Solar energetic particle events in 2006-2012 in the PAMELA experiment data

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Abstract. The PAMELA magnetic spectrometer launched in June 2006 has observed the last strong energetic solar particle event of the 23rd solar cycle in December 2006. Subsequent long minimum of solar activity and weak development of the 24th solar cycle led to a deficit in the solar energetic particle events on the Earth orbit. As a result, only few events with protons accelerated above 100 MeV occurred in 2010-2012. The paper gives the preliminary results on energetic solar particles in the beginning of the 24th solar circle as measured with the PAMELA instrument.
1. Introduction
The mechanisms of acceleration of high-energy solar energetic particles (SEP) are not understood sufficiently till now. It is believed that particles are accelerated in powerful explosive processes on the Sun, which could be accompanied by the powerful X-rays, gamma and radio bursts and coronal mass ejections (CME). It is clear that the process of particle acceleration is influenced by several mechanisms, the main of which are the stochastic acceleration, the acceleration at the shock front and acceleration in the electric field arising in the process of reconnection of magnetic lines. The acceleration can occur in the region of a flare, in the solar corona and even in the interplanetary space. Thus, the energy spectrum of SEPs provides valuable information for the study of the Sun and processes in the interplanetary space [e.g., 1-3].

The PAMELA orbital spectrometer [4] is the only instrument capable to observe directly SEPs in the energy range from ~80 MeV/n to several GeV/n. It is important because the fluxes of the GeV SEPs were previously derived from the effects on the ground-based installations and were dependent on response functions. PAMELA was lucky to measure the solar protons and He in the last GLE of the 23th solar cycle on 13 December 2006 [5].

The most long-lasting and the deepest solar minimum of the cycles 23/24 led to absence of SEP events till August 2010. Before May 2012 the GOES Space Environment Monitor [6] detected 11 SEP events with discernible flux of >100 MeV protons, among them 7 events were observed by PAMELA. This paper presents a brief preliminary overview of these results.

2. Solar energetic particle activity in the cycle 24
Figure 1 demonstrates the time history of recent solar activity including decay, minimum, and enhancement in the cycle 24. The monthly averaged and smoothed sunspot numbers [7] shown on the upper panel reveal a long-lasting minimum and beginning of a new cycle which appears to be close to its maximum nowadays. Crosses at the top of the lower panel mark the time of occurrence of the SEP events with >100 MeV protons [6]. Green curve indicates the CME rate as recorded by the CACTUS package [8]. Blue curve is the monthly number of the X ray bursts of M and X classes [9]. It can be seen that the SEP activity started in the cycle 24 at higher level of solar activity than it ended in the previous cycle. From figure 1 it is not possible to prefer CME or flares as a main source of SEPs.

April 2012 is the 40th month of the solar cycle 24. We can compare the number of different SEP events recorded during the first 40 months in several solar cycles (see Table 1). Since the cycles differ in their power we used for the cycle characteristic the accumulated $R_{zacc}$, i.e. a sum of monthly $R_z$ numbers for the first 40 months. GLE stands for SEP events with the GeV particles detected by the ground based installations, $J_{10}>1$ denotes the number of small events with the maximum intensity of >10 MeV protons above 1 cm$^{-2}$s$^{-1}$sr$^{-1}$. The latter are taken for the cycles 21 and 22 from [10], while for the cycles 23 and 24 they are preliminary. Here we can see that the cycle 24 is rather abundant in the low-energy SEP events. The ratio of $J_{10}>1$ events to $R_{zacc}$ is significantly higher in this cycle than in
the previously ones. At the same time there were no GLEs during the first 40 months. It happened only in May 2012.

| Cycle | Start month 40 | $R_{zacc}$ | Number of SEP events |
|-------|----------------|------------|----------------------|
| 21    | 1976.5         | 2844.20    | 6 11 43              |
| 22    | 1986.8         | 3678.95    | 7 25 56              |
| 23    | 1996.4         | 1813.99    | 4 15 22              |
| 24    | 2008.9         | 1113.3     | 0 11 27              |

3. The PAMELA results

PAMELA was launched on 15 June 2006 on board the “Resurs-DK1” satellite on quasi-polar orbit with $70^\circ$ inclination and 350–610 km altitude. The instrument was designed to accurately measure the spectra of charged particles (including light nuclei) in the cosmic radiation, including SEPs, over an energy interval ranging from ~80 MeV to several hundred GeV.

Figure 2. Examples of the energy spectra of protons and He nuclei as observed by PAMELA in the quiet time and during SEP events.

PAMELA is built around a permanent magnet spectrometer equipped with a tracking system, which allows the determination of the particle charge and rigidity (momentum/charge) with high precision. A sampling electromagnetic calorimeter is mounted below the spectrometer. A time-of-flight (ToF) system allows velocity and energy loss measurements, and provides the main trigger for the experiment. A detailed description of the PAMELA apparatus along with an overview of the entire mission can be found in [4].
During the period of January 2011- May 2012 the PAMELA spectrometer registered several solar events with >100 MeV protons. The most powerful was event on 7 March 2012. Some characteristics of these events are listed in table 2. The examples of the PAMELA results are given in figure 2. The spectral features are similar to analogues events of the previous solar cycle. It should be noted that few strong events were missed due to pauses in the data acquisition during maintenance operations with the satellite (e.g. SEPs on 04-09 August 2011). A detailed analysis of recorded events is in preparation.

Table 2. SEP events registered by PAMELA in 2011-2012

| №  | Date       | Flare | Composition                      |
|----|------------|-------|----------------------------------|
| 1  | 21.03.2011 | NA    | Protons up to 300 MeV, Helium up to 120 MeV/nuc. |
| 2  | 07.06.2011 | M2.5  | Protons up to 600 MeV            |
| 3  | 04.11.2011 | X1.9 (3.11) | Protons up to 200 MeV          |
| 4  | 23.01.2012 | M8.7  | Protons >100 MeV                 |
| 5  | 27.01.2012 | X1.7  | Protons >100 MeV                 |
| 6  | 07.03.2012 | X1.5  | Protons up to 500 MeV, Helium up to 200 MeV/nuc. |
| 7  | 13.03.2012 | M7.9  | Protons >100 MeV                 |
| 8  | 17.05.2012 | M5.1  | Protons up to 600 MeV, Helium up to 150 MeV/nuc. |

4. Conclusion

During the first 41 months of the solar cycle 24 the PAMELA spectrometer observed 8 SEP events with >100 MeV protons. The current solar cycle manifests rather low solar activity. As a consequence the number of powerful SEP events is not high. The first GLE was observed at the 41\textsuperscript{st} month since the cycle beginning. At the same time a number of the low-energy SEP events is relatively high indicative of some energy redistribution in solar activity towards the less powerful phenomena.

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References

[1] Lee M A 2005 Astrophys. J. Sup Ser 158 38
[2] Bombardieri D J et al 2008 Astrophys. J. 682 1315
[3] Bazilevskaya G 2009 Adv. Space Res. 43 530
[4] Picozza P et al 2007 Astroparticle Physics 27 296
[5] Adriani O et al 2011 Astrophys. J. 742 102
[6] http://www.swpc.noaa.gov/
[7] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL
[8] http://sidc.be/cactus/
[9] http://www.wdcb.ru/stp/data/FL_XXIII/FL_XXIV.txt
[10] Logachev YuI ed. Catalog of solar proton events 1970-1979, IZMIRAN, Moscow, 1983, 184p; Solar Proton Events. Catalogue 1980-1986, Soviet Geophysical Committee of the Academy of Sciences of the USSR, Moscow, 1990 160p.