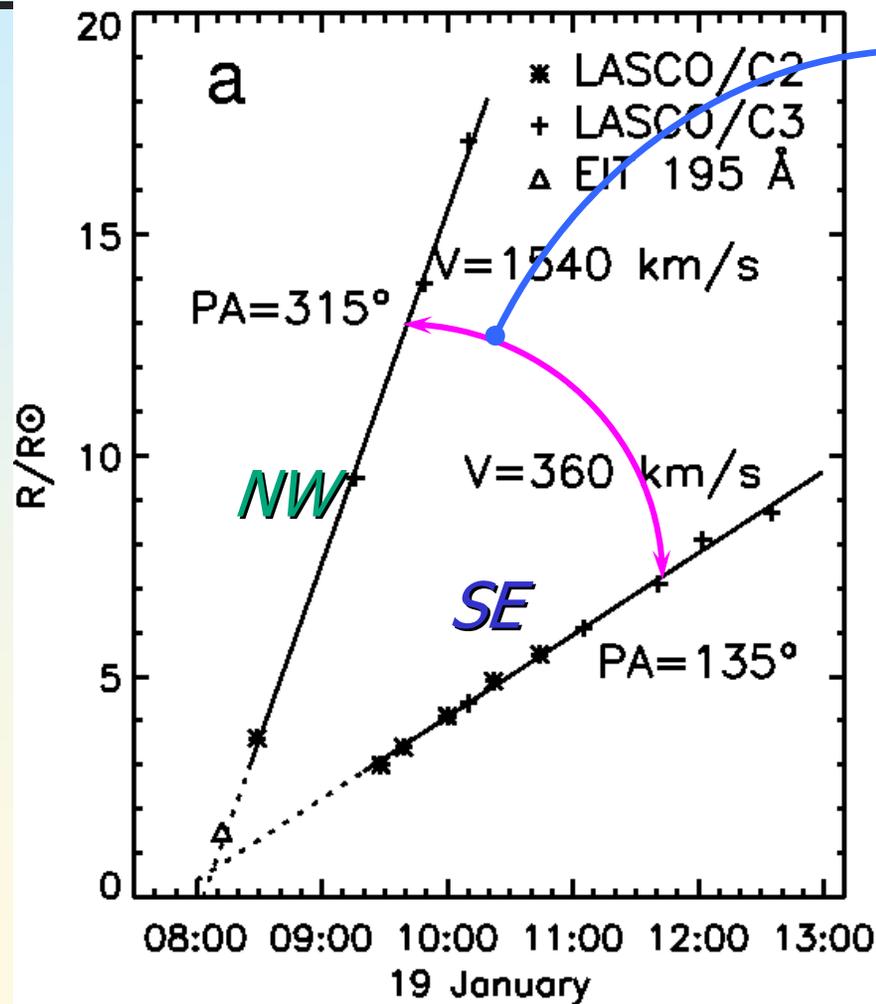
Day-by-day CMEs



Homologous Eruptions on 19 and 20 Jan.

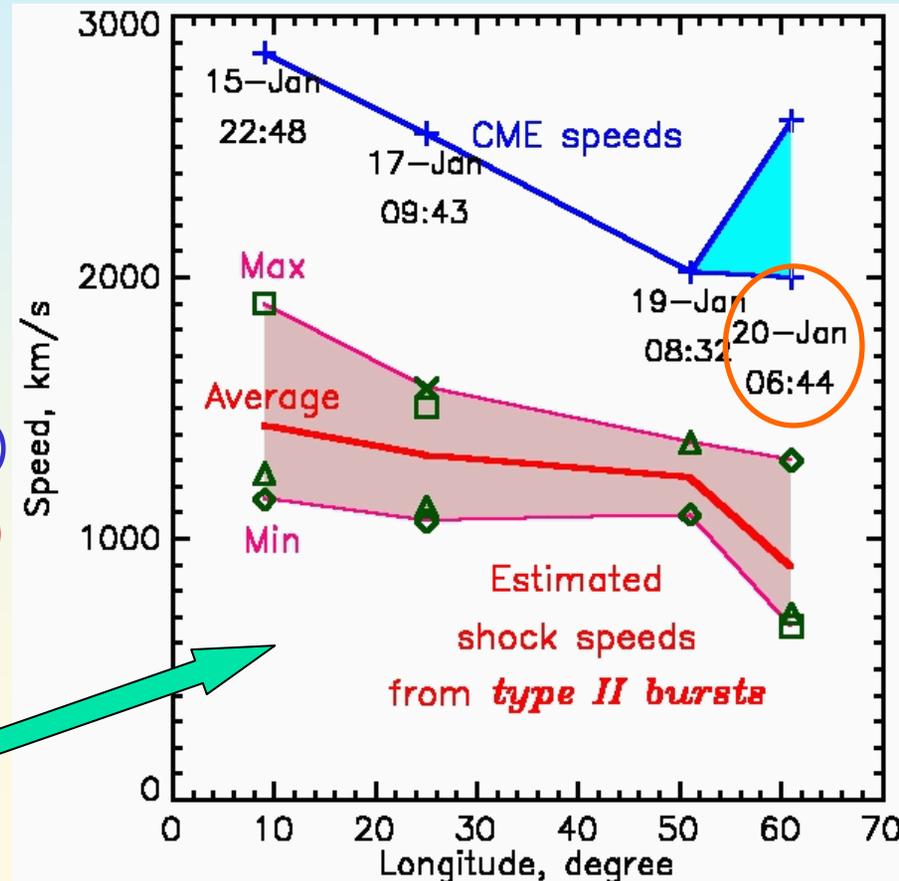


From speed ratios: 2000-2600 km/s



Estimates of CME speed

- From homology of 19 and 20 January CMEs: 2000-2600 km/s
- From ICME velocity:
 - Geomagnetic storm on 21 Jan, at 17 UT: $\langle V \rangle_{\text{Sun-Earth}} \sim 1200$ km/s
 - Solar Mass Ejection Imager: ICME ~ 1280 km/s (Jackson, Webb 2006)
 \Rightarrow Owens & Cargill (2004) $\Rightarrow \sim 2200$ km/s: high, but not extraordinary
- ESS from drift rates of type II bursts \Rightarrow **not underestimated**



Major LDE Events from AR720

Date	Time	GOES	Position	Microwaves		Protons			CME
				8.8 GHz	15.4 GHz	>10	>50	>100 MeV	V, km/s
15	22:48	X2.6	N14W09	20000	18000	300	10	0.4	2860
17	09:43	X3.8	N15W25	<u>16000</u>	<u>17000</u>	<u>3000</u>	<u>300</u>	<u>25</u>	2550
19	08:32	X1.3	N15W51	17000	15000	<100	<3	~0.1	2020
20	06:44	X7.1	N14W61	<u>41600</u>	<u>77400</u>	<u>1800</u>	<u>1100</u>	<u>680</u>	2000-2600

