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Proton activity of the Sun in current solar cycle 24 *

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Abstract We present a study of seven large solar proton events in the current solar cycle 24 (from 2009 January up to the current date). They were recorded by the *GOES* spacecraft with the highest proton fluxes being over 200 pfu for energies >10 MeV. In situ particle measurements show that: (1) The profiles of the proton fluxes are highly dependent on the locations of their solar sources, namely flares or coronal mass ejections (CMEs), which confirms the “heliolongitude rules” associated with solar energetic particle fluxes; (2) The solar particle release (SPR) times fall in the decay phase of the flare emission, and are in accordance with the times when the CMEs travel to an average height of 7.9 solar radii; and (3) The time differences between the SPR and the flare peak are also dependent on the locations of the solar active regions. The results tend to support the scenario of proton acceleration by the CME-driven shock, even though there exists a possibility of particle acceleration at the flare site, with subsequent perpendicular diffusion of accelerated particles in the interplanetary magnetic field. We derive the integral time-of-maximum spectra of solar protons in two forms: a single power-law distribution and a power law roll-over with an exponential tail. It is found that the unique ground level enhancement that occurred in the event on 2012 May 17 displays the hardest spectrum and the largest roll-over energy which may explain why this event could extend to relativistic energies.

Key words: acceleration of particles — Sun: flares — Sun: coronal mass ejections

1 INTRODUCTION

Solar energetic particles (SEPs), with energies from a few keV to ≥10 GeV, are produced by the rapid release of magnetic energy during solar eruptions. In these events, solar protons are one of the significant components of interplanetary particle streams that determine important properties of space weather. At the Earth’s orbit these protons are registered as a solar proton event (SPE). Usually,

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detections of an SPE are defined as a flux of $\geq$10 MeV protons greater than 1 pfu, or particle flux unit (1 pfu = 1 $\mathrm{particle\ cm^{-2}\ s^{-1}\ sr^{-1}}$). This is the threshold for proton energy intensity that is applied in research work (e.g., Miroshnichenko 2003, and references therein). For some practical reasons in the past (see the discussion in Miroshnichenko 2003), the NOAA Space Environment Service Center (NOAA SESC) suggested using an intensity of 10 pfu for $\geq$10 MeV protons as a reliable signature of an SPE. In our study of the most intensive SPEs of solar cycle 24 we use the NOAA SESC criterion. According to the survey of NOAA SESC, a total number of 258 SPEs were recorded by the series of satellites that were part of the Geostationary Operational Environment Satellite (*GOES*) program from 1976 January up to the current date (*http://umbra.nascom.nasa.gov/SEP/*).

SPEs are always associated with flares and coronal mass ejections (CMEs) concomitantly, and both of them are theoretically capable of accelerating charged particles to high energies (Ellison & Ramaty 1985; Litvinenko 1996; Somov & Kosugi 1997; Zank et al. 2000). Whether SPEs originate from flaring active regions (ARs) in the solar corona or from CME-driven shocks propagating through the corona to interplanetary space remains controversial (Aschwanden 2012; Gopalswamy et al. 2012; Li et al. 2012; Miroshnichenko et al. 2013; Reames 2013; Miroshnichenko 2015). The extension of SPEs to relativistic energy, which can generate sufficient secondary particles that are registered by ground-based neutron monitors (NMs), is the so-called ground level enhancement (GLE) of solar cosmic rays (SCRs). The first GLE event was evidently observed on 1942 February 28 (Forbush 1946). Since then 71 GLE events have been recorded by the worldwide network of cosmic ray stations in the last seven solar cycles (Miroshnichenko 2015). Understanding where and how particles are accelerated to high energies in SPEs, especially in GLE events, is still one of the main topics in solar physics.

