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Integral spectra of small GLEs in the 24th cycle of solar activity

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Abstract

- We continue systematical empirical search for small size GLEs ("hidden", or sub-GLEs) by the data of ground-based observations for the period of solar cycle 24. Starting point of this research is a hypothesis that small size GLEs may be indicative of acceleration of solar energetic particles (SEPs) by CME-driven shocks. Crucial parameter for resolving the problem seems to be a SEP energy spectrum at the Earth's orbit measured by spacecraft detectors and ground-based neutron monitors (NMs). We try to recover the SEP spectrum in a wide range of energies – from GOES non-relativistic energy channels to relativistic range by the NM data, as well as by relevant measurements on some ground-based non-standard (mainly muon) cosmic ray detectors. The main factors that may determine the SEP intensity and spectrum shape near the Earth are the source power, location, and/or shock strength. Every "suspected" small GLE is analyzed separately. Finally, we compile a Table (summary) of statistically confirmed small GLEs and give our interpretation within the frame of above hypothesis. Three considered models of shock wave acceleration are not suitable to physically and unambiguously explain some features of observed SCR spectra. The results emphasize the importance of studying the GLEs of low intensity ("hidden GLEs") for better understanding the SEP spectrum formation, especially in the range of relativistic energies. The GLE events from the behind-the-limb sources are of special interest.