⇒ Extremeness of the 20 January event in:

- intensity of short-wave radio emissions and
- their hardness
- Not in CME speed

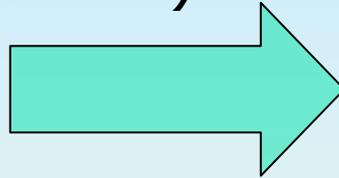
$F_{35 \text{ GHz}} > 10^4$ sfu points at

- Extreme solar events:
 - Flaring in very strong magnetic fields
 - Huge amounts of hard-spectrum electrons
 - Lots of hard-spectrum protons also expectable
- Their expected properties:
 - Strong HXR and gamma-ray burst
 - Strong microwave/millimeter burst, $\nu_{\text{GS peak}} > 20 \text{ GHz}$
 - Flaring close to sunspots' umbrae or just above them
 - White light flare possible

Example: 2006/12/13 event

- Strong microwaves (and HXR):

- $F_{35 \text{ max}} \approx 13600 \text{ sfu}$
 - $\nu_{\text{peak max}} \approx 43 \text{ GHz}$

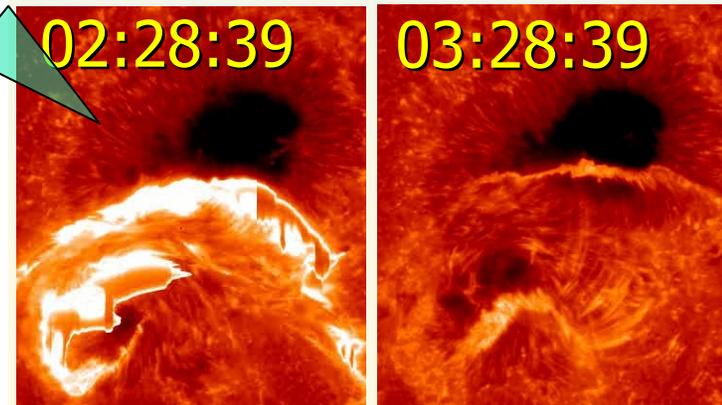
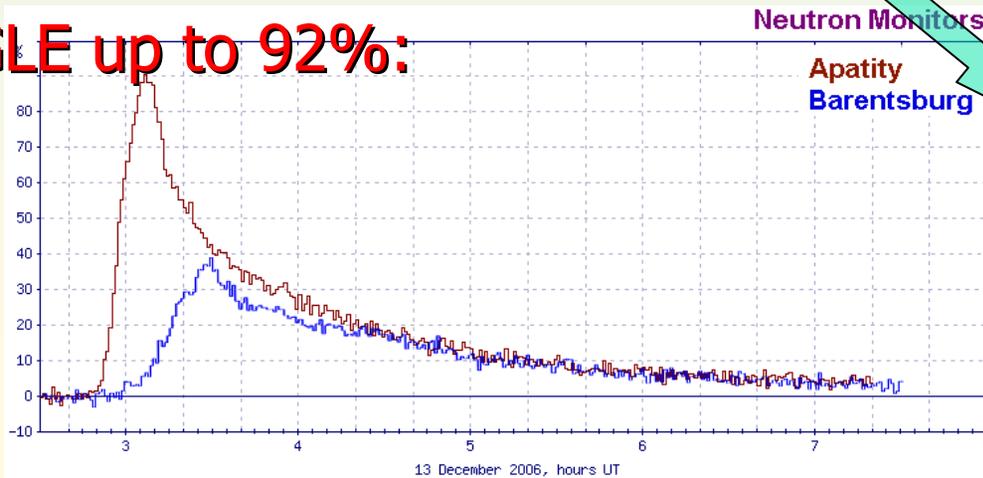
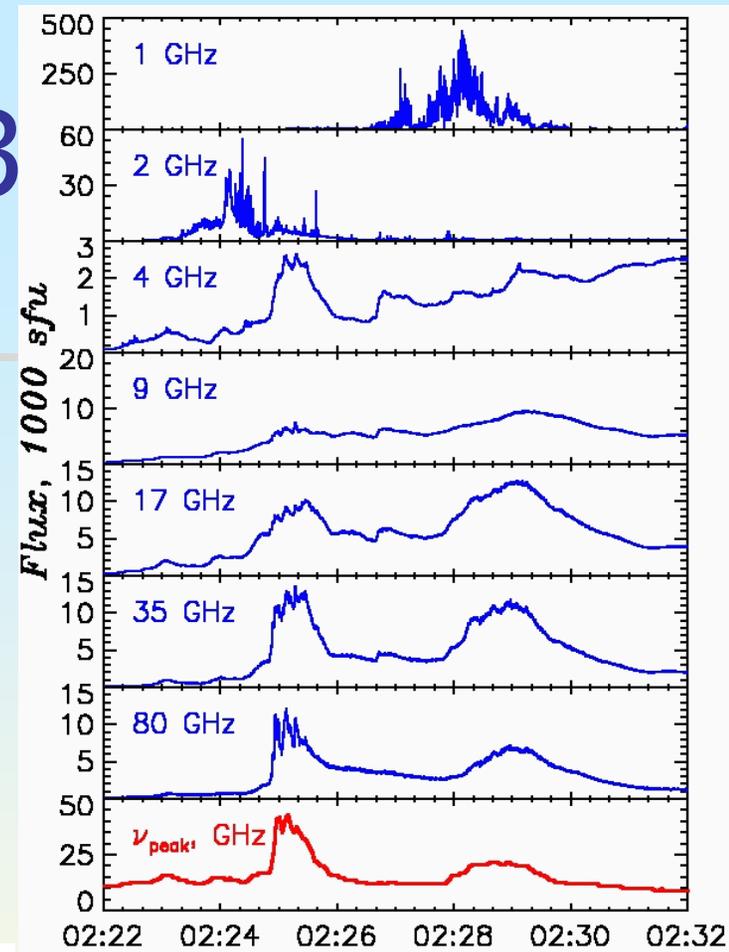


