Relations between strong high-frequency radio bursts and big proton events

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A well-known correlation between big solar energetic particle (SEP) events and strong high-frequency radio bursts was initially regarded as evidence of flare-related origin of SEP. However, S.Kahler (1982) explained the above correlation by the "Big Flare Syndrome", i.e., a general correspondence between the energy release in an eruptive flare and its various manifestations and argued acceleration of SEP by CME-related shocks. Later exaggerations of the shock-acceleration concept have led to underestimation of diagnostic opportunities of microwave bursts. Irrespective of the SEP origins, we analyze relations between microwave bursts recorded with NoRP and NoRH since 1990, on the one hand, and large high-energy proton enhancements, on the other hand.

1. Introduction. Flare emissions in the GLE69 2005-01-20 event had extreme properties with a microwave flux up to almost 10^5 sfu and a turnover frequency up to ~30 GHz (Grechnev et al., 2008). These parameters suggested radiation of a large number of high-energy electrons in very strong magnetic fields, which were only possible above the umbrae of sunspots. The observed locations of the flare ribbons confirmed this conjecture. Keeping in mind that strong high-frequency radio bursts were typical of major SEP events (e.g., Croom, 1971), we really found that the $F_{35GHz} > 10^4$ sfu criterion selected most SEP events (Chertok et al., 2009). Besides 9 out of 12 (75%) west events, SEP events occurred also in moderately east events with very large fluxes. Then we extended our analysis to a larger set of events with 10^3 sfu < F_{35} < 10^4 sfu occurring during the NoRP observational daytime. For brevity we denote the microwave fluxes similar to the GOES class: mX are microwave-eXtreme events ($F_{35} > 10^4$ sfu), mS are microwave-Strong events (10^3 sfu < F_{35} < 10^4 sfu), and mM are microwave-Moderate events (10^2 sfu < F_{35} < 10^3 sfu). To reveal the events missed by our criteria, we also considered all near-Earth >100 MeV proton enhancements exceeding $J_{p100} > 10$ pfu [1 pfu = 1 particle/(cm^2 s ster)].

2. Data processing. We calculated parameters of the bursts from NoRP records by involving, when necessary, NoRH data. For damaged NoRP 35 GHz records F_{35} was interpolated from the 17 and 80 GHz data. The 80 GHz fluxes during 1995–2005 were corrected with a factor of $[T_{[year]}/1995.83]^{630}$ (H.Nakajima, priv. comm.) Both the 35 GHz and 80 GHz radiometers did not operate on 2004-11-10, and parameters of this event were roughly estimated from lower-frequency data and NoRH correlation plots. The results are listed in Table I and plotted in Fig. 1 (non-SEP events fall outside the plotting region). Proton fluxes from east events (○) are additionally shown as ● being compensated for the dependence of $\exp\{-[(\lambda-54)/63]^2\}$ on the longitude λ (A.Belov, priv. comm.)

