The development of solar neutron search method with PAMELA neutron detector

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Abstract. With the help of the PAMELA magnetic spectrometer continuous measurements of the cosmic-ray fluxes were carried out on board the RESURS-DK1 satellite during 10 years from the end of the 23rd solar activity cycle to the minimum of 24 cycle. The satellite was launched on June 15, 2006 into an elliptical orbit of 350-610 km height. The background channel of the neutron detector which was the part of the spectrometer and served for improving the separation between electrons and protons detected in the calorimeter. Simultaneously it was possible to monitor neutron fluxes in orbit. The technique for processing neutron detector data was developed to reduce the fluctuations of the counting rates associated with instrumental effects. The analysis of the latitudinal dependences of the neutron detector counting rates was done for various geomagnetic cut-off intervals from 0 to 16 GV during the time from 2006 to 2016. The new technique of data handling was applied for 29 solar proton events. Time dependencies obtained revealed the number of features that require further analysis.

1. Introduction
During 10 years from the end of the 23rd solar activity cycle to a minimum of 24 cycle continuous measurements of cosmic ray fluxes were carried out using a PAMELA magnetic spectrometer. The Resurs-DK1 satellite with the PAMELA magnetic spectrometer on board was launched on June 15, 2006 to a circumpolar elliptical orbit with the height of 350-610 km and the inclination of 70.4° [1]. The neutron detector of the PAMELA spectrometer [2] which serves for improving the separation of electrons and protons registered in the calorimeter simultaneously allowed the detection and investigation of neutron fluxes in orbit.

During powerful solar events neutrons of solar origin can reach the vicinity of the Earth. Such neutrons move along direct trajectories without being influenced by magnetic fields in contrast with charged particles. Therefore they reach the Earth faster. These neutrons carry important information about the onset and the place of particle injection on the Sun as well as about the processes of particle acceleration that occurs during solar flares.

2. Methods of data analysis and results
The PAMELA magnetic spectrometer is an assembly of six microstrip detectors placed in a quasi-homogeneous magnetic field of 0.48 T and allowing to determine the rigidities of charged particles in the range 0.1-1000 GV by the curvatures of their trajectories. At the same time the instrument includes the calorimeter with a thickness of 16 radiation lengths measuring the energy and the time-of-flight
system for measuring the velocity of charged particles as well as a system of scintillation counters for anticoincidences (see Figure 1). A special role in the instrument was played by a neutron detector located under the calorimeter which includes two layers of neutron counters filled with $^3$He and surrounded by moderator and served to separate the leptons and hadrons that generate the shower in the calorimeter.

![Figure 1. PAMELA Magnetic Spectrometer: TOF-time-of-flight system, ANTICOINCIDENCE - anti-coincidence system SPECTROMETER-magnetic spectrometer, CALORIMETER-calorimeter, SCINT. S4- shower leakage detector, NEUTRON DETECTOR-neutron detector.](image)

The background channel of the neutron detector provided continuous monitoring of neutron fluxes throughout the flight. However at high rates of neutron counting errors occurred due to a small volume of memory because of the neutron detector memory overflow.

Figure 2 shows the dependence of the count rate of the neutron detector on the rigidity of the geomagnetic cutoff for different time intervals $\Delta t$ between the trigger events detected by the magnetic spectrometer. With $\Delta t<15$ ms it is possible to avoid memory overflow of the neutron detector. However in this case the statistics of registered neutrons are rather low.

![Figure 2. Dependence of the neutron count rate on the geomagnetic cutoff rigidity for various selection criteria for events. Green curve: the time interval between events is $\Delta t<11$ ms, the blue curve is $\Delta t<15$ ms, the red curve is $\Delta t<200$ ms (month’s data).](image)
This method was used to analyse solar events in 2006–2015 when neutrons could be generated but a low level of data statistics (see for example, Figure 3, the blue curve) did not allow to reveal the fact of solar neutron registration because of the background fluctuations.

To increase the statistics and to reduce the effect of the memory overflow affecting on the process of neutron flux measurement a new technique was developed based on the analysis of the neutron counting rate dependence on latitude. This allows the use of large time intervals between the trigger signals of the PAMELA spectrometer. For this purpose the mean values of neutron counting rates for the big number of rotations versus latitude were used. From these data the minimum values of the counting rates expected in a given range of magnetic rigidity for any time interval of measurements were determined. This made it possible to correct the number of registered neutrons by the volume of memory in those cases when the number of registered neutrons was distorted because of its overflow. The correction was made for each plane of the neutron detector separately since their counting rates were slightly different.

Figure 3. Dependence of the neutron count rate on the geomagnetic cutoff rigidity on September 1, 2014 for various selection criteria. The red curve is of a new technique.