- Hinode/SOT (Ca): ribbons cross both umbrae

- White light emission probable

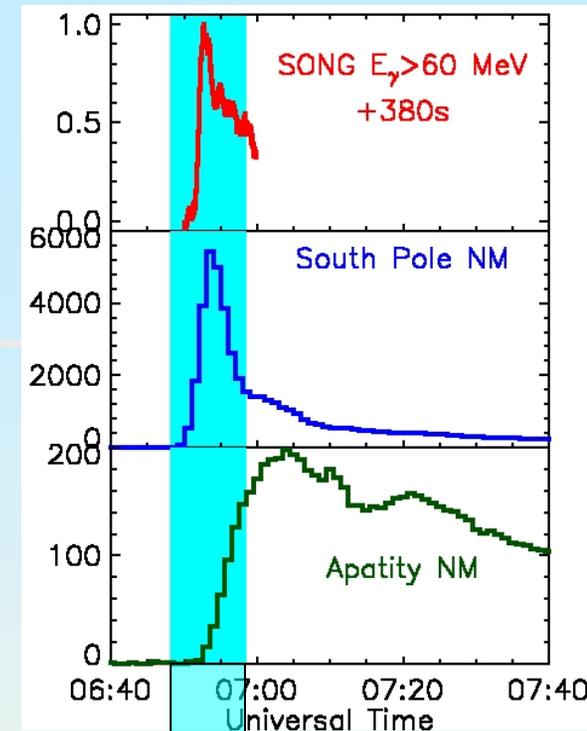
- CME: 1774 km/s

- GLE up to 92%:



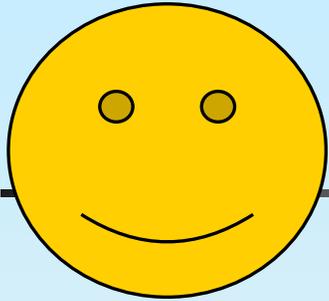
Conclusion

- Particles responsible for **leading** GLE spike on 20 January were predominantly accelerated within magnetosphere of the solar active region.
- 20 Jan. 2005 event was typical major proton flare.
- Microwaves in such events are generated by large number of hard-spectrum electrons in strongest magnetic fields (sunspots' umbrae).
- **Uncertainty still persists about later manifestations, when three kinds of mechanisms might contribute:**
 - Flare-acceleration (strong B, high n, T~20 MK, impulsive)
 - CME-driven shock (weak B, low n, T~1.5 MK, impulsive)
 - Post-eruptive acceleration (moderate B, low n, T~5 MK, gradual)



Questionable

Predominant flare acceleration



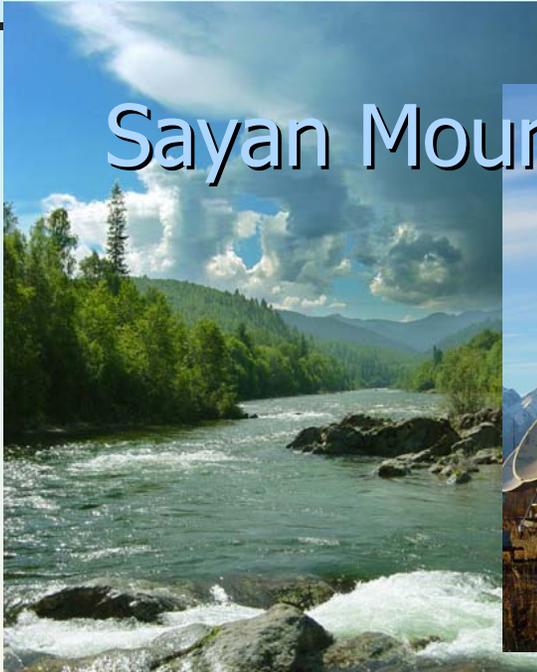
Thanks!

- For your attention
- For the opportunity to participate this meeting
 - Great Special Thanks to Allan Tylka for invitation, assistance, and discussions

We also thank G.Share, G.Hurford, M.Livshits, G.Rudenko, S.Bogachev, A.Struminsky, S.White, B.Dennis, and K.Tolbert

Regards from Eastern Siberia!

Sayan Mountains, SSRT, Baikal Lake



Extra Comments

RHESSI/HXR & SXR, TRACE 1600 Å

Background:

TRACE 1600 Å.

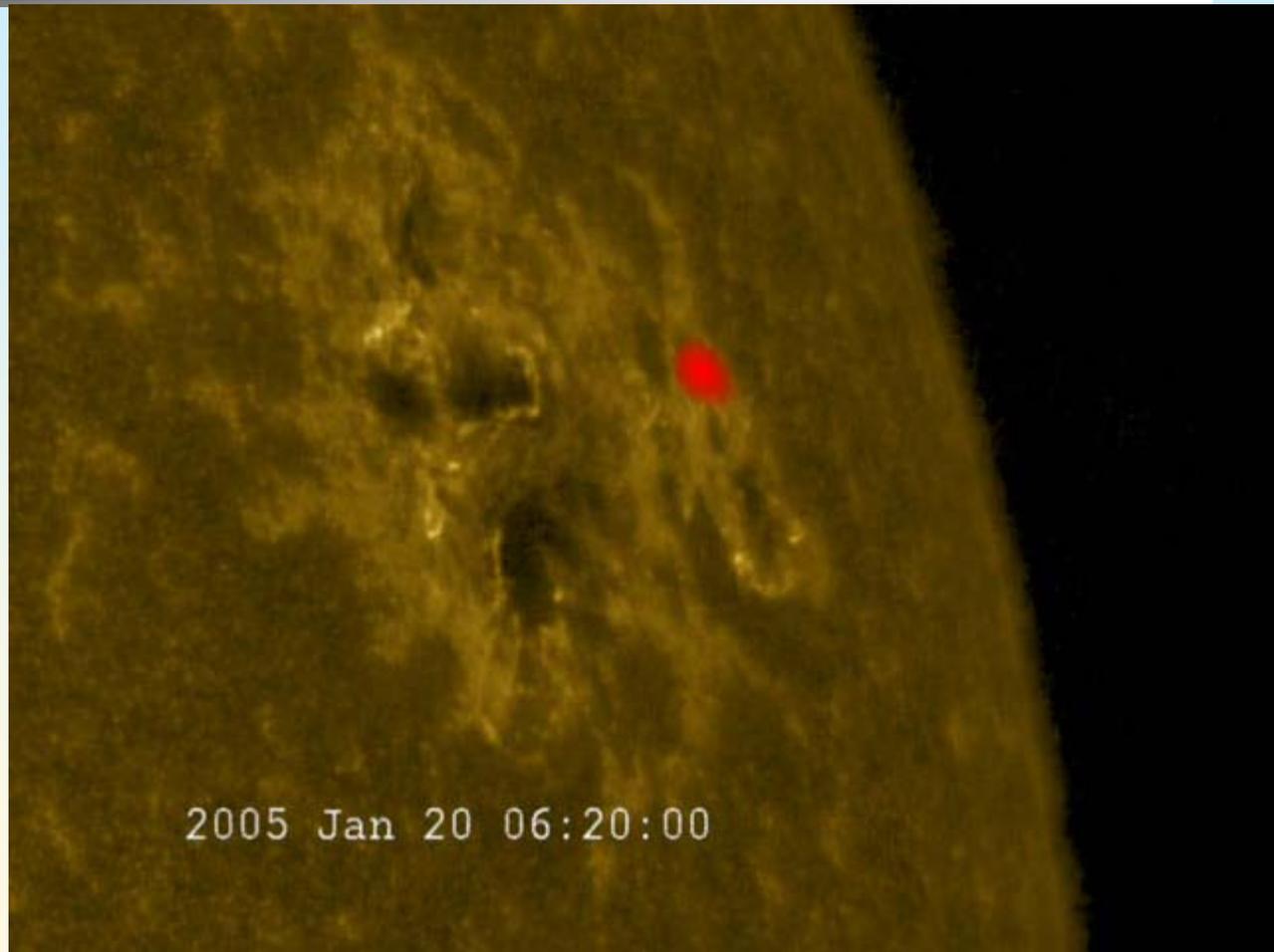
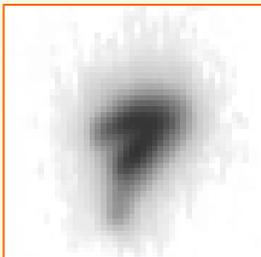
No images

