

RESEARCH ARTICLE

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Key Points:

- The GCR proton spectra measured by PAMELA are well described by the force-field model
- PAMELA data are in good agreement with neutron monitors for low solar activity in 2006–2012 but diverge for higher activity in 2013–2014
- The systematic discrepancy is possibly related to an underestimate of the neutron monitor yield function in the high-energy range

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A Solar Cycle of Cosmic Ray Fluxes for 2006–2014: Comparison between PAMELA and Neutron Monitors

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Abstract A comparison of cosmic proton spectra directly measured by the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) experiment during 2006–2014 with data of polar neutron monitors for the same time interval is presented. It is shown that the measured spectra are well described by the force-field model for the modulation potential range 350–750 MV. The obtained modulation potential agrees with that calculated from the data of the world neutron monitor network for low solar activity between 2006 and 2012 but diverges during the maximum of solar cycle. The empirical relation between the modulation potential and the (inverted) neutron monitor count rate appears somewhat steeper than the modeled one, as confirmed also by data from fragmentary balloon-borne measurements. A reason for the discrepancy is unclear and calls for additional study using independent data sets.

Plain Language Summary A global network of ground-based neutron monitors is the main tool to monitor cosmic ray variability since the 1950s, but its absolute calibration to the cosmic ray flux in the open space is somewhat uncertain and based on models. Here we performed a comparison of cosmic proton spectra directly measured in space by the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics experiment during 2006–2014 with data of polar neutron monitors for the same time intervals. We have shown that the measured spectra are well described by the existing models for the period of weak/moderate solar activity but diverges during the maximum of solar cycle, suggesting that the models may be not precise. A reason for the discrepancy is unclear and calls for additional study using independent data sets.

1. Introduction

Galactic cosmic rays (GCRs) depict a great deal of variability as measured near Earth, while their flux can be assumed constant outside the heliosphere. Thus, the flux of GCR near Earth serves as a probe for the large-scale heliosphere and its changes, both cyclic and transient. The worldwide network of ground-based neutron monitors (NMs) is the main instrument to record GCR variability since 1951 (Bazilevskaya et al., 2014; Belov, 2000; Shea & Smart, 2000; Simpson, 2000). Because of the geomagnetic shielding, most sensitive are (sub)polar NMs located in regions with small geomagnetic rigidity cutoff. As an example, the variability of GCR recorded by a polar Oulu NM is shown in Figure 1 and depicts the dominant 11-year cyclic modulation as well as shorter noise-like transient changes. Since a NM detects not the primary GCR particles but secondary nucleonic component of the atmospheric cascade, it is not straightforward to relate the NM count rates to the GCR flux. A NM is an energy-integrating instrument, which is most sensitive to the primary GCR with energy ranging between a few gigaelectron volts to several tens of gigaelectron volts. Sometimes it is assumed that NM count rate is linked to a fixed energy of GCR, for example, median (Ahluwalia et al., 2010) or effective (Alanko et al., 2003; Asvestari et al., 2017) ones. However, more accurate is to evaluate the parameters of the GCR energy spectrum, described in the form of a force-field approximation (Caballero-Lopez & Moraal, 2004; Gleeson & Axford, 1968), directly from NM count rates (Usoskin et al., 2002).

To assess the GCR spectrum (more exactly, the modulation potential ϕ) from NM data, one needs to know the yield function of the NM to energetic particles, that describes the sensitivity of a detector to primary particles as a function of their energy (Dorman, 2004). The NM yield function is typically calculated using a full Monte Carlo simulation of the nucleonic-muon-electromagnetic atmospheric cascade triggered

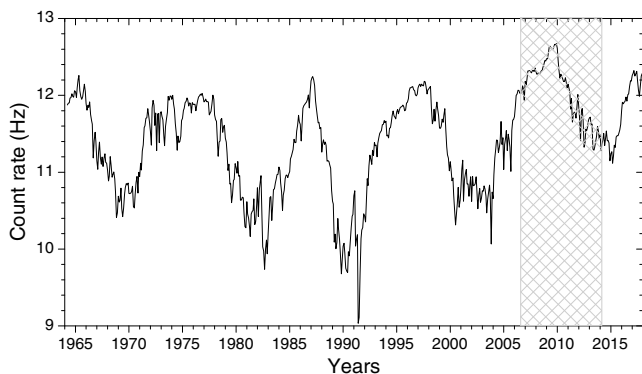


Figure 1. Monthly averaged count rate (Hz/counter) of Oulu neutron monitor (<http://cosmicrays.oulu.fi>) since 1964. The hatched interval depicts the period covered by Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) measurements (Table 1).