Table I. Analyzed events

No	Date	T_{peak} 35 GHz	Flare		Duration 35 GHz	Microwave burst		Proton flux			
			Hα/GOES	AR	min	F_{35}, sfu	f_{peak}, GHz	J_{p100}, pfu	J_{p10}, pfu	$\delta_p = \lg(J_{10}/J_{100})$	GLE, %
mX events with extreme fluxes at 35 GHz (> 10000 sfu)											
1	1990-04-15	02:59	2B/X1.4	N32E54	66	19600	11	0.04	9	2.4^4	–
2	**1990-05-21**	**22:15**	**2B/X5.5**	**N34W37**	**6.6**	**37900**	**47**	**18**	**300**	**1.22**	**24**
3	1991-03-22	22:44	3B/X9.4	S26E28	2.4	122500	35	55	**28000**	2.70	–
4	**1991-03-29**	**06:45**	**3B/X2.4**	**S28W60**	**6.6**	**10900**	**30**	**<0.1**	**20**	–^{4}	–
5	**1991-05-18**	**05:13**	**2N/X2.8**	**N32W87**	**26**	**20500**	**26**	**<0.1**	**7**	–^{4}	–
6	1991-06-04	03:41	3B/X12	N30E60	15	130000^1	44	2	**50**	1.40	–
7	1991-06-06	01:09	3B/X12.5	N33E44	17	130000^1	46	2.5	**200**	1.90	–
8	**1991-06-09**	**01:39**	**3B/X10**	**N34E04**	**6.6**	**74000**	**36**	**1.2**	**80**	**1.82**	–
9	**1991-06-11**	**02:06**	**3B/X12.5**	**N32W15**	**18**	**46000**	**30**	**42**	**2500**	**1.77**	**12**
10	1991-10-24	02:38	3B/X2.1	S15E60	0.6	34000	35	0	–^{4}	–^{4}	–
11	**1992-11-02**	**02:54**	**2B/X9**	**S23W90**	**15**	**41300**	**35**	**70**	**800**	**1.06**	**6.5**
12	**2001-04-02**	**21:48**	**?/X17.1**	**N18W82**	**6**	**25000**	**35**	**4.8**	**380**	**1.90**	–
13	2002-07-23	00:31	2B/X4.8	S13E72	17	15000	35	0	–^{4}	–^{4}	–
14	**2002-08-24**	**01:00**	**1F/X3.1**	**S02W81**	**16**	**11000**	**18**	**27**	**220**	**0.91**	**14**
15	**2004-11-10**	**02:10**	**3B/X2.5**	**N09W49**	**7**	**>10000^{2,3}**	**>17^{2,3}**	**2**	**75**	**1.57**	–
16	**2005-01-20**	**06:46**	**2B/X7.1**	**N12W58**	**25**	**84500**	**28**	**680**	**1800**	**0.42**	**5400**
17	**2006-12-13**	**02:21**	**4B/X3.4**	**S06W24**	**31**	**13600**	**45**	**88**	**695**	**0.89**	**92**
18	**2012-03-07**	**00:24**	**3B/X5**	**N17E15**	**80**	**10500**	**17**	**67**	**1500**	**1.35**	–
19	**2012-07-06**	**23:06**	**?/X1.1**	**S15W63**	**3**	**17000**	**35**	**0.27**	**22**	**1.91**	–
mS events with strong fluxes at 35 GHz (> 1000 sfu)											
20	1990-05-11	05:42	X2.4/SF	N15E13	9	19650	15	0	–	–	–
	…	…	…	…	…	…	…	…		…	…
	…	…	…	…	…	…	…	…		…	…
90	**2011-08-04**	**03:57**	**2B/M9.3**	**N16W49**	**11**	**1400**	**11**	**1.5**	**77**	**1.71**	–
91	**2011-08-09**	**08:05**	**2B/X6.9**	**N17W83**	**6**	**1000**	**14**	**2.5**	**22**	**0.94**	–
92	**2012-01-23**	**03:59**	**2B/M8.7**	**N29W36**	**39**	**2000**	**4**	**2.3**	**2700**	**3.07**	–
mM events with strong proton fluxes ($J_{>100\,MeV}$ > 10 pfu)											
93	**2000-11-08**	**23:28**	**1N/M7.8**	**N10W75**	**53**	**140**	**2.8**	**320**	**14000**	**1.64**	–
94	**2001-12-26**	**05:06**	**1B/M7.1**	**N08W54**	**26**	**780**	**6.9**	**47**	**700**	**1.17**	**13**
95	**2002-04-21**	**01:15**	**1F/X1.5**	**S14W84**	**83**	**300–480^{1,2}**	**5**	**20**	**2000**	**2.00**	–
96	**2012-05-17**	**01:41**	**1F/M5.1**	**N09W74**	**17**	**200**	**10**	**18**	**230**	**1.11**	**16**
mO backside events with strong proton fluxes ($J_{>100\,MeV}$ > 10 pfu)											
97	1990-05-28	04:30	C1.4	N36W120	8	100	1.4	43	430	1.00	6
98	2001-04-18	02:15	C2.2	S20W115	4	–	–	12	230	1.28	26
99	2001-08-15	23:50	–	W>120	–	–	–	27	470	1.24	–