between 06:18
and **06:52:30**

Red: RHESSI SXR

Blue: RHESSI HXR

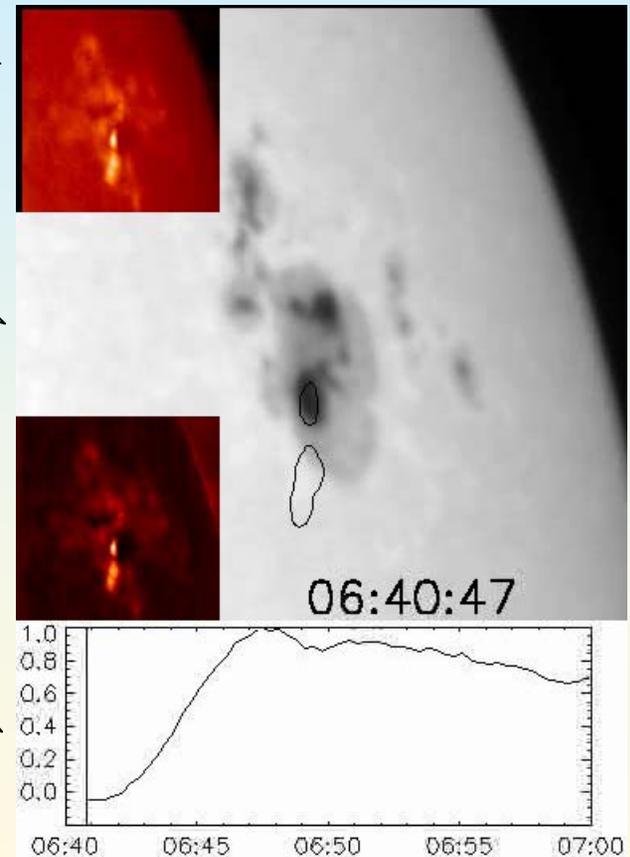
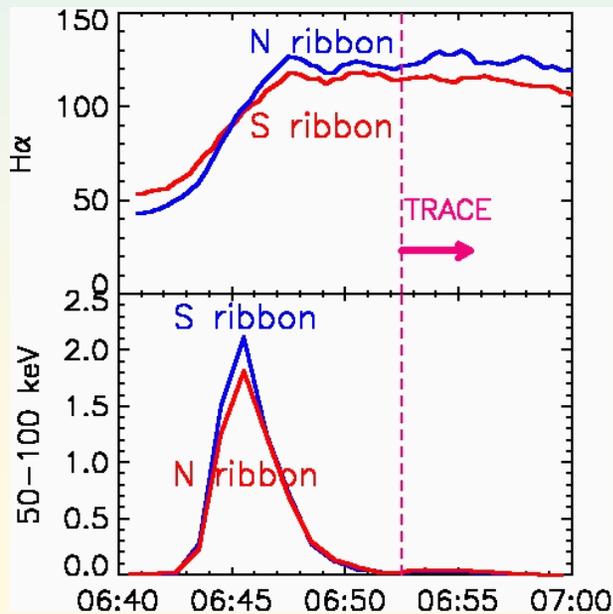
GOES/SXI:



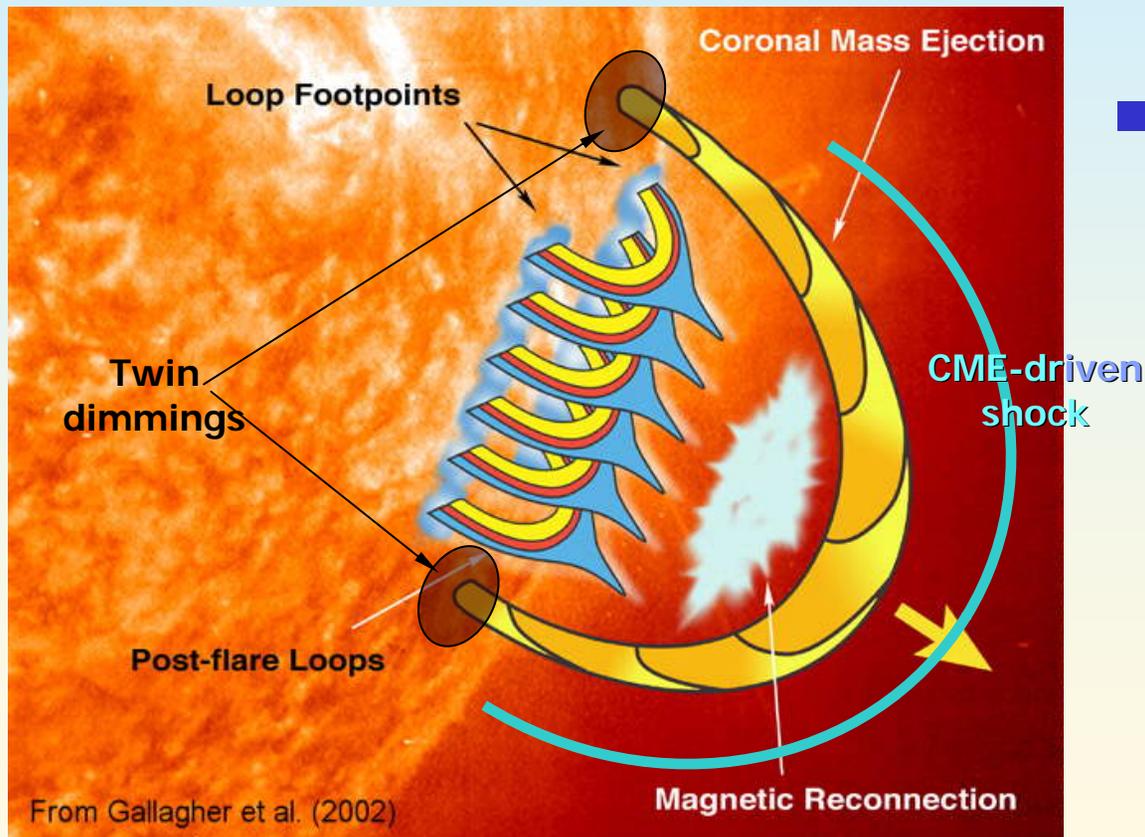
Movie: <http://svs.gsfc.nasa.gov/vis/a000000/a003100/a003161/>