The intensities of non-relativistic particles resulting in GLE events are generally larger than those of normal ones, and the associated flares and CMEs are generally stronger and faster (Kahler et al. 2012; Mewaldt et al. 2012; Shea & Smart 2012). This is, however, not the case for the recent GLE 71 that occurred on 2012 May 17 (see references Gopalswamy et al. 2013; Li et al. 2013; Papaioannou et al. 2014; Plainaki et al. 2014). In particular, among the seven most intensive SPEs in this study, GLE 71 shows the lowest proton peak flux of 255 pfu at an energy threshold of $\geq$10 MeV, and it was associated with a relatively weak flare (M5.1 class) and slow CME (1582 km $\mathrm{s^{-1}}$). With this inspiring insight, we concentrate below on the key aspects that motivate this study: (1) general weakness of activity in the current cycle; (2) how the highest *GOES* energy channel ($\sim$433 MeV) being near the limit of the cutoff energy (or the cutoff rigidity of 1 GV) affects detections of polar NMs; (3) possible registration of hidden, poorly-identified GLEs by polar NMs. In this context, we try to interpret the observational and physical differences between the unique case of GLE 71 and the other SPEs that have occurred in the current solar cycle up to now.

Section 2 describes in detail proton observations and data analysis, including fluxes, timing and spectra. Summary and discussion are given in Section 3.

2 OBSERVATIONS AND DATA ANALYSIS

A common consensus has been reached that the current solar cycle 24 is still in a very low level of activity. In particular, from 2009 January up to the current date, only seven large SPEs have occurred with proton peak fluxes over 200 pfu at energies $>$10 MeV, compared to 20 similar intensive SPEs during the same period in the previous solar cycle 23. The GLE event on 2012 May 17 is the first and thus far only GLE event of solar cycle 24. In the last solar cycle 23 and during the same period, nine GLE events were recorded. Table 1 lists the seven most intensive SPEs of the current solar cycle 24.

2.1 Proton Fluxes

The in situ proton measurements are obtained from the *GOES* 13 spacecraft, which is in geostationary orbit above the Pacific Ocean at $L = 6.6$ where the geomagnetic effects are minor for protons

Table 1 Large SPEs of Solar Cycle 24

Event No.	Date of Event	I (>10 MeV) (pfu)	GLE	Source Location	Flare class	CME Speed (km s^{-1})	SPR (UT)	Flare peak (UT)	CME height (R_s)	Spectral index	Energy (MeV)
1	2012 January 23	6310	N	N28W36	M8.7	2175	04:14	03:59	6.59	2.19	12.5
2	2012 January 27	796	N	N27W71	X1.7	2508	18:39	18:36	7.02	1.85	17.5
3	2012 March 7	6530	N	N17E15	X5.4	1825	02:29	00:24	14.3	1.25	35.7
4	2012 March 13	469	N	N18W62	M7.9	1884	17:39	17:40	4.71	1.39	19.5
5	**2012 May 17**	**255**	**Y**	**N12W83**	**M5.1**	**1582**	**01:49**	**01:47**	**3.07**	**1.05**	**47.8**
6	2013 May 22	1660	N	N15W70	M5.0	1466	13:44	13:32	6.91	1.36	35.0
7	2014 January 7	1033	N	S15W11	X1.2	2095	19:29	18:31	12.7	1.70	16.6

Notes: Bold text indicates the parameters of GLE 71. The spectral index is derived from a single power-law distribution, and the roll-over energy is from the power law roll over with an exponential tail.

≥10 MeV. *GOES* 13 has a differential channel, No. 10, that is part of the High Energy Proton and Alpha Detector (HEPAD) detector that can detect protons with an energy between 420–510 MeV. In combination with a number of other channels, we can estimate integral flux for the mean energy of about 433 MeV (see the description of HEPAD[1]).

We examine the time-intensity profiles of the seven SPEs at the energy bands of >10, >30, >50, >60 and >100 MeV. The numbers and dates of the events under study are the following: (1) 2012 January 23; (2) 2012 January 27; (3) 2012 March 7; (4) 2012 March 13; (5) 2012 May 17; (6) 2013 May 22; and (7) 2014 January 7. As shown in Figure 1, the spiral pattern of the interplanetary magnetic field (IMF) gives rise to the longitude-dependent solar proton profiles. This process can be interpreted as proton acceleration by an expanding shock in the IMF (Cane et al. 1988; Reames et al. 1996; Reames 1999). Assuming the strongest acceleration occurs near the central nose of the shock and it is weakest at the flank, an observer on the Earth should see an initial prompt increase when a solar eruption occurs near the well-connected region (∼W60) and a gradual increase in the far eastern side.