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[1] Interpolated from data at 17 and 80 GHz
[2] Estimated from NoRH data
[3] Estimated from lower-frequency data
[4] Uncertain

3. Results. Three groups of events have been revealed. **(1)** The majority (14) of mX bursts (totally 19) in 16 west to moderately east flares (boldface in Table I) was indeed associated with near-Earth > 100 MeV proton enhancements $J_{p100} > 1$ pfu (74% out of both west and east mX events, 84% out of favorably located mX events). Short impulsive events indeed had a reduced proton productivity, but their duration was not crucial being probably somehow combined with the total flux. The analysis of the proton events with $J_{p100} > 10$ pfu has revealed **(2)** three big proton enhancements associated with microwave-Occulted (mO) backside events (beyond the plotting region), for which no conclusion can be drawn, and **(3)** four exceptional mM events with large protons fluxes. Two of them produced GLE63 (2001-12-26) and GLE71 (2012-05-17). The peculiarity of these events is supported by the absence of $J_{p100} > 10$ pfu enhancements in the mS events.

Except for these deviations, most SEP events show a general correspondence with the F_{35} fluxes being mostly within the band bounded with rather arbitrary lines of $(F_{35}/1500)^2$ and $(F_{35}/15000)^2$, which reflect a direct flare–SEP relation. The scatter is large for obvious reasons, e.g., flare-accelerated protons are affected by escape conditions from active regions; shock-accelerated protons are influenced by the plenitude of a seed population; and all depend on the Sun-Earth connections.

The SEP spectra were hard ($\delta_p \le 2$, see Table I) in west events with high $f_{peak} > 15$ GHz, while after non-flare-related filament eruptions $\delta_p \sim 3$ (see Chertok et al., 2009).

