Comparison of solar energetic particle events observed by PAMELA experiment and by other instruments in 2006-2012

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Abstract: PAMELA is a magnetic spectrometer launched into a near-Earth orbit in June 2006. Its main task is investigation of the high-energy cosmic rays including electrons, protons, and nuclei as well as positrons and antiprotons. PAMELA is valuable for measurements of solar energetic particles (SEPs) since it is the only instrument recording protons and nuclei within the energy range from about 100 MeV/n to several GeV/n. Such an interval could earlier be covered only by several different types of detectors including the ground-level ones. PAMELA was lucky to observe the last powerful SEP events of the 23rd solar cycle in December of 2006. To date PAMELA has observed at least 10 events with $E > 100$ MeV protons. This paper reviews the particle fluxes, energy spectra and intensity-time profiles of SEP events recorded by PAMELA with the aim to compare them with the results of other observations, namely neutron monitors, balloons, and spacecrafts.

Keywords: solar energetic particles, orbital spectrometer.

1 Introduction

PAMELA is a magnetic spectrometer launched into a near-Earth orbit in June 2006 [1]. Its primary objective is to study cosmic antimatter, but many other problems of the space physics are also addressed, e.g. [2, 3, 4]. Among the goals of the high-energy charged particle measurements fulfilled by the PAMELA spectrometer is observation of particle fluxes enhancements after a sudden energy release at the Sun, so called solar energetic particles (SEPs).

Solar energetic particles constitute a distinct population of energetic charged particles, which can be often observed in the near Earth space. They bear information about processes of acceleration and propagation of charged particles in the solar and heliospheric plasma. Although SEPs have already been under thorough investigation during more than half a century the main problems concerning acceleration and further SEP behavior remain rather obscure, e.g. [5]. SEP observation is a necessary part of any space project directed to study of high energy particles, plasma physics or space weather. In powerful SEP events, the particle fluxes occupy more than eight orders of magnitude and the energy range of SEPs extends over more than four orders of magnitude, from MeVs to tens of GeVs. Before the PAMELA advent the relativistic SEPs were recorded only by the ground-based installations, transition from the counting rates to the particle intensity being dependent on the response function.

PAMELA was lucky to observe the last powerful SEP events of the 23rd solar cycle on 13 and 14 December of 2006 [6, 7, 8]. Solar protons of 0.08-3 GeV and He up to 1 GeV^{-1} were recorded. Satisfactory agreement was found with the results of the spacecraft, balloon-borne and ground-based instruments that performed simultaneous observations. However, the SEP events are very complicated and various in their appearance. That is why study of any physical phenomenon where SEPs are involved cannot be based on a single SEP event. Physicists should use data bases comprised of tens or even hundreds SEP events compiled in the Catalogues, e.g. [9, 10, 11]. The most precious is information about powerful SEP events with the spectrum covering from MeVs to GeVs. The same events are most dangerous for human beings and instruments and therefore important for space weather. The SEP energy spectrum cannot be measured by a single instrument because of very wide energy and particle intensity spread. PAMELA has actually filled a gap between the 100 MeV and several GeV particles.

However, SEPs with energy below 100 MeV are observed by other spacecraft-borne instruments while for the most energetic particles the ground-based installations are irreplaceable because of low SEP intensity. A large geometric factor is needed which is provided by the worldwide instrument (e.g. neutron monitor) network acting as a single particle detector. Homogeneity of the data sets is of crucial importance. Any SEP study starts from building an intensity-time profile and the energy spectrum evolution during the event. Therefore it is necessary to compare the records of different instruments before including an event in the data base. The aim of the present paper is to introduce the PAMELA results taken during the SEP events into common usage.

2 PAMELA instrument and data selection

The PAMELA instrument consists of a number of detectors capable of particle detection in a energy range from tens of MeV to several TeV. It contains anticoincidence and time-of-flight systems, a magnetic spectrometer, an imaging calorimeter, a shower tail catcher, and a neutron detector. A detailed description of the device and its schematic view can be found in [1, 2]. The magnetic spectrometer, consisting of silicon tracking system placed inside the permanent magnet with induction of 0.43 T is the central part of the PAMELA instrument. The spatial resolution of the