by primary cosmic ray (CR) particles (Clem & Dorman, 2000; Mangeard, Ruffolo, Sáiz, Madlee, & Nutaro, 2016; Mishev et al., 2013) but is still somewhat uncertain in the low- and high-energy ranges. In particular, it has been shown by Mishev et al. (2013) that the lateral spread of atmospheric cascades enhances the NM sensitivity to high-energy CR, considering the finite deadtime of the detector. Sometimes the yield function is defined empirically from the NM latitudinal surveys (e.g., Caballero-Lopez & Moraal, 2012), but it is limited to low-energy range (below about 15 GeV) and cannot be applied to higher-energy CRs whose contribution to the NM count rate is high (Usoskin et al., 2005). Moreover, a calibration to direct GCR spectral data, obtained by spaceborne or balloon-borne measurements, is required for each individual NM to account for the exact surrounding (electronic setup, building, etc.) of the NM (e.g., Mangeard, Ruffolo, Sáiz, Nuntiyakul, et al., 2016).

First attempts to link the NM count rate with the modulation potential were made a while ago (O'Brien & Burke, 1973). However, earlier studies were limited in the use of calibration to balloon-borne data measuring the

GCR spectrum in the energy range below a few GeV/nuc, or to spaceborne data in low-energy range of below a few hundred MeV/nuc, which does not correspond to the effective energy of NMs. A more systematic calibration was performed later (Usoskin et al., 2005, 2011) using the GCR spectral measurements in a wide energy range performed by the Alpha Magnetic Spectrometer (AMS-01) space experiment during a quiet period in June 1998 (Alcaraz et al., 2000, 2002) and balloon-borne measurements MASS89 (Webber et al., 1991) for a very active solar period in September 1989. A significant source of uncertainty of linking NM count rates to the heliospheric modulation is related to the NM yield function. Earlier yield functions (Clem & Dorman, 2000; Debrunner et al., 1982; Matthiä, 2009) systematically underestimated the contribution of high-energy nucleons. This led, in particular, to a clear discrepancy between modeled and experimental results of the NM latitudinal surveys (Clem & Dorman, 2000; Mishev et al., 2013). Accordingly, an ad hoc empirical correction was used by Usoskin et al. (2005) and Usoskin et al. (2011) to “match” models with observation.

A new NM yield function, computed by Mishev et al. (2013), explicitly accounts for the finite lateral spread of the CR-induced atmospheric cascade and the deadtime of the detector. This effect has eliminated problems with the comparison of modeled and measured NM responses, in particular for latitude surveys (Gil et al., 2015). Another recent NM yield function by (Mangeard, Ruffolo, Sáiz, Nuntiyakul, et al., 2016) also models the NM count rate in a realistic way.

New systematic measurements of the GCR proton spectra performed by the PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) detector in space (Adriani et al., 2011, 2014) made a more detailed comparison possible, for the period 2006–2009 (Adriani et al., 2013). A recent reconstruction of the modulation potential for the NM era was performed by Usoskin et al. (2017) using this PAMELA data set and the NM yield function by Mishev et al. (2013). Similar efforts were performed by Corti et al. (2016) and Ghelfi et al. (2016). Taking into account different local interstellar spectra and yield function models used there, the results are consistent with each other. The data, analyzed there, corresponded to a minimum of the solar cycle and very low modulation of GCR. Accordingly, the validity of the relation between direct spectrum measurements and models based on NM data remain unresolved for the full range of the modulation. Recently, a new data set of PAMELA measurements of the GCR proton spectra has been published (Martucci et al., 2018) for the period 2010–2014, covering the rising and maximum phase of solar cycle 24. Thus, presently, we have direct measurements of GCR proton spectra for the period 2006–2014 from the late declining phase of solar cycle 23 to the maximum of cycle 24 (see the hatched area in Figure 1), which allows one to study the relation between measured and modeled spectra in great details. This forms the subject of the present work.