The initial time-intensity profiles of the seven SPEs can be divided into three groups: (1) gradual increase in a solar source that is located in the eastern hemisphere of region A (event 3, E15), (2) quick increases in a solar source located not far from the meridian of region B (event 1, W36 and event 7, W11), and (3) very impulsive increases in a solar eruption that occurs near the well-connected region C (event 2, W71, event 4, W62, event 5, W83, and event 6, W70). It can be noticed that the time ranges for the profiles of the seven SPEs shown in Figure 1 are the same for 18 hours, which makes the comparison of the increased tendencies reasonable.

On the whole, the plots in Figure 1 confirm that the SPEs of the 24th cycle obey the same "heliolongitude rules" as in the previous cycles (Cane et al. 1988; Reames et al. 1996); for details also see Reames (1999). The results seem to support the scenario that particles are accelerated by an expanding CME-driven shock. However, we cannot rule out the possibility of particle acceleration at the flare site with subsequent perpendicular diffusion or cross-field propagation in interplanetary space (Qin et al. 2011; Giacalone & Jokipii 2012; Wiedenbeck et al. 2013).

2.2 Event Timing

Estimates of solar particle release (SPR) times, with respect to the multi-wavelength observations of solar eruptions, provide a critical method for determining the mechanism causing particle acceleration. We first estimate the SPR times of solar protons by subtracting $\Delta t = l/v - 8.3$ min from the in situ onset times, where l is the path length of IMF lines deduced from the solar wind model (Parker 1958, 1963), and the velocity of solar protons, v, is taken to be $\sim 0.7c$ corresponding to the highest