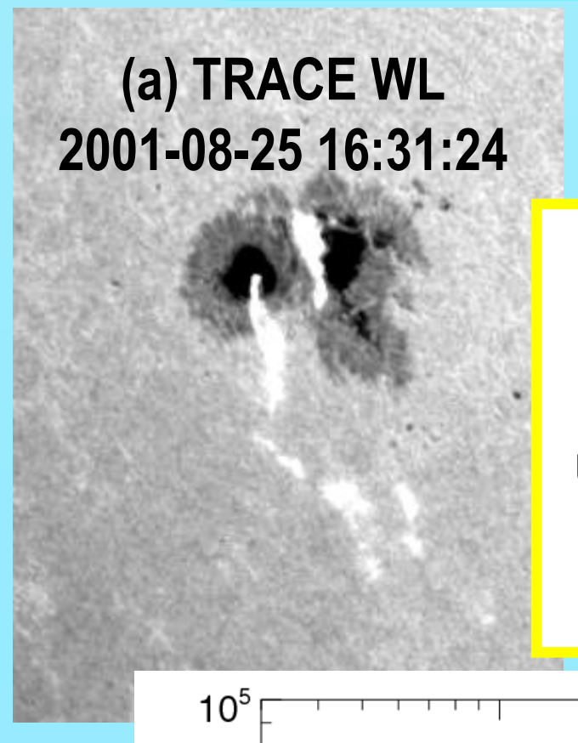
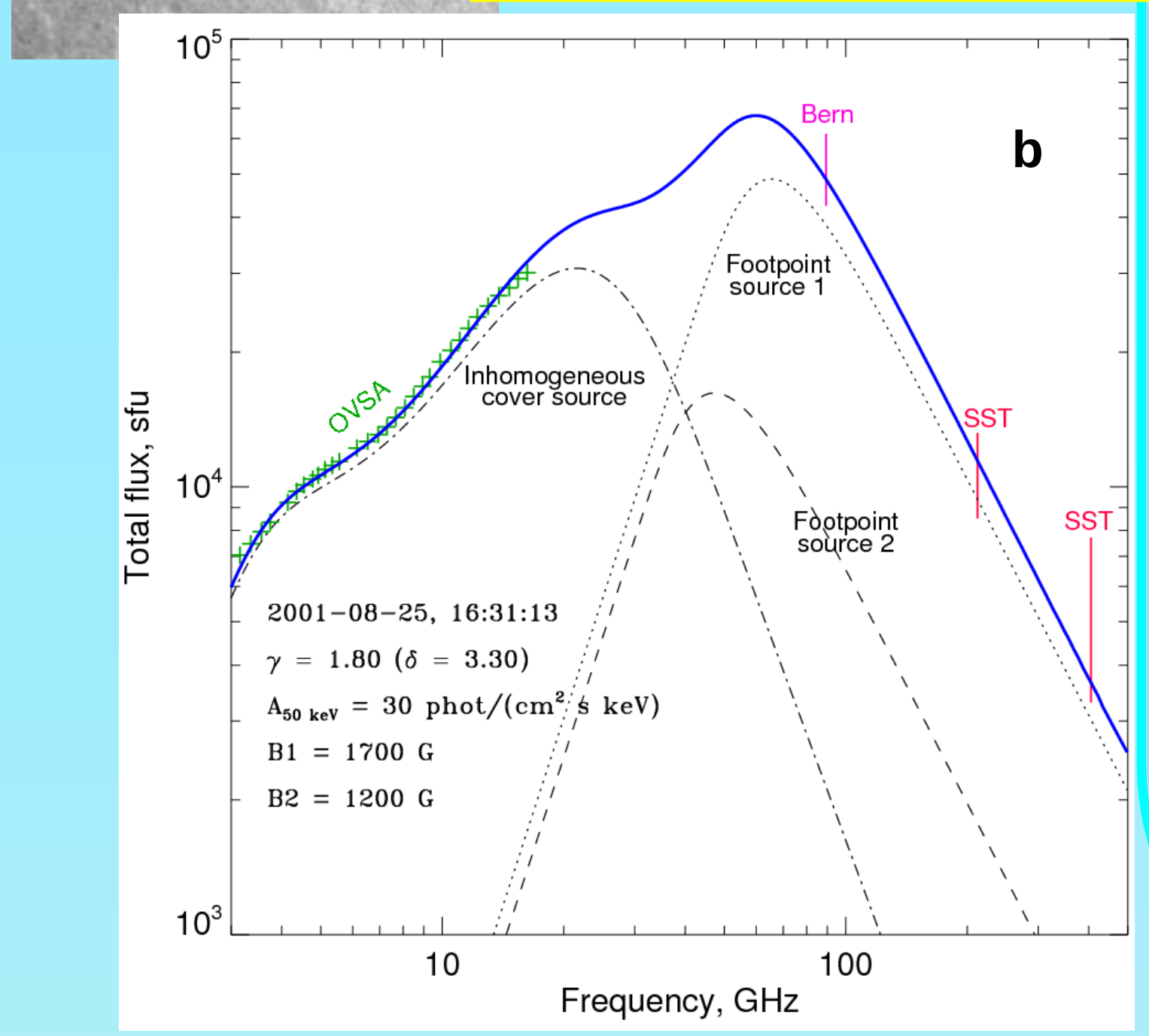


Fig. 2. The 2001-08-25 extreme flare: a) flare ribbons above sunspot umbrae, b) GS spectrum (symbols observations, blue curve model)



4. Discussion.

4.1. Properties of SEP-associated flares. Belonging for the majority of events to the optically thin region, high-frequency emissions seem to be most sensitive to large numbers of high-energy electrons gyrating in strong magnetic fields being thus directly related to the rate of energy release in the flare–CME formation process. The mX events, whose peak frequencies mostly exceeded 30 GHz, are favored by flaring above the sunspot umbrae, where strongest magnetic fields are reached.