2. Data Sets

2.1. PAMELA Data

PAMELA spectrometer (Adriani et al., 2011) is a spaceborne particle detector on board the *Resurs-DK1* satellite on a highly inclined (about 70°) elliptical low orbit. The instrument was in nearly continuous operation from the launch in June 2006 until January 2016. PAMELA provided measurements of charged energetic

Table 1

Solar Modulation Potential ϕ Values (for the Local Interstellar Spectrum by Vos & Potgieter, 2015) Fitted for the Complete PAMELA Data Set 2006–2014 (Section 3)

#	Start	End	ϕ (MV)	#	Start	End	ϕ (MV)
1	2006-7-7	2006-7-26	561 ± 13.5	43	2009-9-15	2009-10-11	369 ± 17
2	2006-7-27	2006-8-22	547 ± 13	44	2009-10-12	2009-11-7	387 ± 17.5
3	2006-8-24	2006-9-19	536 ± 13	45	2009-11-8	2009-12-5	363 ± 17.5
4	2006-9-20	2006-10-16	521 ± 13	46	2009-12-6	2010-1-1	372 ± 17.5
5	2006-10-17	2006-11-12	522 ± 13	47	2010-1-2	2010-1-23	371 ± 12.5
6	2006-11-13	2006-12-4	518 ± 12.5	48	2010-1-3	2010-1-30	351 ± 12
7	2007-1-11	2007-2-2	508 ± 12.5	49	2010-1-30	2010-2-27	392 ± 11
8	2007-2-3	2007-3-2	503 ± 13	50	2010-2-27	2010-3-26	395 ± 10
9	2007-3-3	2007-3-29	498 ± 13	51	2010-10-30	2010-11-26	438 ± 10.5
10	2007-3-30	2007-4-25	481 ± 12.5	52	2010-11-26	2010-12-24	447 ± 10.5
11	2007-4-26	2007-5-22	474 ± 12.5	53	2010-12-24	2011-1-20	426 ± 10.5
12	2007-5-23	2007-6-17	475 ± 12.5	54	2011-1-20	2011-2-16	431 ± 10.5
13	2007-6-27	2007-7-16	467 ± 12.5	55	2011-2-16	2011-3-16	461 ± 11
14	2007-7-17	2007-8-12	463 ± 13	56	2011-3-16	2011-4-12	506 ± 11
15	2007-8-13	2007-9-6	472 ± 13	57	2011-4-12	2011-5-9	514 ± 10.5
16	2007-9-9	2007-10-6	461 ± 12.5	58	2011-5-9	2011-6-5	531 ± 12
17	2007-10-7	2007-11-2	455 ± 13	59	2011-6-5	2011-7-3	567 ± 11.5
18	2007-11-03	2007-11-29	446 ± 13	60	2011-7-3	2011-7-30	526 ± 11
19	2007-11-30	2007-12-27	444 ± 12.5	61	2011-8-26	2011-9-22	547 ± 11.5
20	2007-12-28	2008-1-23	453 ± 12.5	62	2011-10-19	2011-11-16	538 ± 11
21	2008-1-24	2008-2-19	456 ± 12.5	63	2011-11-16	2011-12-13	525 ± 11
22	2008-2-20	2008-3-17	454 ± 12.5	64	2011-12-13	2012-1-9	502 ± 11
23	2008-3-19	2008-4-14	474 ± 13	65	2012-1-9	2012-2-6	514 ± 11.5
24	2008-4-15	2008-5-11	463 ± 12.5	66	2012-2-6	2012-3-4	538 ± 11
25	2008-5-12	2008-6-7	470 ± 12.5	67	2012-3-31	2012-4-28	594 ± 12
26	2008-6-8	2008-7-4	468 ± 13	68	2012-5-25	2012-6-21	588 ± 11.5
27	2008-7-5	2008-8-1	464 ± 13	69	2012-8-15	2012-9-11	677 ± 11.5
28	2008-8-2	2008-8-28	452 ± 13	70	2012-9-11	2012-10-8	641 ± 11.5
29	2008-8-29	2008-9-11	441 ± 12.5	71	2012-10-8	2012-11-4	686 ± 11.5
30	2008-10-1	2008-10-21	445 ± 13	72	2012-11-4	2012-12-2	667 ± 11.5
31	2008-10-22	2008-11-18	417 ± 12.5	73	2012-12-2	2012-12-29	636 ± 11
32	2008-11-19	2008-12-15	423 ± 12.5	74	2012-12-29	2013-1-25	619 ± 11.5
33	2008-12-20	2009-1-11	440 ± 12.5	75	2013-1-25	2013-2-22	602 ± 11
34	2009-1-12	2009-2-8	414 ± 12.5	76	2013-2-22	2013-3-21	594 ± 11.5
35	2009-2-21	2009-3-7	396 ± 12	77	2013-6-11	2013-7-8	755 ± 12.5
36	2009-3-8	2009-4-3	381 ± 12.5	78	2013-7-8	2013-8-4	714 ± 11.5
37	2009-4-4	2009-5-1	378 ± 12	79	2013-8-4	2013-8-31	732 ± 12
38	2009-5-2	2009-5-28	384 ± 12.5	80	2013-8-31	2013-9-28	741 ± 12
39	2009-5-29	2009-6-24	389 ± 12.5	81	2013-9-28	2013-10-25	725 ± 12
40	2009-6-25	2009-7-21	379 ± 12	82	2013-11-21	2013-12-19	731 ± 12
41	2009-7-22	2009-8-18	367 ± 12.5	83	2014-1-15	2014-2-11	735 ± 11.5
42	2009-8-19	2009-9-14	380 ± 12.5				