[1] *http://goes.gsfc.nasa.gov/text/databook/section05.pdf*

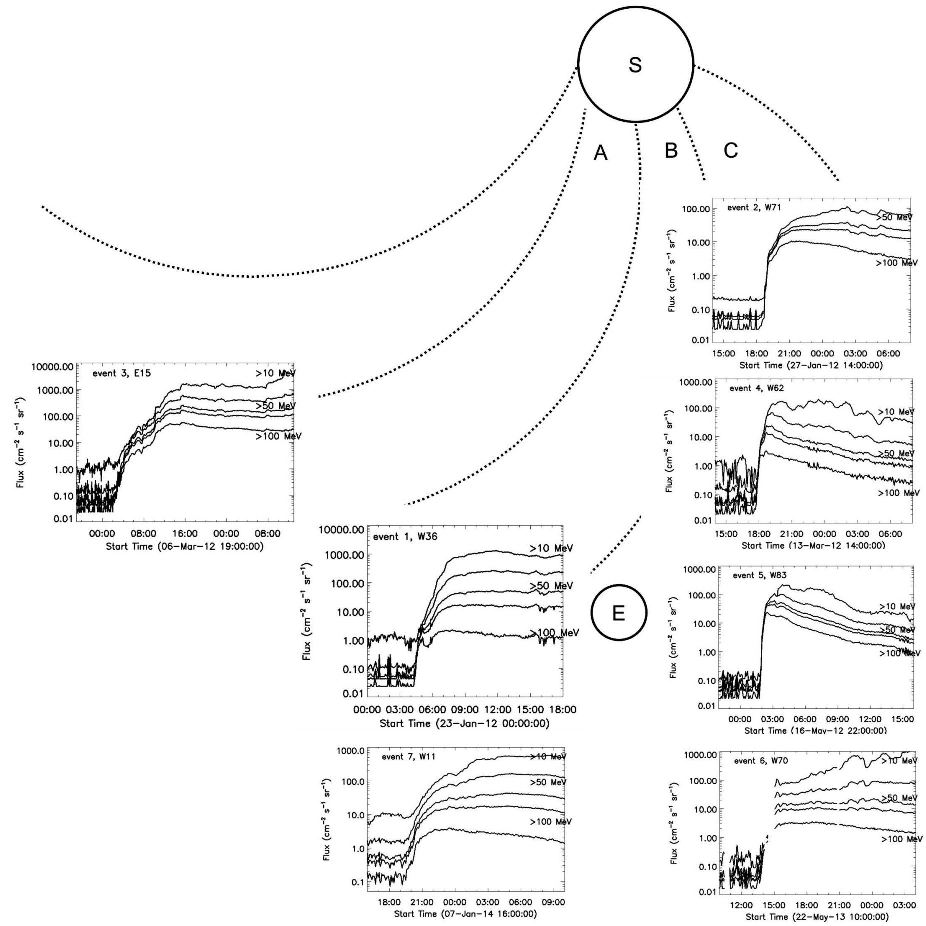

Fig. 1 Time-intensity profiles of the seven SPEs observed by the *GOES* spacecraft near the Earth. The longitude-dependent profiles are grouped into three types according to the locations of solar sources.

energy channel of 433 MeV for *GOES*. We then compare the SPR times to the flare soft X-ray (SXR) or hard X-ray (HXR) emission and the CME white-light observation.

Figure 2 displays the intensity-time profiles of the flare SXR fluxes detected by *GOES* in the soft range of 1–8 Å (red curves), for all seven SPEs. The profiles of SXR fluxes are shifted and combined with the peak emission time of each flare (vertical red line). The time derivatives of SXR fluxes (blue curves) are generally considered to be a good proxy of the non-thermal HXR fluxes (Neupert 1968). The proton SPR times are indicated by the vertical dashed lines with an error estimate of 5 min. It is clear that the SPR times fall into the decay phase of the flare's SXR emission, except for event 4 where the SPR time coincides with the SXR peak emission. All the SPR times of the seven SPEs are tens of minutes later than the peak times of HXR fluxes.

Another interesting phenomenon is the following: the farther the solar source is away from the well-connected region, the larger the time delay is between the flare SXR peak and the SPR time. For instance, the time delay of event 3 which has its solar source at E15 is 125 min. Also, for event 7 which has its solar source at W11, the time delay is 58 min. A time delay was not observed for