To verify this idea, we modeled the gyrosynchrotron (GS) spectrum for the 2001-08-25 white-light flare (Fig, 2a; 3B/X5.3, S17E34; Metcalf et al., 2003) responsible for a big neutron event and extreme hard X-ray (HXR) and gamma-ray emissions. The GS spectrum of this flare (occurred during the Nobeyama night) recorded with a unique coverage at 1–18 GHz (OVSA), 89.4 GHz (Bern), 212 and 405 GHz (SST – Solar Sub-mm Telescope) (Raulin et al., 2004) is shown with symbols in Fig. 2b. A three-component model (Kundu et al., 2009) simulates two footpoint sources and an inhomogeneous frequency-dependent cover source (see Bastian et al., 1998). We used parameters of the HXR spectrum evaluated by V.Kurt from CORONAS-F/SONG and Yohkoh/GRS & HXT data. The magnetic field strength was evaluated by referring of a one-week-long irregularly 'saturated' set of 96-min MDI magnetograms to NoRH 17 GHz images, which showed on 27 August manifestations of the gyroresonance emission. Correspondence of the blue modeled spectrum in Fig. 2b to the observations confirms our idea. Taking account of the inhomogeneous source removes the limitation of $B \le 1000$ G which restrained considerations of Raulin et al. (2004).

Thus, flaring above the sunspot umbrae appears to be typical of mX and some mS events (Fig. 3). This was the case in the big June 1991 flares (Sakurai et al., 1992). (See also Kundu et al., 2009).