Table 1: Selected events

Table 1 Observed, predicted, and identified weak GLEs of SC 24.

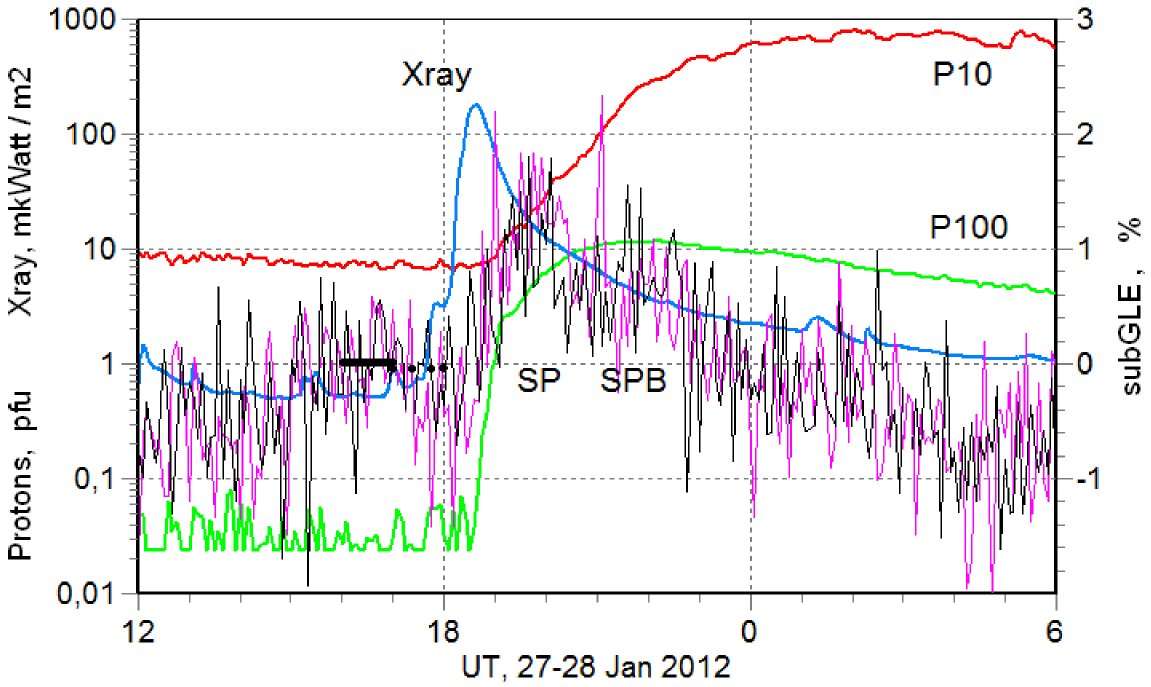
No	Date of event	Intensity $I_{max}(\geq 10$ MeV), pfu	Source location	Flare class	CME speed, km/s	References, comments
1	7 Mar 2011	50	N24W59	M3.7/S	NW-limb, 2000	NOAA, 2020; Makhmutov et al., 2013; hidden GLE?
2	23 Jan 2012	6310	N28W36	M8.7	2175	Belov et al., 2015a, 2015b; Makhmutov et al., 2013; hidden GLE?
3	27 Jan 2012	796	N27W71	X1.7	2508	Belov et al., 2015a, 2015b; http://gle.oulu.fi: sub-GLE
4	07 Mar 2012	6530	N17E15	X5.4	1825	Belov et al., 2015a, 2015b; http://gle.oulu.fi: sub-GLE
5	13 Mar 2012	469	N18W62	M7.9	1884	Belov et al., 2015a, 2015b; hidden GLE?
6	17 May 2012 rather weak GLE	255	N12W83	M5.1	1582	GLE071: 4 polar NMs, maximum ≈16% in 5-min data; Li et al., 2013
7	22 May 2012	1660	N15W70	M5.0	1466	Li, Miroshnichenko, and Fang, 2015; hidden GLE?
8	23 Jul 2012	5000	Back-sided	Back-sided	Partial halo	Gopalswamy et al., 2016: sub-GLE?
9	19 Nov 2013	No data	S70W14	–	–	Makhmutov et al., 2015; hidden GLE?
10	06 Jan 2014. Observed by several NMs (South Pole, Barentsburg, Tixie, McMurdo and others)	42 Miroshnichenko and Yanke, 2016: $I_{max}(\geq 1.0$ GV)= 1.11×10^{-4}, pfu	S18W102	N.O.	2095	Thakur et al., 2014; Balabin et al., 2015; Li, Miroshnichenko, and Sdobnov, 2016; http://gle.oulu.fi: sub-GLE
11	09 Jan 2014 Standard SPE	1033	S15W11	X1.2	No data	NOAA, 2020: standard SPE, GOES15
12	07 Jun 2015 http://gle.oulu.fi: Observed by several polar NMs; Gil et al., 2018: Local anisotropy of the Forbush decrease?	No data	No data	No data	No data	Pérez-Peraza and Juárez-Zuñiga, 2015: predicted GLE? Gil et al., 2018: Specific sub-GLE