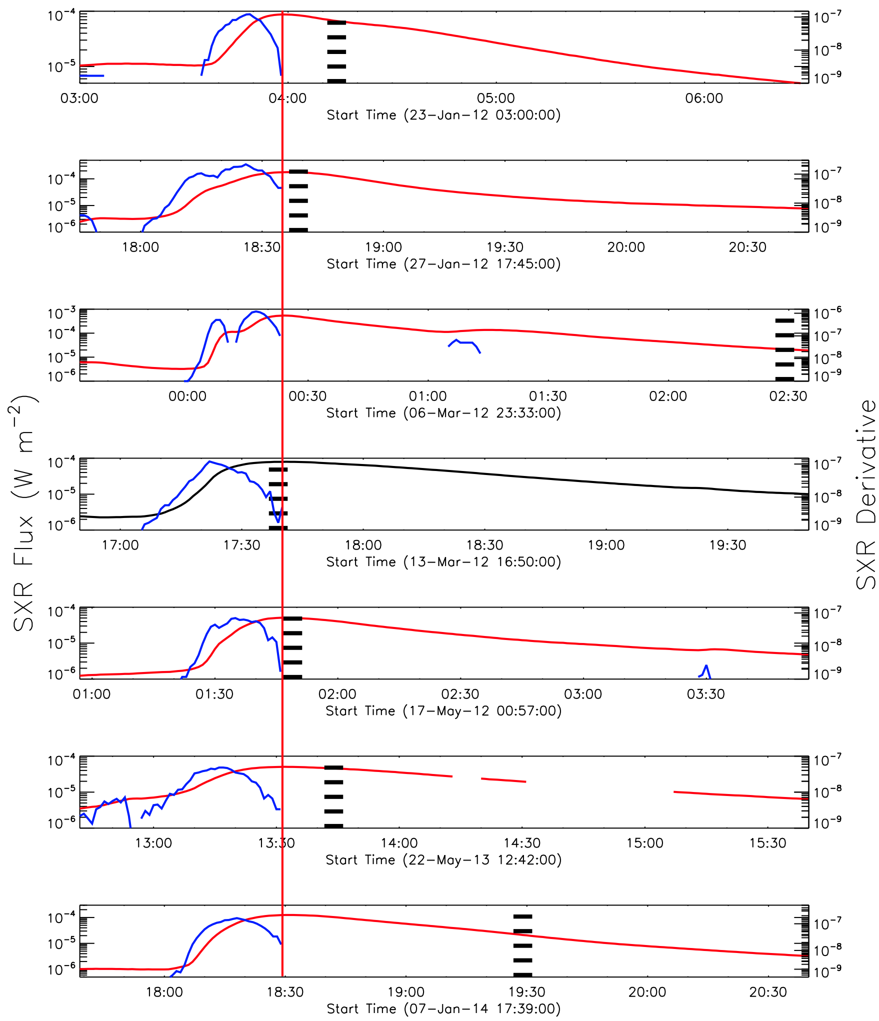

Fig. 2 Temporal profiles of the seven SPEs, in which the *GOES* 1 – 8 Å SXR fluxes are indicated with the red curves, their derivatives are indicated with blue curves, and the proton SPR times are indicated by the black dashed lines.

event 4 which had the solar source at W62 (the well-connected region). The results seem to favor a phenomenon that can be described such that the time delay is due to the connection of IMF lines with the expanding CME-driven shock. However, again we cannot exclude the possibility that the time delay is due to the cross-field propagation of accelerated particles from the flare site.

Under the assumption of proton acceleration by the CME-driven shock, we estimate the acceleration height derived from a linear fit of the CME speed. For event 3 and event 7, the acceleration heights are 14.3 and 12.7 solar radii ($R_{\rm s}$) respectively, which are much larger than the other SPEs due to the poor connection with their source regions. The average acceleration height of the seven SPEs is 7.90 $R_{\rm s}$. It can be noticed that the acceleration height of GLE 71 is 3.07 $R_{\rm s}$ (Li et al. 2013), which is consistent with the results of Gopalswamy et al. (2012) and lower than the other SPEs. This suggests that the acceleration of relativistic particles occurs at a lower coronal site.

2.3 Proton Spectra

The energy spectrum of SEPs is generally considered as an indicator of their acceleration sources and/or mechanisms. Here we apply the method of integral time-of-maximum (TOM) spectrum, which is a proxy of their source spectrum (Forman et al. 1986; Miroshnichenko 1996; Dietrich & Tylka 2003; Miroshnichenko & Perez-Peraza 2008). Here the proton spectra are fitted in two forms: a single power-law distribution $f(E) = AE^{-\gamma}$ and a power law roll-over with an exponential high-energy tail $f(E) = AE^{-\gamma}\exp(-E/E_0)$. The latter form was first obtained by Ellison & Ramaty (1985) to explain the particle acceleration by a diffusive shock. More recently, a test-particle simulation by Liu et al. (2009), with self-consistent MHD electric and magnetic fields, indicated that charged particles accelerated by the direct current (DC) electric field in the magnetic reconnection region also generate a spectrum with the latter form.

Figure 3 shows the integral TOM spectra of two SPEs on 2012 January 23 and 2012 May 17 (GLE 71), respectively. For the power-law distribution, the spectral index is 2.19 for the 2012 January 23 event, which is much softer than that for the 2012 May 17 GLE event ($\sim$1.05). For the distribution of power law with an exponential tail, the roll-over energy of the 2012 January 23 event is 12.5 MeV, which is much smaller than that of the 2012 May 17 GLE event with a roll over energy of 47.8 MeV. The spectral index and roll over energy of the seven SPEs are listed below in Table 1. It is clear that, even though GLE 71 displays the lowest proton peak flux of 255 pfu at an energy threshold $>$10 MeV, it demonstrates, however, the hardest power law spectrum, and the roll-over energy represented by the exponential high-energy tail is larger than in the other SPEs. This explains why GLE 71 is unique in that it can extend to relativistic energies.