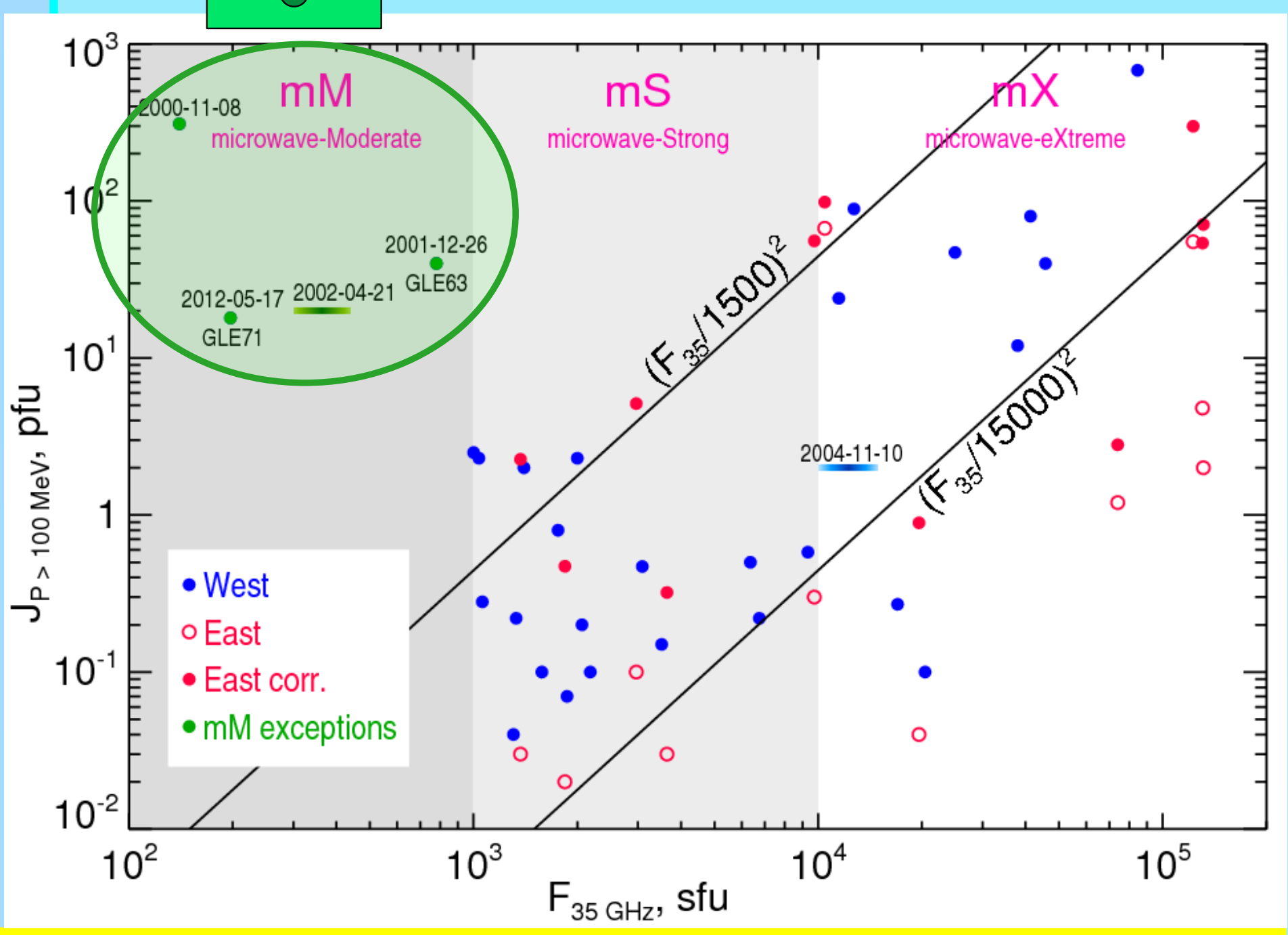


Fig.1. Fluxes of > 100 MeV protons vs. radio fluxes at 35 GHz. The black solid lines are arbitrarily chosen to verify a direct relation between the observables.