Table 1: Continuation

13	22 Jun 2015, Gil et al., 2018: Local anisotropy of the Forbush decrease?	1070	N13W00	M2.0	Full halo	This work: Acceleration in IMF, hidden GLE?
14	29 Oct 2015: Observed by two NMs (South Pole and Dome C) (e.g. Mishev, Poluianov, and Usoskin, 2017)	23	Far-sided on the W limb S11/29 Oct 02:36	Far-sided on the W limb S11/29 Oct 02:36	N.O.	Pérez-Peraza and Juárez-Zuñiga, 2015: Predicted GLE? http://gle.oulu.fi: sub-GLE
15	10 Sep 2017: Rather small GLE (e.g. Struminsky, 2019), contradictory results	1490	S08W83	X8 (8.9?)	Asymmetric full halo/10 Sep. 16:00 UT	GLE72 GLE: Maximum 6% in 5-min NM data e.g. Kurt et al., 2018

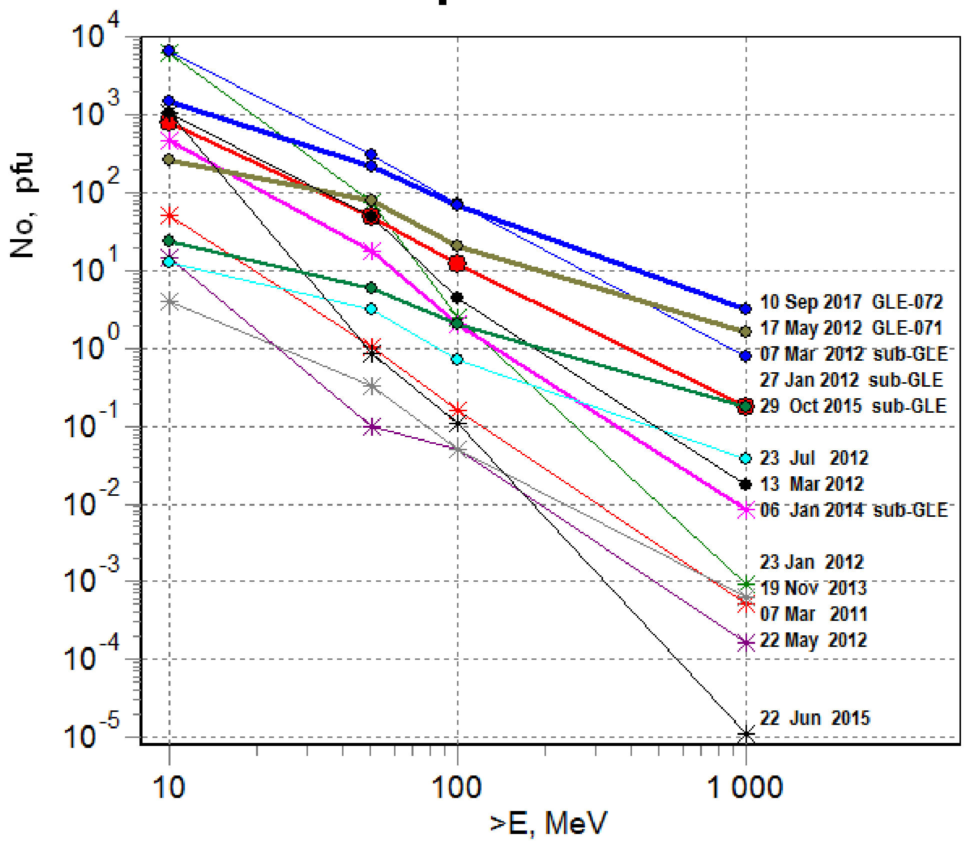
Method of event selection

- Choice of the base period for the analysis of the solar proton event of 27-28 January 2012 (bold horizontal line and/or points).



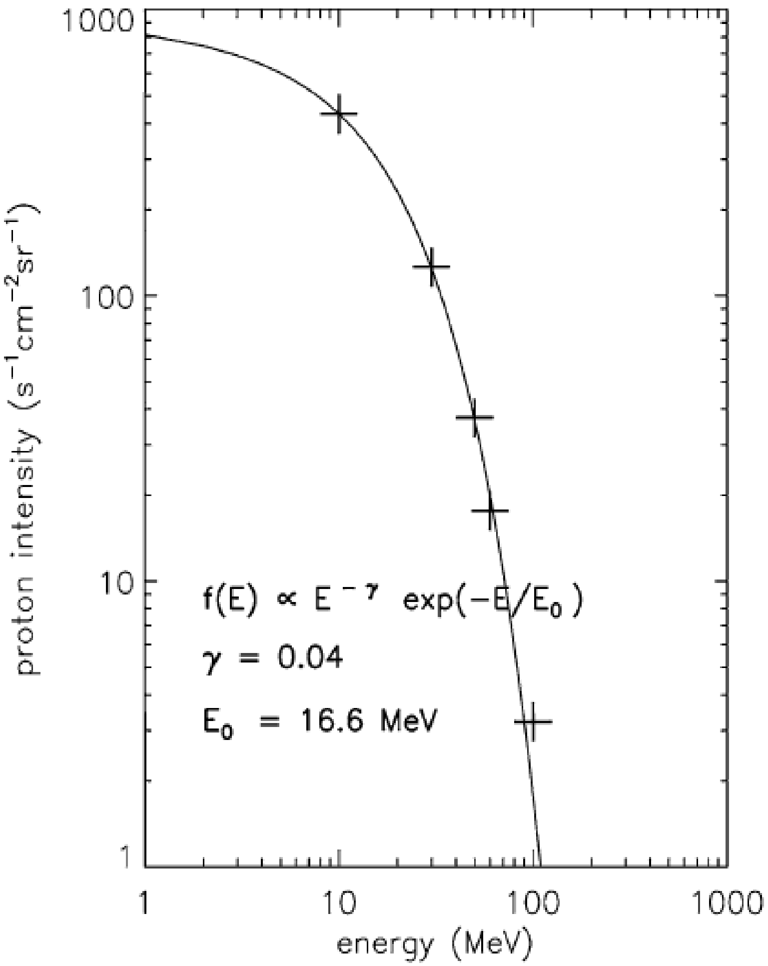
Integral energy spectra

- Integral energy spectra constructed for the events of Table 1 in a power-law form.