H α flare (Culgoora)

- Red colors: H α
- Gray: White light (SOHO/MDI)
- Contours: H α ribbons
- Plot: total over both H α ribbons



Model concept



- Twin dimmings near ends of the arcade – footprints of ejected flux rope

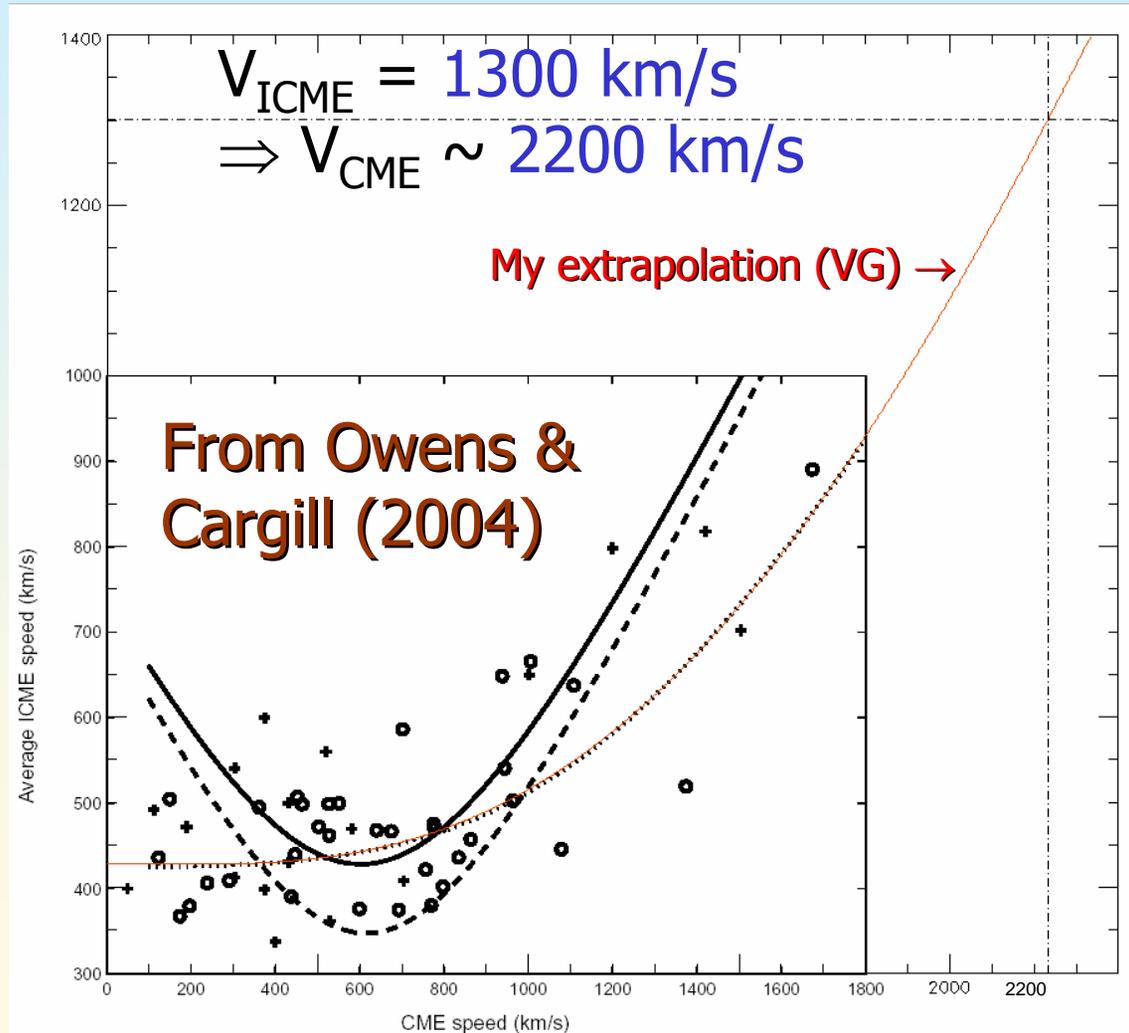
(Hudson & Webb, 1997;
Zarro et al., 1999;
Webb et al., 2000)

Probable reason for homology

- Continuous development of the active region towards strengthening flare-productive configuration
- under
- Persistence of main structural components for both active region and its large-scale environment
- the basis to compare CMEs on 19 and 20 January

Estimation ICME \rightarrow CME speed

- Jackson, Webb (2006): Solar Mass Ejection Imager – ICME ~ 1280 km/s
 - Geomagnetic storm on 21 January at ~ 17 UT: average Sun – Earth velocity $\langle V \rangle \sim 1200$ km/s
- $\Rightarrow V_{\text{CME}} \sim 2200$ km/s:



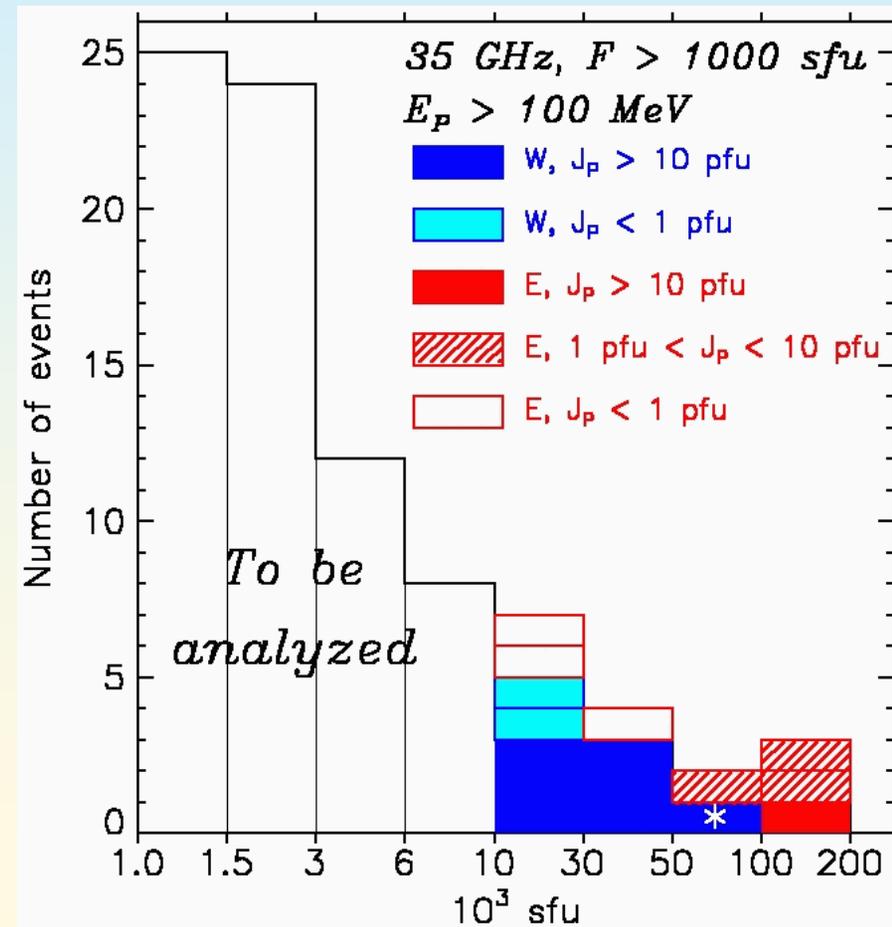
Was this event exceptional?

$F_{35} > 10^4$ sfu \rightarrow 16 out of 644 NoRP events (2.5%), 77% proton events

Date	Peak Time	35 GHz	80 GHz	$J_{P>10\text{ MeV}}$	$J_{P>100\text{ MeV}}$	GLE	Position	Flare	
1990-04-15	02:59	19615	-	12	0.04	-	N32E57	X1.4	
1990-05-21	22:14	37913	29083	410	12	14	N35W36	X5.5	
1991-03-22	22:44	122522	12469	43000	55	-	S26E28	X9.4	
1991-03-29	06:45	10871	2196	~20	<0.1	-	S28W60	X2.4	89%
1991-05-18	05:13	20429	3376	7	0.1	-	N32W85	X2.8	
1991-06-04	03:41	131163	165816	60	2	-	N30E65	X12	
1991-06-06	01:08	130439	186980	200	4.8	-	N33E44	X12	
1991-06-09	01:38	73994	23630	80	1.2	-	N34E04	X10	69%
1991-06-11	02:05	45671	10025	3000	40	14	N31W17	X12	
1991-10-24	02:38	33967	10637	<10	<0.1	-	S15E60	X2.1	
1992-11-02	02:49	41312	12000	2000	80	7	S23W90	X9	
2001-04-02	21:47	24952	8000	1110	47	-	N17W78	X20	
2002-07-23	00:30	14821	4000	<20	<0.1	-	S13E72	X4.8	
2002-08-24	01:00	11477	2700	317	24	5	S02W81	X3.1	
2005-01-20	06:46	84500	50000	1800	680	277/5500	N14W61	X7.1	
2006-12-13	02:21	13600	12140	698	88	92	S06W24	X3.4	
1990-05-28	04:30	100	20	400	45	6	N36W115	-	OCC
2000-11-08	23:28	-	-	14800	310	-	N20W66	M7.4	
2001-04-18	02:14	48	-	320	12	14	S23W117	C2.2	OCC
2001-08-15	~23:50	-	-	492	27	-	Backside	-	OCC
2001-12-26	05:05	764	111	780	40	7	N08W54	M7.1	PEA?
2002-04-21	01:15	480	150	2500	20	-	S14W84	X1	PEA?

Strong 35 GHz NoRP bursts and proton events

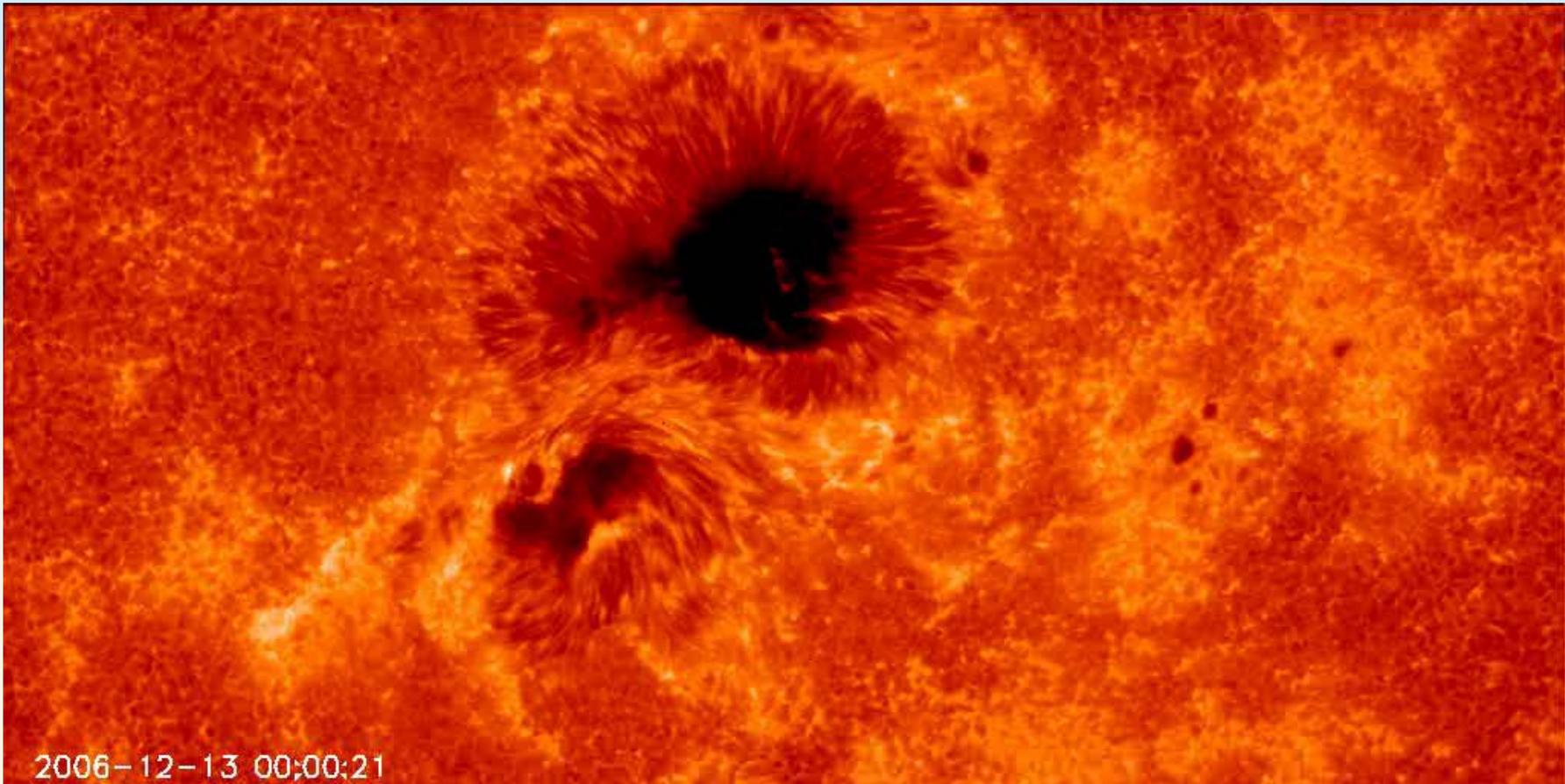
- Most $F_{35} > 10^4$ sfu flares are powerful proton events
- This concerns also eastern events
- Eastern events cause powerful proton fluxes only if radio fluxes are extremely strong