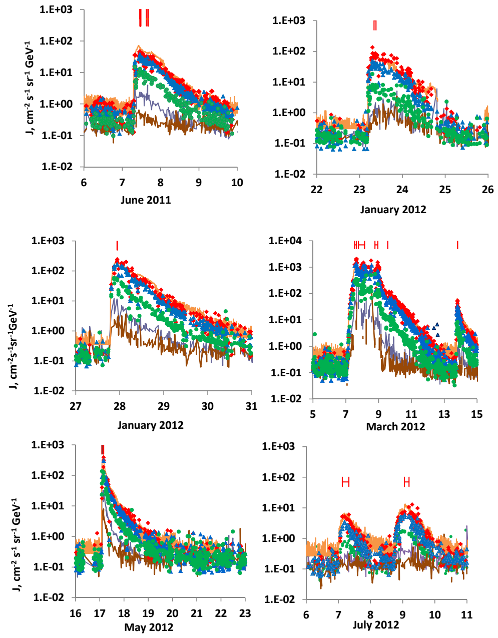

Figure 1: Intensity-time profiles of SEP events recorded by PAMELA in 2011-2012 in comparison with 0.1 GeV intensity from GOES 13 (orange line). The data are 5-min averages. PAMELA intensities are given for 0.102 GeV (red rhombs), 0.121-0.144 GeV (blue triangles), 0.169-0.235 (green circles), 0.276-0.378 GeV (grey line), 0.440-0.592 GeV (brown line). Red bars in the upper part of each panel indicate time periods for the energy spectrum compilation.

tracking system is $\approx 3\mu$m, which allows to measure a particle rigidity up to $\approx$ 1TV.The dimensions of the permanent magnet define the geometrical factor of the PAMELA experiment to be 21.5 cm^2 sr. In the SEP observations, the spectrometer is used for determination of the particle rigidity and a particle charge by dE/dx measurement. The calorimeter mounted beneath the spectrometer is sometimes used for hadron/lepton separation and can help with additional noise suppression in condition of high particle intensity.

This paper discusses only solar proton observations although PAMELA has detected during several SEP events some He with energy above 100 MeV/n which will be discussed elsewhere. For analysis, the usual proton selection in PAMELA spectrometer was implemented described in detail in [4, 6]. The data on absolute proton fluxes and energy dependence were retrieved with account of the tracker efficiency. In the SEP study an important point concerns the PAMELA orbit at an altitude of $\approx$ 570 km with inclination of 70°. The low energy of SEPs do not access the regions with high geomagnetic cutoff. Therefore, only segments of the orbit were used where the McIllwain L parameter was more than 5. PAMELA spent only about 15 minutes at a northern or southern polar region during one rotation and $\approx$5 min data were sampled. In case the longer time period is indicated in figures of this paper that means that the data were averaged over several polar passes. Only the standard deviations are shown as error bars; in figures they are mostly within the symbols.

3 Other instrument data selection

From the low-energy part the PAMELA results adjoin the data of several spacecraft instruments such as GOES and ERNE onboard SOHO. In the high-energy range PAMELA overlaps with the results of balloon observations and with energy spectra deduced from the neutron monitor (NM) network.

3.1 GOES and ERNE data

GOES is a geostationary satellite for monitoring the near-Earth space. The GOES Space Environment Monitor (SEM) system contains 3 instruments observing solar protons. For comparison with the PAMELA results we selected differential channels of the GOES EPEAD device with effective energies in GeV: 0.015, 0.03, 0.05, 0.06, 0.1 ("cpflux"); 0.012, 0.031, 0.063, 0.165, 0.433 ("p17ew"); and the GOES HEPAD device with energies: 0.375, 0.465, 0.605 [12]. All the data were corrected for possible electron contamination. However, secondary responses may exist from other particles and energies and from directions outside the nominal detector entrance aperture [13].

In addition to the GOES, we used the data of the HED sensor of the ERNE detector onboard the SOHO [14], situated in the L1 Lagrangian point. We chose differential proton intensity in channels with nominal energies in GeV 0.015, 0.020, 0.031, 0.041, 0.052, 0.073, and 0.0998.

3.2 Balloon data

Long-term balloon measurements of charged particle fluxes in the Earth's atmosphere are being fulfilled by Lebedev Physical Institute [15]. Main task of the project is monitoring of galactic cosmic rays with energies above $\approx$0.1 GeV. High-energy solar protons intrude into the atmosphere and are detected by a balloon-borne detector. Protons with energies 0.1-0.5 GeV loss their energy mainly via ionization in the atmosphere and their energy spectrum can be reconstructed from their absorption in the air [16]. Unfortunately, the balloon launching is now only 3 times per week.

3.3 Neutron monitor data

Ground-based NMs record the secondary cosmic rays, mainly neutrons [17]. There is a world-wide network of standard NMs which makes a single powerful instrument with a huge geometric factor to observe temporal variations of cosmic rays. SEPs with energies above $\approx$1 GeV cause increasing in the count rates of NMs and demonstrate so called ground level enhancement (GLE). A special methods were developed [18, 19, 20, 21] to derive energy spectra and angular anisotropy of solar particles using the enhancements in the count rates of NMs. The particle fluxes derived from the NM data are model dependent and require knowledge of response function. Nevertheless, only the ground-based installations can provide the sufficient geometric factor to measure the low intensities of the solar protons of highest energy.