After the introduction of this correction the linear dependence of the number of registered neutrons on the duration of the measurement interval was maintained up to 100 ms that is much higher than the mean value of this interval (30 ms). As a result it became possible to use time intervals longer than before to determine the rates of neutron counting to increase the statistics and thus to reduce the count rate fluctuations. After this correction the statistical fluctuations of the neutron counting rates decreased and did not exceed 1-2% that is quite enough to reveal the effect of solar neutron recording at the level of several percent. Figure 3 shows the dependence of the neutron counting rate on rigidity, obtained by the new technique for the duration of time intervals of 100 ms (red curve) and in figure 4 the dependence of the number of registered neutrons on the sampling interval is shown for the magnetic rigidity range 0–1 GV.

A new technique was used to search for solar neutrons in 29 solar events the list of which is presented in the table. Their characteristics were taken from the data of the GOES satellite [4]. According to the position of the Resurs-DK1 in orbit the possible observation times of solar neutrons during flares were determined. For example figure 5 shows the behavior of the neutron detector counting rate during the flare on January 6, 2014. It is evident that the number of counts is in excess under the average account rate for the previous day. This excess could be treated as the registration of neutrons from the Sun. However to interpret the excess of neutron counting rate in this way since the change in the neutron counting rate can be related to other phenomena.
Figure 4. Dependence of the number of registered neutrons on the time interval of measurements in the rigidity range from 0 to 1 GV.

Figure 5. The neutron counting rate on January 6 2014: SF is the time of the solar flare onset (08:00). The blue curve is the expected mean background count rate obtained from the data a few days before the flare, the red points are the count rate on January 6 2014, the green curve is the result of subtraction - the count rate of the "solar neutrons".

As it can be seen from the table there were detected some variations of neutron detector counting rate during several solar events which could be interpreted as solar neutrons.

For example another source of neutron intensity variations recorded by the PAMELA neutron detector can be associated with solar activity which leads to variations in cosmic ray fluxes and consequently neutron detector counting rates due to the generation of neutrons in the calorimeter.
material. To study these variations, the analysis of the latitudinal dependences of the neutron detector counting rate was done for various geomagnetic cutoff rigidity intervals in the period from 2006 to 2016. The analysis revealed the presence of variations that correlate with the indications of a ground facility monitoring high-energy cosmic radiation - the neutron monitor located at the polar station Oulu (Finland), see Figure 6.

Table 1

| Date            | Flare | Flare start time | Arriving Time of protons E>100 MeV |
|-----------------|-------|------------------|-----------------------------------|
| 06 December 2006 | X9.0  | 10:35            | No data                           |
| 13 December 2006 | X3.4  | 02:40            | 03:12                             |
| 14 December 2006 | X1.5  | 22:15            | 23:05                             |
| 06 September 2011 | X2.1  | 22:20            | No                                |
| 08 September 2011 | M6.7  | 15:46            | No                                |
| 03 November 2011 | X1.9  | 20:27            | No                                |
| 07 March 2011   | M3.7  | 20:12            | No                                |
| 07 June 2011    | M2.5  | 06:16            | 7:50                              |
| 23 January 2012 | M8.7  | 03:38            | 04:50                             |
| 27 January 2012 | X1.7  | 17:37            | 19:20                             |
| 05 March 2012   | X1.1  | 04:05            | No                                |
| 07 March 2012   | X5.4  | 00:24            | 4:10                              |
| 09 March 2012   | M6.3  | 03:45            | 04:55                             |
| 13 March 2012   | M7.8  | 17:25            | 18:35                             |
| 17 May 2012     | M5.1  | 01:47            | 02:07                             |
| 06 July 2012    | X1.1  | 23:01            | No                                |
| 19 July 2012    | M7.7  | 04:17            | 08:00                             |
| 11 April 2013   | M6.5  | 06:55            | 09:35                             |
| 12 April 2013   | M3.3  | 20:38            | No                                |
| 22 May 2013     | M5.0  | 13:08            | No                                |
| 06 January 2014 | –     | 08:00            | 08:50                             |
| 07 January 2014 | X1.2  | 18:04            | 20:48                             |
| 20 February 2014| M3.0  | 07:56            | No                                |
| 29 March 2014   | X1.0  | 17:48            | No                                |
| 18 April 2014   | M7.3  | 13:03            | No                                |
| 08 July 2014    | M6.5  | 16:20            | No                                |
| 01 September 2014| C1.6  | 18:03            | No                                |
| 07 June 2015    | –     | 14:30            | 02:55                             |
| 29 October 2015 | –     | 02:40            |                                    |
Figure 6. Dependence of the counting rate on time for the polar region, the cutoff rigidity is \(<\) 1 GV. The red line is the PAMELA neutron detector, the black line is the Oulu neutron monitor.

3. Conclusion
A time analysis of the counting rates of the neutron detector for 29 solar flares when neutron generation on the Sun was possible was carried out. A noticeable excess (> 10 Hz) over the expected background channel count rate of the neutron detector was not detected. Nevertheless it should be noted that in the time dependencies obtained during solar-proton events a number of features have been identified that require further analysis.

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