$F_{35} > 10^4$ sfu: *Big Flare Syndrome?*

- S.Kahler, "BFS" (JGR 1982, 87, 3439):
 - "... statistical correlation between ... flare energy release and magnitude of flare energy manifestations in general."
 - "Most correlations between proton fluxes and microwave and HXR parameters can be accounted for by the BFS."
 - BFS hardly can explain correspondence between:
 - Spectral indices of microwaves and near-Earth proton fluxes (Chertok 1982, Geomag. Aeron., 22,182):
$$0.9 \frac{S_9}{S_{15}} + 0.4 \cong \lg \left(\frac{J_{Ep>10MeV}}{J_{Ep>100MeV}} \right)$$
 - Their time profiles
 - $F_{35} > 10^4$ sfu selects a distinct class of extreme events
- ⇒ **No, $F_{35} > 10^4$ sfu is a diagnostic criterion**

Hinode/SOT/Ca 2006/12/13



From Hinode Web site:

- http://solar-b.nao.ac.jp/news/070321Flare/SOT_ca_061213flare_cl_lg.mpg

Proton Event Alert?

- USAF RSTN Radio Solar Telescope Network:
 - 245, 410, 610, 1415, 2695, 4995, 8800, 15400 MHz
- Total flux measurements sufficient
- For flares in sunspot umbrae, which are rare, but extremely hard-proton-dangerous, important are
 - Higher frequency, $15 \text{ GHz} < \nu < 100 \text{ GHz}$: **currently no real time data on-line** (NoRP: $\sim 22 - 08 \text{ UT}$).
 - Measurements of strong magnetic fields (**MDI: $< 2000 \text{ G}$, currently NO DATA from Kislovodsk or Mt. Wilson!**)

Do Data on Heavier Ions Favor CME-Driven Shock Acceleration Only?

- Charge state in “gradual events”: shocks or post-eruptive acceleration in/above ARs?
- Fe/O ratio?
- Acceleration & escape time?
- SEP fluxes in different events?

- Somov & Chertok 1996, Chapman Conf. "CMEs: causes and consequences", Montana State University, Bozeman, Montana

"Gradual events": shocks or post-eruptive acceleration in/above ARs?

The time of Maxwellian temperature establishment in the reconnecting current sheets (τ_{pp}) depends on the plasma density (n) and should be compared with the acceleration time of particles (τ_{acc}).

- **Impulsive events:** $n \approx 2 \times 10^{11} \text{ cm}^{-3} \implies \tau_{pp} \leq \tau_{acc}$

The ions may have a sufficient time 'to acquire' the charge state corresponding to the temperature that are characteristic for the low-altitude (high-density) flare current sheets.

- **Gradual events:** the post-CME reconnecting current sheet high in the corona

$$n \approx 2 \times 10^9 \text{ cm}^{-3} \implies \tau_{pp} \gg \tau_{acc}$$

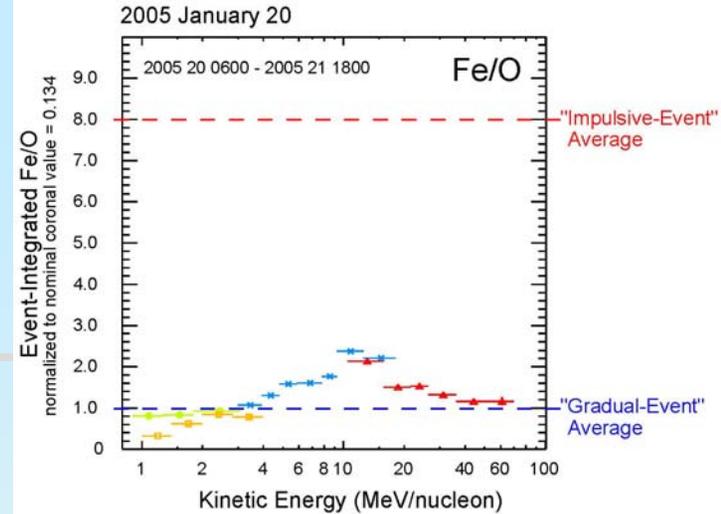
The ions certainly have not a sufficient time 'to acquire' the charge state matching the effective temperature of the high-altitude (low-density) post-eruption coronal current sheet; they still 'remember' the background coronal temperature and coronal ionization state.

Conclusion: From the charge state point of view, the particle acceleration in the post-CME reconnecting current sheet high in the corona cannot be excluded as a plausible source of the gradual SEP events.