4 Comparison between results of different measurements

Event of 13.12.2006 was a ground-level enhancement (GLE 70), so this was the first opportunity to compare the data of direct observations of relativistic solar protons (PAMELA) with the proton fluxes and energy spectra de-

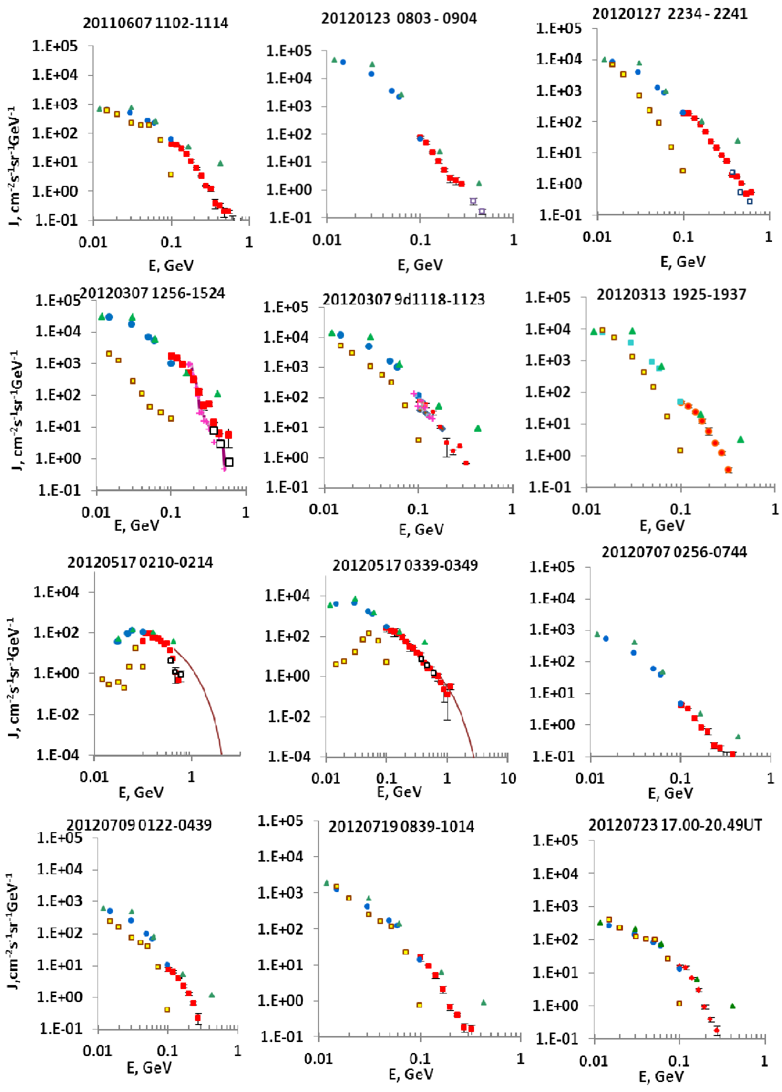

Figure 2: Selected energy spectra of solar protons as measured in 2011-2012. Time is given in format of YYYYMMDD HHMM UT. Figure legend is as following: red squares - PAMELA, blue circles - GOES 13 EPEAD ”cpflux”, green triangles - GOES 13 EPEAD ”p17ew”, light squares - GOES 13 HEPAD, yellow squares - ERNE HED, brown line - neutron monitor network, brown rhombs - balloon data. The background determined from records before the SEP event is removed.

rived from measurements of secondary particles by the ground-based installations: world-wide NM network [22] and the IceTop air shower array [23]. Good agreement of the PAMELA results with the proton fluxes and spectra derived from the IceTop observations was found while consistency with the NM spectra was slightly worse. After the publication [6] the NM community reanalyzed their results, so the agreement between the PAMELA and NM proton energy spectra in the GLE 70 became excellent [24]. Reasonable agreement of the PAMELA results with observations of the GOES and ACE spacecrafts was found for the events of 13.12.2006 and 14.12.2006.

In 2011-mid 2012 PAMELA has recorded 13 SEP events, 9 of them connected with activity at the western solar hemisphere, 2 events originated from the eastern hemisphere, and one event, from the far side of the Sun. 5 events occurred after X-ray bursts of the X-class, and 6, after the M-class. No X-ray burst preceded the SEP event of 21.03.2011. Powerful coronal mass ejections (CMEs) were observed in all cases, 12 of 13 CMEs were halo-shape. The SEP events which are discussed in this paper are: 07.06.2011, 23.01.2012, 27.01.2012, 07.03.2012, 13.03.2012, 17.05.2012, 07.07.2012, 08.07.2012, 19.07.2012, and 23.07.2012. The intensity-time profiles and the selected energy spectra are plotted in figures 1 and 2.