Of special interest is that a recent SPE on 2014 January 6 (one day before event 7) was recorded with measurements that were taken at some ground-based cosmic ray stations, for example, at two NMs at the South Pole (SOPO and SOPB). According to data from the Neutron Monitor Database

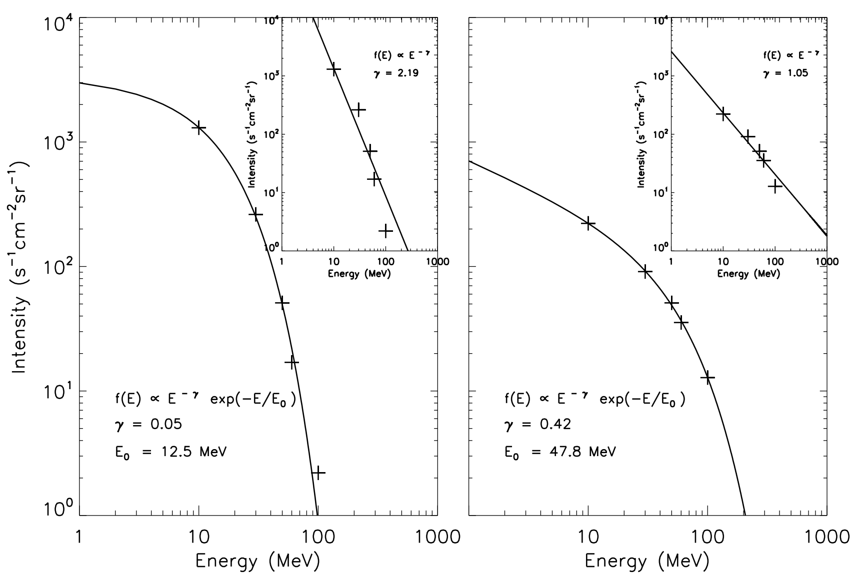

Fig. 3 Integral TOM spectra of two SPEs on 2012 January 23 and 2012 May 17 (GLE 71), respectively. The integral proton fluxes are obtained from *GOES* 13 at the energy bands of $>$10, $>$30, $>$50, $>$60 and $>$100 MeV.

(NMDB, *http://www.nmdb.eu*), the peak flux of the SPE was only 40 pfu at an energy threshold $>$10 MeV. We have also derived the integral TOM spectrum of the SPE or the "hidden GLE 72." The spectral index is 0.33 for the power law distribution, and the roll over energy is 103.6 MeV for the exponential high-energy tail. Therefore, the "hidden GLE72" might have some relativistic particles that were detected by cosmic ray detectors located near the poles.

3 SUMMARY AND DISCUSSION

We have investigated the seven most intensive SPEs of the current solar cycle 24 up to date, including the unique case of GLE 71 on 2012 May 17. Table 1 lists a summary of the SPEs and the associated flares and CMEs. The in situ proton measurements and remote sensing solar observations lead to the following results:

(1) It was confirmed that in the current solar cycle the initial intensity-time-profiles are highly dependent on the locations of solar sources (i.e., they obey the same "heliolongitude rules"), with gradual increases from active regions located in the eastern hemisphere and very impulsive increases from sources in the well connected regions.
(2) The SPR times are in the decay phase of the flare emission, and the time delays between the SPRs and SXR peaks are also dependent on the locations of solar sources.
(3) The proton acceleration occurs when the CME travels to 3–15 $R_{\rm s}$ with an average height of 7.9 $R_{\rm s}$. The acceleration height of GLE 71 is 3.07 $R_{\rm s}$, suggesting relativistic particles are accelerated in a relatively lower coronal site.
(4) Compared to the other SPEs, GLE 71 displays the hardest power law spectrum and the largest energy for the exponential high-energy tail. This explains why processes associated with this unique GLE event can extend to relativistic energies.