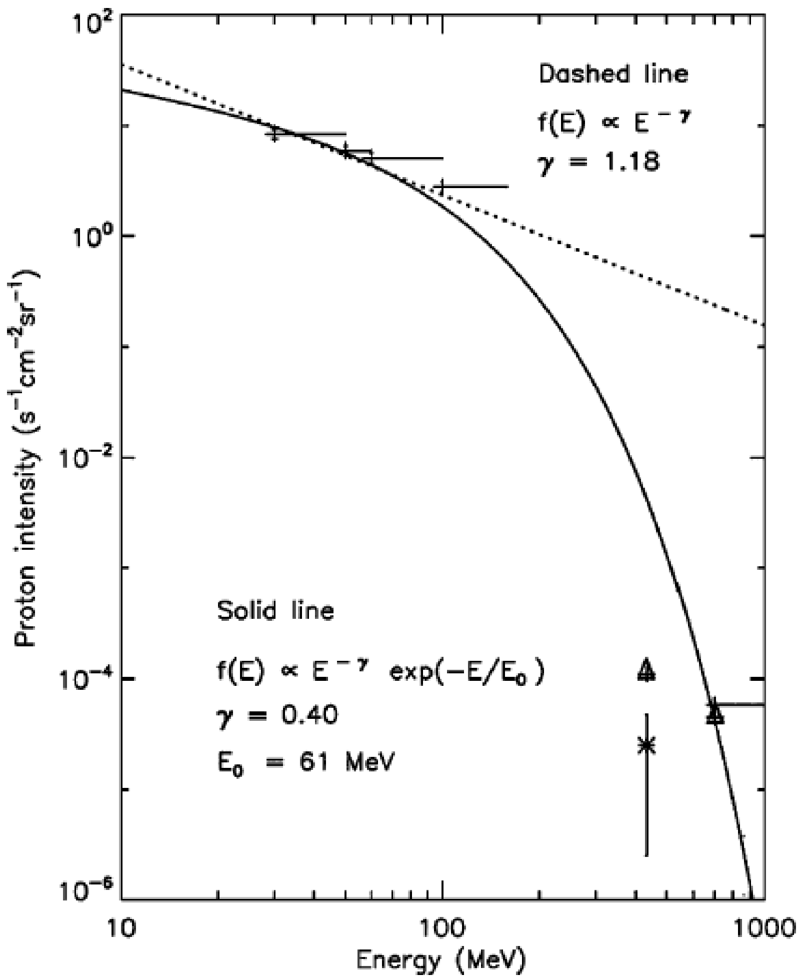
Spectrum of standard SPE of 9 January 2014

Figure 3 Integrated TOM spectrum in the approximation represented by Equation 1 for the standard SPE of 9 January 2014, obtained from measurements onboard the GOES15 spacecraft.