Intensity-time profiles in figure 1 are typical for the SEP events: all events connected with the western solar hemisphere have fast increase and rather sharp maximum while the eastern event of 07.03.2012 is more extended. Figure 1 shows an overall agreement between the 0.1 GeV proton channels of PAMELA and GOES 13. There are some minor discrepancies which are not systematic. However, the corresponding channel of ERNE (0.0998 GeV) measures too low intensity (not shown in figure 1).

More detailed comparison can be fulfilled looking at the energy spectra in figure 2. Time of the data averaging in figure 2 is given according to PAMELA measurement. The GOES and ERNE data are taken within limits of ±

2.5 min of the PAMELA time. Here, we can see that in the range below 0.1 GeV the GOES 13 devices are not always quite consistent with each other too. The GOES channel 0.165 GeV shows sometimes higher intensity than PAMELA while records of the GOES channel of 0.433 GeV is always too high. The GOES HEPAD device is consistent with PAMELA results given that such energetic solar particles were available.

The ERNE channel of 0.0998 GeV shows always lower itensity than PAMELA and GOES records. As to the other ERNE channels they respond to lower energies than PAMELA spectrometer. It is seen in figure 2 that they sometimes match to the results of GOES and sometimes not. It seems that ERNE sensors suffer from saturation during large SEP events.

The presented balloon data refer to times close to the PAMELA observation: 07.03.2012 at 1235-1326 UT and 09.03.2012 at 1256-1320 UT. They are in good agreement with PAMELA, similarly to the results published in [6].

In GLE 71 (17.05.2012) PAMELA recorded the first solar proton arrival. At 0210-0214 UT we see strong discrepancy with the spectrum derived from the NM world-wide network [24]. It is explained by the strong anisotropy of the first arriving solar protons. The spectrum derived from the NM data refers to direction of maximum particle intensity while PAMELA records particle arriving from the asymptotic direction being rather far from the direction of maximum intensity. Later, at 0339-0349 UT the agreement between PAMELA and the NM spectrum is excellent. These results are similar to those obtained for GLE 70. [6].

In all examined cases the proton energy spectra constructed from the data of PAMELA and the data in adjacent/overlapping energy intervals demonstrate rather smooth energy dependence without sharp rollovers in the MeV-GeV range. In [6] we tried to fit the obtained energy spectra of two SEP events of 2006 by a number of functions which are believed to be connected with certain mechanisms of particle acceleration. The best fit was obtained for the exponential in kinetic energy function. However, χ^2 value was high enough, so the conclusion was that no functions considered could fit the observed spectra satisfactorily. Now we have confirmed this result on base of events 2011-2012. The powerful SEP events are always accompanied both the flares and CMEs. Most probably, powerful SEP events stem from several different processes including acceleration by different mechanisms and possibly in different sites of solar corona and even in the interplanetary space. In addition, while propagating from the Sun particles change their energy too. Thus, it is reasonable that spectra covering large energy interval cannot be described by a single law. A detailed analysis should deal with a lot of events to establish the most probable signatures of certain mechanisms of acceleration and propagation.

5 Conclusions

PAMELA enables to extend the direct measurement of the SEP energy range up to GeVs and to fill up the hundreds MeV region which was earlier rather scanty. Two GLEs (number 70 and 71) were recorded by PAMELA, and a good agreement with the ground-based installations (Ice Top air shower array and the neutron monitor world-wide net) was obtained with exception for the anisotropy phase of a GLE. The PAMELA results are in reasonable consistency with the data of the GOES spacecraft and balloons in adjacent and overlapping energy intervals with exception for the GOES channel of 0.433 GeV which is always too high. The ERNE $\approx$0.1 GeV channel overlapping with the PAMELA response gives too low proton intensity. Combined proton energy spectra constructed from the data of PAMELA and other instruments demonstrate rather smooth energy dependence without sharp rollovers in the MeV-GeV range. However, the spectra cannot be described by power-law or exponential functions in kinetic energy or rigidity. Actually analysis of energy spectra needs better statistics and should be performed in future.

Acknowledgment: We acknowledge support from the Russian Space Agency (Roscosmos), and the Russian Foundation for Basic Research (grants 13-02-00612a, 13-02-00931a), the Italian Space Agency (ASI), Deutsches Zentrum fuer Luft und Raumfahrt (DLR), the Swedish National Space Board, the Swedish Research Council. We thank the neutron monitor network teams maintaining NM Data Base, the GOES and the ERNE teams for providing the data accessible through the Internet.

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