In this context, it should be noted that according to a theoretical model by Zank et al. (2000), rather high energies may be reached at the early stages of shock evolution. In particular, energies of the order of 1 GeV are possible for young shock waves. On the other hand, as was convincingly shown by Berezhko & Taneev (2003), with heliocentric distance r, the efficiency of acceleration by the spherical shock wave decreases rather rapidly, and it causes the effective SCR acceleration to terminate when the shock reaches a distance of 2–3 $R_{\rm s}$. As a result, SCR particles intensively escape from the vicinities of the shock. Our estimate of the acceleration height for GLE 71 (3.07 $R_{\rm s}$), evidently does not contradict calculations by Berezhko & Taneev (2003).

Even though the observational results appear to support the scenario of proton acceleration by the CME-driven shock, we cannot exclude the possibility of particle acceleration at a flare site with subsequent perpendicular diffusion or cross-field propagation in the IMF, as mentioned before. On the other hand, as demonstrated by Aschwanden (2012), extended acceleration in the flare site is possible and can be diagnosed by prolonged HXR and gamma-ray emission in many GLE events. It was also noted that the coincidence of the SPR time with the impulsive flare phase takes place in only 50$\%$ of the GLE cases. Therefore, the time delay between the SPR time and flare peak emission obtained for some of the seven most intensive SPEs of cycle 24 (with an error estimate of 5 min, see Fig. 2) can be supposedly explained by extended particle acceleration and/or trapping.

Furthermore, stochastic acceleration in the flare source is another potential mechanism of SEPs, especially for GLE events. The theoretical expression of the stochastic spectra was obtained by Callegos-Cruz & Perez-Peraza (1995), and this analytical expression was then successfully applied to model the spectra of GLE protons (Pérez-Peraza et al. 2006, 2008; Bombardieri et al. 2006, 2008). For example, the delayed or gradual component of GLE 59 (2000 July 14 event) was better fitted by the stochastic process rather than the shock acceleration (Bombardieri et al. 2008).

Another fact that comes from this study is that strong flares and fast CMEs in solar cycle 24 are not necessary requisites for a GLE event or relativistic particles, and a large flux of non-relativistic

SEPs is not a reliable signature of the presence of GLEs or relativistic particles. This issue was also noticed in some earlier works (for reviews see, e.g., Miroshnichenko et al. 2013; Miroshnichenko 2015, and references therein). Particles can be accelerated to relativistic ranges under certain conditions, coronal magnetic topologies, electric fields in the reconnection regions, plasma parameters in the solar corona, compression ratios and geometries of shocks, etc.

It is timely to mention here a preliminary result of the analysis of measurements from the CARPET cosmic ray detector (that was established in the Andes mountains of Argentina) on 2011 March 7 and 2012 January 23 (Makhmutov et al. 2013). These authors conclude: (1) statistically significant increases were detected during 20:10–21:30 UT on 2011 March 7 and during 03:30–08:00 UT on 2012 January 23; (2) these increases are indications of the long-lasting presence of high-energy solar protons (>9 GeV). Independent results of the analysis of the characteristics of VLF propagation and riometer records during these events support this conclusion. They note that a more careful analysis of the NMDB records is needed in order to get a final conclusion on the presence or not of solar flare effects in the form of GLEs during these events. Our analysis supports these conclusions and reflects the necessity to measure low-intensity fluxes of SCRs (see also Miroshnichenko et al. 2013).