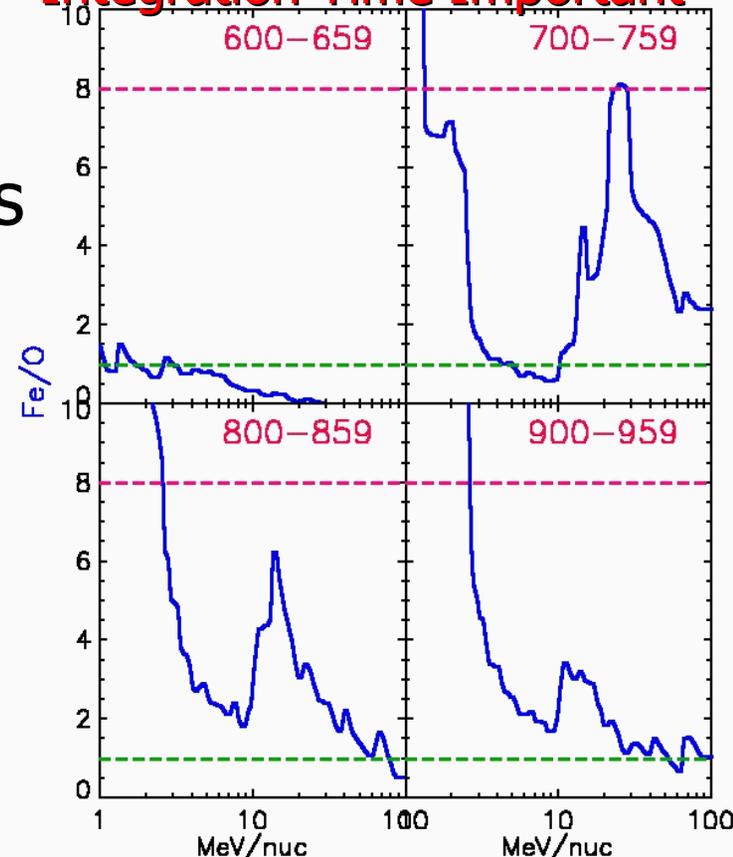
Acceleration & Escape Time, Fe/O Ratio

Labrador et al. 2005, 29th ICRC Pune:

- "...first ... particles left the Sun when the CME shock was $\sim 1.5R_{\odot}$ above the solar surface."
- "imply that < 90 s were available to accelerate and release the particles."
[consistent with γ -rays]

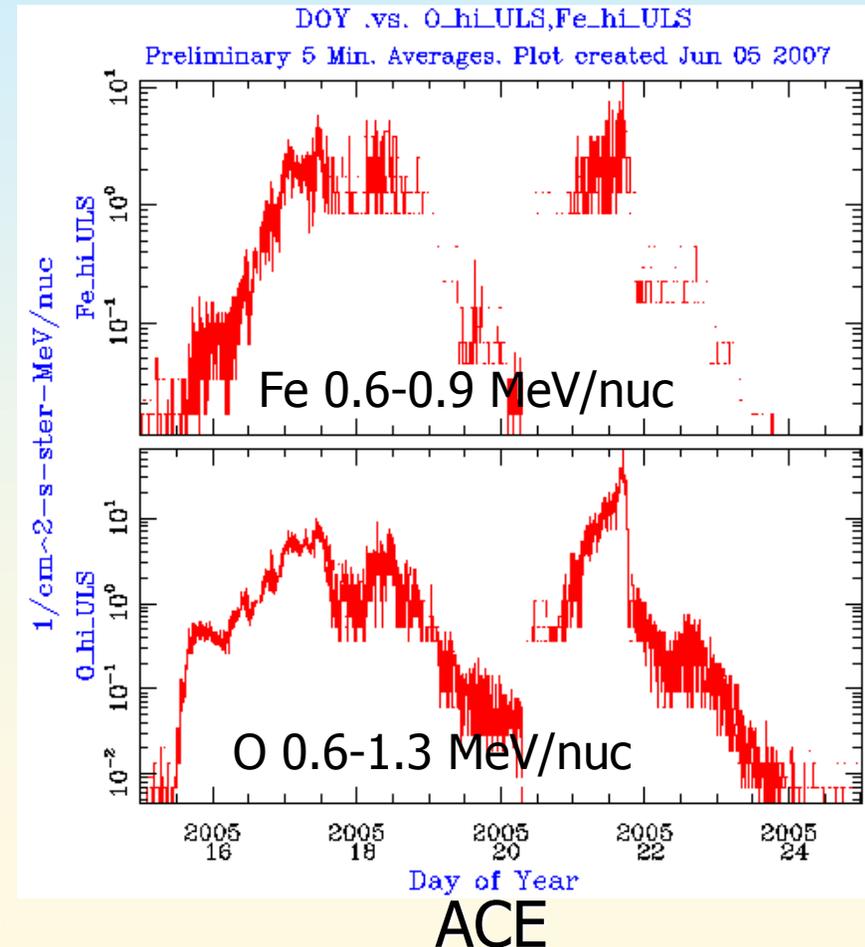
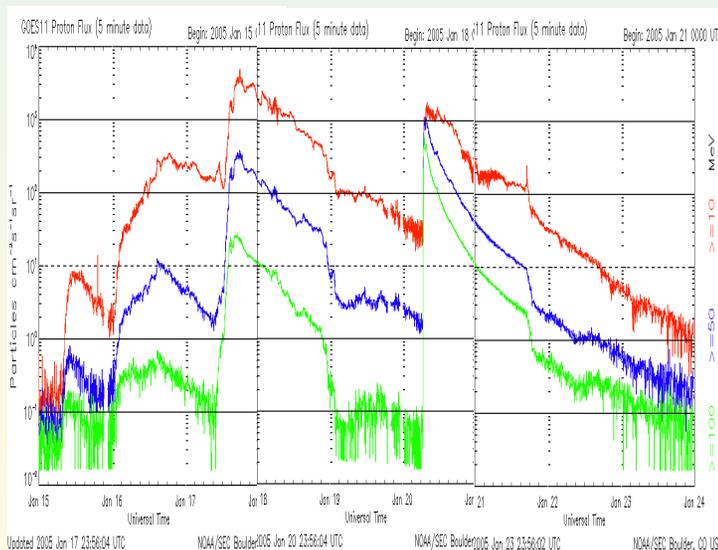


Integration Time Important



SEP fluxes in different events

- Compare fluxes of heavier ions from 15-20 Jan SEP events



Uncertainties:

- SEP properties **do not** certainly **favor** shocks-acceleration only
- **Difficult to distinguish** late-stage manifestations from different acceleration mechanisms:
 - Due to CME-driven shock
 - Post-eruptive acceleration just above active region