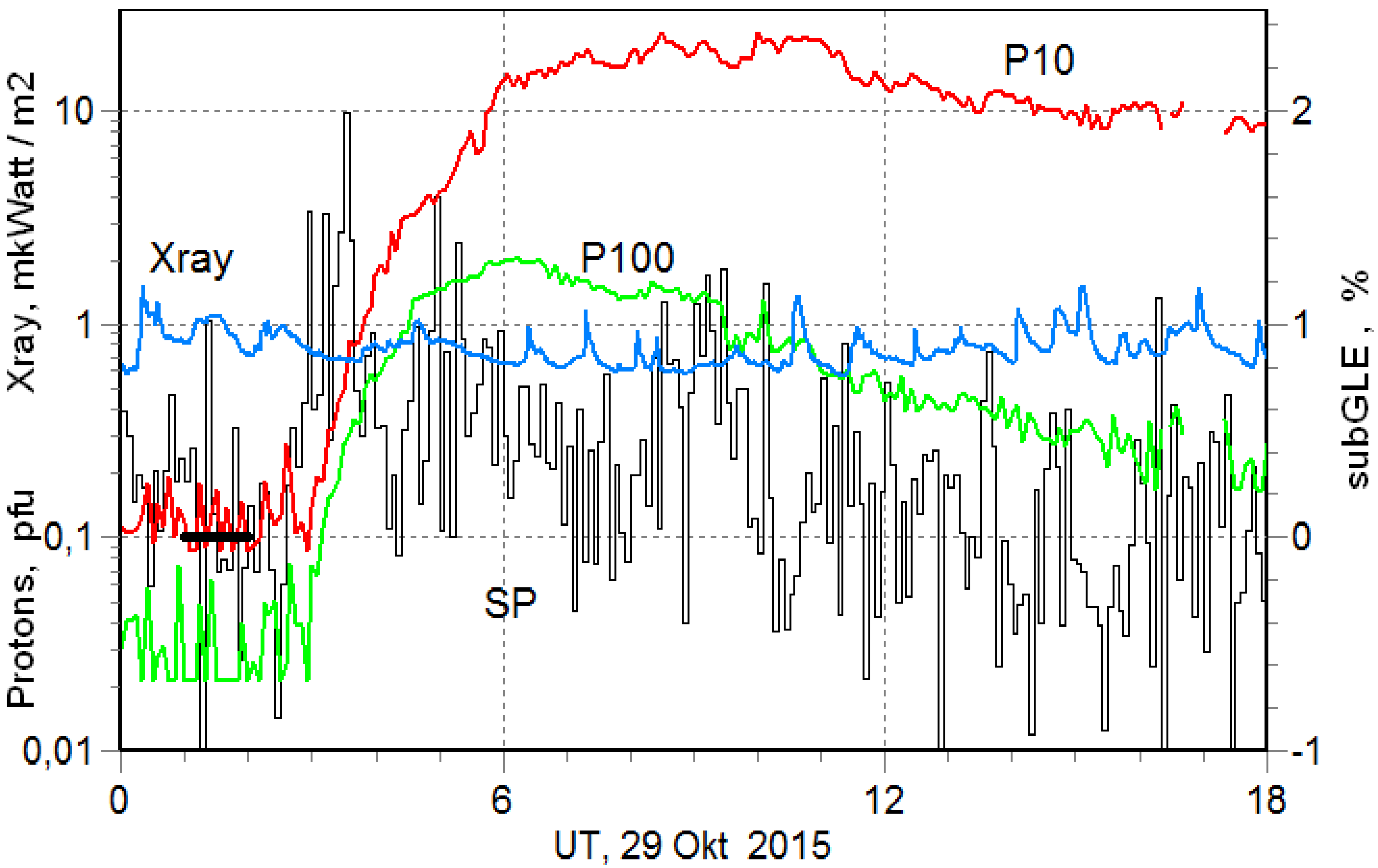


Spectrum of sub-GLE on 6 January 2014

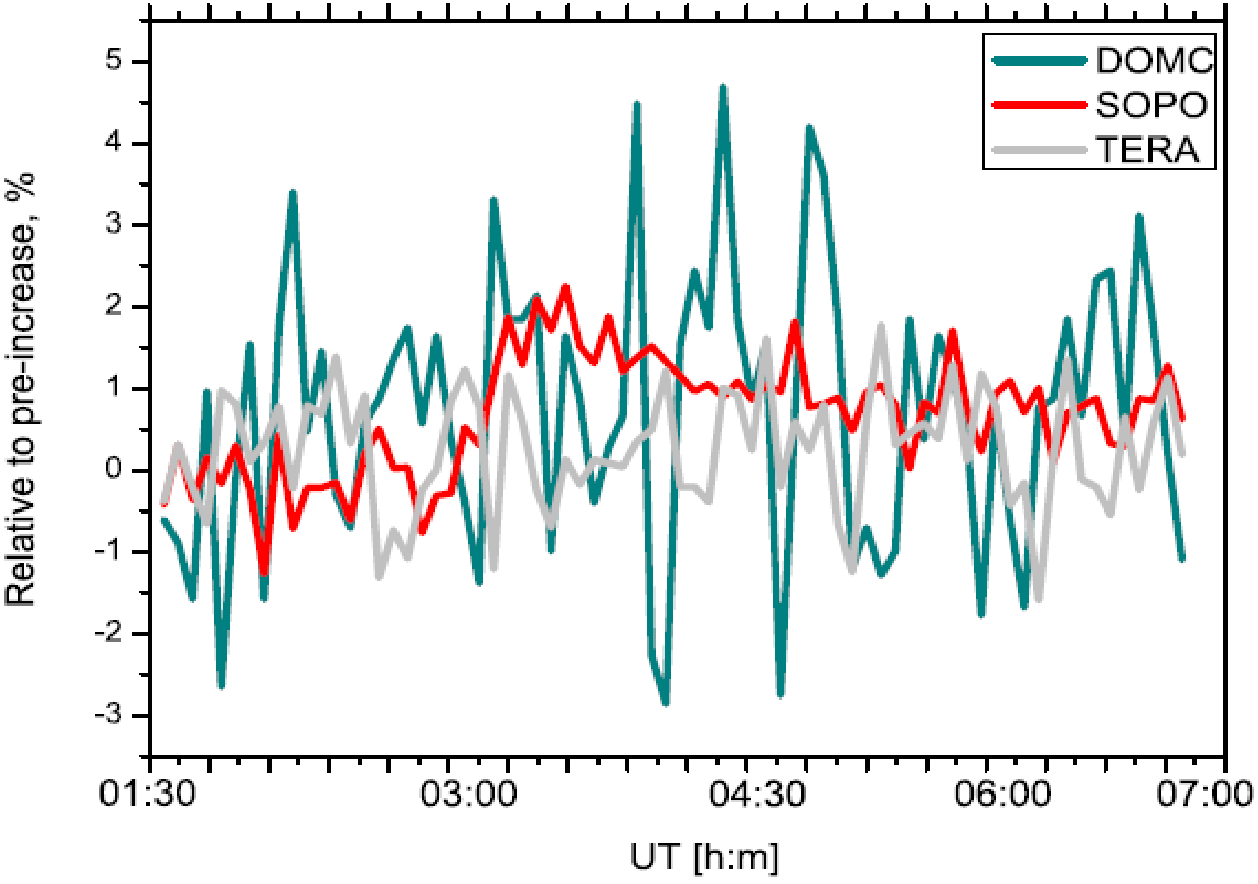
Figure 4 Integrated TOM spectrum obtained from instruments onboard GOES13 spacecraft (top left) and estimates (Li, Miroshnichenko, and Sdobnov, 2016) from NM observations (bottom right) for the sub-GLE of 6 January 2014. The asterisk indicates the proton intensity $I(> 433\ \text{MeV})$ estimated by the method of integral multiplicities (Ilenĉik, Dubinsky, and Miroshnichenko (1978a, 1978b), triangles denote estimates by the method of spectrographic global survey (Li, Miroshnichenko, and Sdobnov, 2016) for the integrated proton intensities $I(> 433\ \text{MeV})$ and $I(> 700\ \text{MeV})$. The solid curve is our approximation of the spectrum using Equation 1. Reproduced from Li, Miroshnichenko, and Sdobnov (2016).