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References

Aschwanden, M. J. 2012, Space Sci. Rev., 171, 3
Berezhko, E. G., & Taneev, S. N. 2003, Astronomy Letters, 29, 530
Bombardieri, D. J., Duldig, M. L., Michael, K. J., & Humble, J. E. 2006, ApJ, 644, 565
Bombardieri, D. J., Duldig, M. L., Humble, J. E., & Michael, K. J. 2008, ApJ, 682, 1315
Callegos-Cruz, A., & Perez-Peraza, J. 1995, ApJ, 446, 400
Cane, H. V., Reames, D. V., & von Rosenvinge, T. T. 1988, J. Geophys. Res., 93, 9555
Dietrich, W. F., & Tylka, A. J. 2003, in Proc. 28th International Cosmic Ray Conference (Tsukuba), 6, 3291
Ellison, D. C., & Ramaty, R. 1985, ApJ, 298, 400
Forbush, S. E. 1946, Physical Review, 70, 771
Forman, M. A., Ramaty, R., & Zweibel, E. G. 1986, in Physics of the Sun. Volume 2, ed. P. A. Sturrock, T. E. Holzer, D. M. Mihalas, & R. K. Ulrich, Vol. 2, 249
Giacalone, J., & Jokipii, J. R. 2012, ApJ, 751, L33
Gopalswamy, N., Xie, H., Yashiro, S., et al. 2012, Space Sci. Rev., 171, 23
Gopalswamy, N., Xie, H., Akiyama, S., et al. 2013, ApJ, 765, L30
Kahler, S. W., Cliver, E. W., Tylka, A. J., & Dietrich, W. F. 2012, Space Sci. Rev., 171, 121
Li, G., Moore, R., Mewaldt, R. A., Zhao, L., & Labrador, A. W. 2012, Space Sci. Rev., 171, 141
Li, C., Firoz, K. A., Sun, L. P., & Miroshnichenko, L. I. 2013, ApJ, 770, 34
Litvinenko, Y. E. 1996, ApJ, 462, 997
Liu, W. J., Chen, P. F., Ding, M. D., & Fang, C. 2009, ApJ, 690, 1633
Makhmutov, V., Raulin, J.-P., De Mendonca, R. R. S., et al. 2013, Journal of Physics Conference Series, 409, 012185
Mewaldt, R. A., Looper, M. D., Cohen, C. M. S., et al. 2012, Space Sci. Rev., 171, 97
Miroshnichenko, L. I. 1996, Radiation Measurements, 26, 421

Miroshnichenko, L. I. 2003, Radiation Hazard in Space, Astrophysics and Space Science Library, 297 (Dordrecht: Kluwer Academic Publishers)

Miroshnichenko, L. I. 2015, Solar Cosmic Rays: Fundamental and Applications (Springer)

Miroshnichenko, L. I., & Perez-Peraza, J. A. 2008, International Journal of Modern Physics A, 23, 1

Miroshnichenko, L. I., Vashenyuk, E. V., & Pérez-Peraza, J. A. 2013, Geomagnetism and Aeronomy, 53, 541

Neupert, W. M. 1968, ApJ, 153, L59

Papaioannou, A., Souvatzoglou, G., Paschalis, P., Gerontidou, M., & Mavromichalaki, H. 2014, Sol. Phys., 289, 423

Parker, E. N. 1958, ApJ, 128, 664

Parker, E. N. 1963, Interplanetary Dynamical Processes. (New York: Interscience Publishers)

Pérez-Peraza, J., Gallegos-Cruz, A., Vashenyuk, E. V., Balabin, E., & Miroshnichenko, L. I. 2006, Advances in Space Research, 38, 418

Pérez-Peraza, J. A., Vashenyuk, E. V., Gallegos-Cruz, A., Balabin, Y. V., & Miroshnichenko, L. I. 2008, Advances in Space Research, 41, 947

Plainaki, C., Mavromichalaki, H., Laurenza, M., et al. 2014, ApJ, 785, 160

Qin, G., He, H.-Q., & Zhang, M. 2011, ApJ, 738, 28

Reames, D. V. 1999, Space Sci. Rev., 90, 413

Reames, D. V. 2013, Space Sci. Rev., 175, 53

Reames, D. V., Barbier, L. M., & Ng, C. K. 1996, ApJ, 466, 473

Shea, M. A., & Smart, D. F. 2012, Space Sci. Rev., 171, 161

Somov, B. V., & Kosugi, T. 1997, ApJ, 485, 859

Wiedenbeck, M. E., Mason, G. M., Cohen, C. M. S., et al. 2013, ApJ, 762, 54

Zank, G. P., Rice, W. K. M., & Wu, C. C. 2000, J. Geophys. Res., 105, 25079