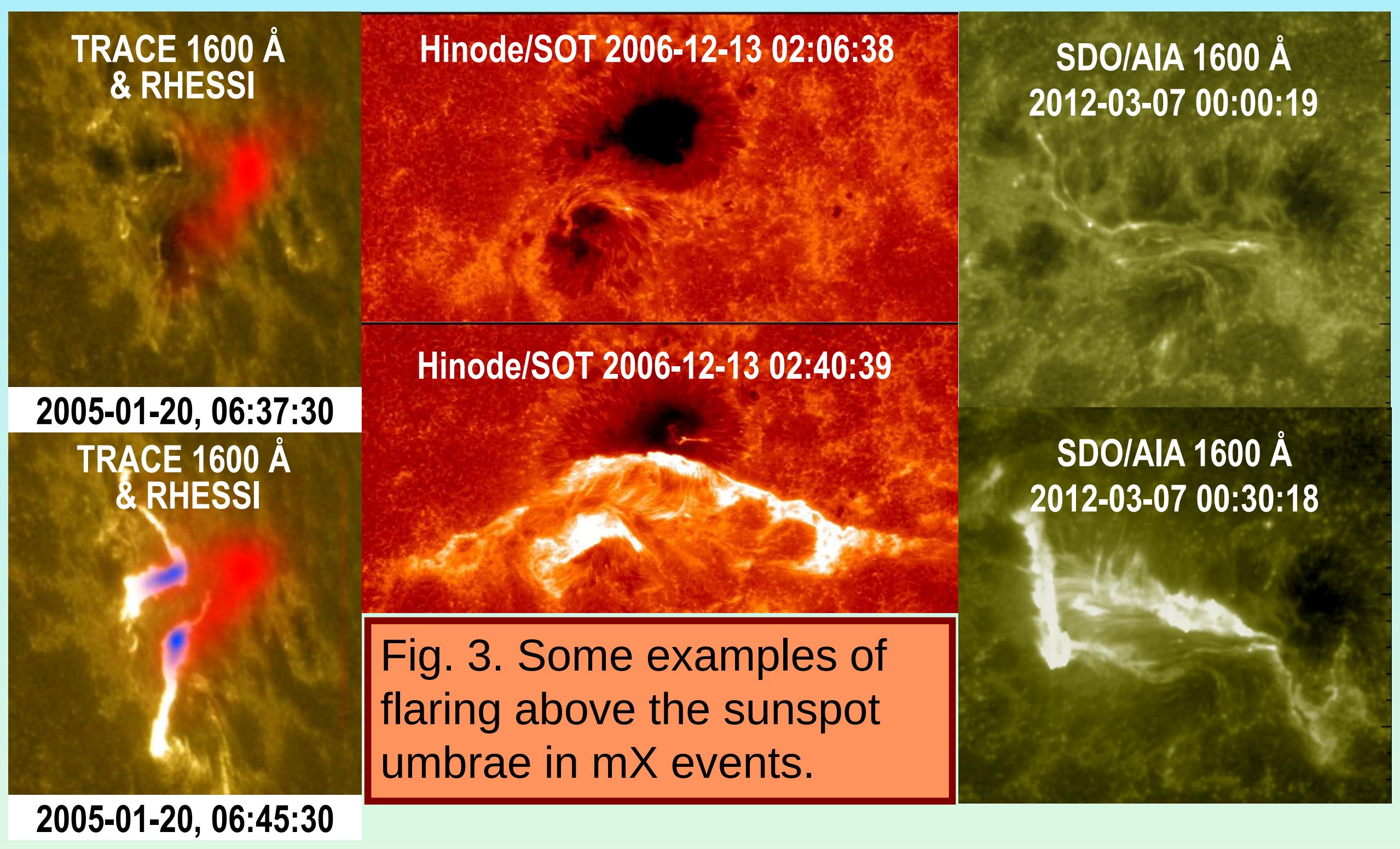


Fig. 3. Some examples of flaring above the sunspot umbrae in mX events.

4.2. Exceptional mM events. The four exceptional mM events (inside the green oval) look challenging: proton enhancements $J_{p100} > 10$ pfu occurred in association with $F_{35} < 1000$ sfu bursts. Peak frequencies in these events were below 10 GHz. Contributions from concurrent backside eruptions are doubtful, but not excluded. The idea of shock-acceleration does not clarify the situation: recent results show that both CME acceleration and shock development are closely associated with a flare and occur simultaneously with HXR and GS bursts (Temmer et al. 2008, 2010; Grechnev et al., 2011). Thus, it is difficult to expect a strong shock while a flare is moderate. The relation between microwave fluxes from the four exceptional events and their proton productivity seems to be distorted for some reasons, e.g., possible contributions from nearly simultaneous backside events. A partial occultation of the 35 GHz emission seems to be possible in the **2002-04-21** event, which occurred exactly on the limb.

Some properties of the 2000-11-08 and 2001-12-26 events look strange. Soft X-ray (SXR) emission in the GLE63 **2001-12-26** event rose more than 2200 s, while in all 15 other GLE events of the solar cycle 23 SXR rose ≤ 1000 s (typically ~500 s). Note that the SXR rise phase corresponds to the integral of the HXR emission (the Neupert effect) and roughly displays the CME velocity. The type II burst started > 15 min before the CME onset time and the microwave burst.

In the **2000-11-08** event, both the CME and type II burst started ~15 min before the microwave burst and the main rise of the SXR emission. However, no appropriate candidates for backside eruptions in both these events were among active regions observed a few days before.

The recent GLE71 **2012-05-17** event was visible both from Earth and STEREO-A, which did not show a candidate for a stronger event behind the west limb. Some kind of absorption of the 35 GHz emission is not excluded, but the moderate M5.1 GOES importance does not support underestimation of the emission in this event. One more possibility is escape of an unusually large fraction of accelerated electrons into the interplanetary space.

Thus, the causes of the mM exceptions can be different. These events need careful investigation. The group of such events can be actually larger, because we did not consider SEP events with $J_{p100} < 10$ pfu *or* those occurring beyond the observational daytime in Nobeyama.

5. Conclusions.

1. **Big SEP events are favored by flares occurring above sunspot umbrae.**
2. **Strong high-frequency bursts and flare ribbons crossing the sunspot umbrae can be employed to promptest alert of SEP events.**
3. **Extreme bursts at 35 GHz indicate big SEP events with hard energy spectra.**
4. **Events associated with big SEP enhancements and moderate microwave bursts need understanding.**
5. **NoRP and NoRH observations are highly important in further investigating into the SEP problem.**

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