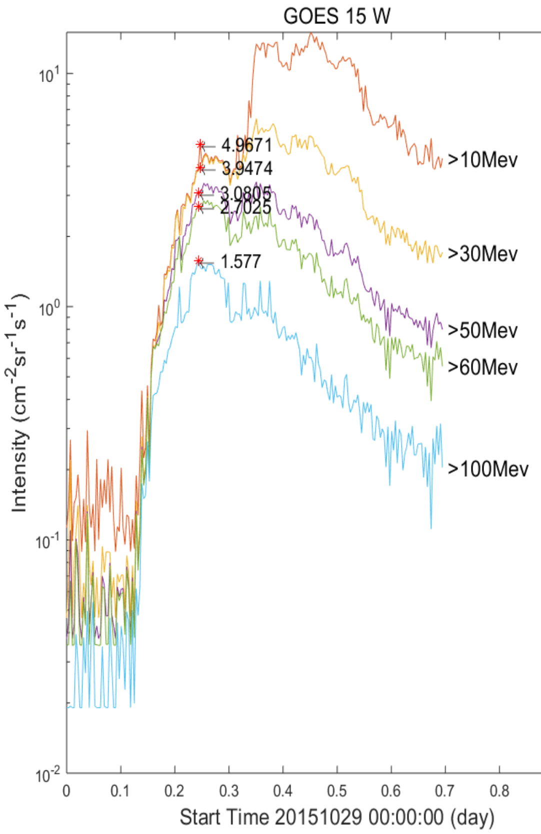
Sub-GLE of 29 Octoder 2015

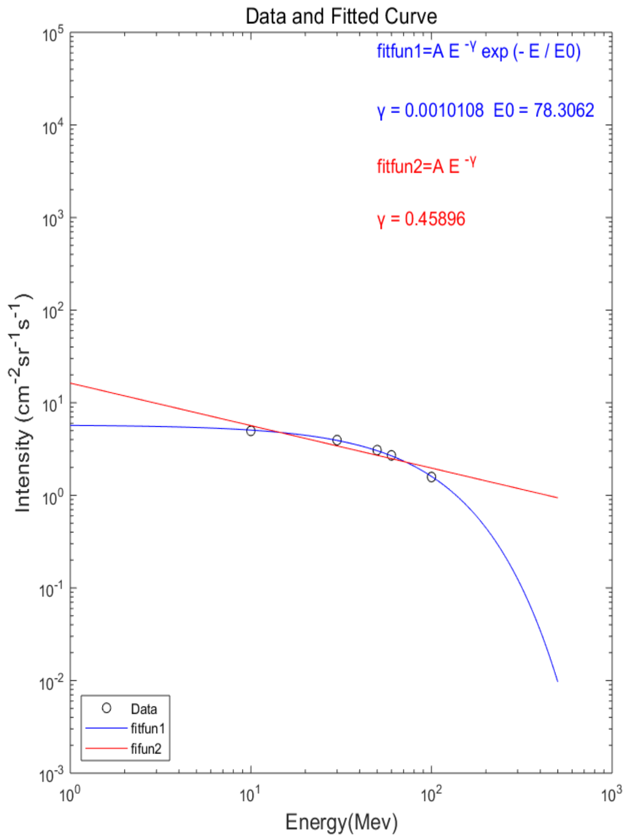


Data of Antarctic NMs



Data of GOES 15 and our spectrum approximation





Instead of conclusions…

- Based on SCR data for the solar cycle 24, the authors tried to give a systematic presentation of the problem of weak GLEs and/or sub-GLEs from both the observational and theoretical points of view. We understand that the problem is at the very beginning of real study. Nevertheless, in our opinion, our results may help to make clearer several important issues, as follows:
- 1. List of weak GLEs of solar cycle (Table 1) includes five really observed sub-GLEs and several “suspected hidden GLEs” that deserve to be investigated more thoroughly. Mildly relativistic particles of solar origin.
- 2. Three SW models of SEP acceleration considered above are not suitable to physically and unambiguously explain some features of observed SCR spectra, *e.g.*, the existence of so-called spectral “bump” in the range of 4-80 MeV (for protons). New observational (direct and indirect) data in the range of several hundred MeV are necessary, in particular, ground-based observations at high-altitude polar NM stations.
- 3. Our results and the facts discovered by Zimovets and Struminsky (2009) underline once more the need to create space-based solar proton and electron detectors with a low level of intrinsic background. Such detectors are necessary for measuring low-intensity SCR fluxes (the “hidden GLEs” problem).

Thank you!

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