Note. Columns are number #, start and end of the time intervals, and the best fit value of ϕ with its 68% confidence interval.

Table 2

Best Fitted Values of the Modulation Potential ϕ (Local Interstellar Spectrum as for Vos & Potgieter, 2015) for GCR Spectra Measured in Various Balloon-Borne and Spaceborne (in Bold) Experiments

Experiment	Start	End	ϕ (MV)
LEAP1987	1987-8-21	1987-8-21	454 ± 29
MASS89	1989-9-5	1989-9-5	1149 ± 23
MASS91	1991-9-23	1991-9-23	1035 ± 50
IMAX92	1992-7-16	1992-7-17	812 ± 30
BESS1993	1993-7-1	1993-7-1	609 ± 30
BESS1994	1994-7-1	1994-7-1	623 ± 32
CAPRICE1994	1994-8-8	1994-8-9	565 ± 25
BESS1995	1995-7-25	1995-7-25	489 ± 27
BESS1997	1997-7-27	1997-7-27	435 ± 19
CAPRICE1998	1998-5-28	1998-5-29	619 ± 40
BESS1998	1998-7-29	1998-7-29	519 ± 20
BESS1999	1999-8-11	1999-8-12	606 ± 20
BESS2000	2000-8-10	2000-8-11	1202 ± 23
BESS-TeV	2002-8-7	2002-8-7	992 ± 22
BESS-POLAR I	2004-12-13	2004-12-21	705 ± 13
BESS-POLAR II	2007-12-22	2008-1-19	495 ± 12
AMS1	1998-6-2	1998-6-12	501 ± 20
AMS2	2011-5-19	2013-11-26	650 ± 20

Note. AMS = Alpha Magnetic Spectrometer.

particles with energy above 80 MeV. Here we use published data (digital data are available in the ASDC database at tools.asdc.asi.it/CosmicRays/) of proton spectra measurements averaged over roughly Carrington rotation period, as summarized in Table 1. Original data for the period 2006–2009 (Intervals 1–47 in the table) were published by Adriani et al. (2013) and for 2010–2014 (Intervals 48–83) by Martucci et al. (2018). Intervals 47 and 48 overlap, bridging the first and the second sets of data, as needed for a consistency check. These measured spectra were fitted by the force-field model to estimate the modulation potential as described in section 3.

2.2. NM Data

Here we used data from long-operating sea level (sub)polar NMs with stable parameters over the analyzed period of 2006–2014. The question of long-term stability was considered elsewhere (see Figure 5 in Usoskin et al., 2017), and we selected Oulu (9NM64, geomagnetic cutoff rigidity $P_c = 0.8$ GV, location 25.47°E 65.05°), Inuvik (18NM64, $P_c = 0.3$ GV, 133.72°W 68.36°N) and Kerguelen (18NM64, $P_c = 1.1$ GV, 70.25°E 49.35°S) NMs. Count rates (corrected for barometric pressure and efficiency) of these NMs for the same intervals (Table 1) were collected from NMDB (nmdb.eu) and IZMIRAN (cr0.izmiran.ru/common/links.htm) databases for Inuvik and Kerguelen NMs and directly from the Oulu NM database (cosmicrays oulu.fi).

2.3. Other Balloon-Borne and Spaceborne Data

To compare the results of this study, we also employed other measurements of CR spectra performed on board balloon flights or the AMS space missions (see Table 2). Exact periods and measured spectra for balloon and AMS data were taken from the ASDC database with the original references to (Abe et al., 2016; Adriani et al., 2013; Aguilar et al., 2015; Alcaraz et al., 2000; Bellotti et al., 1999; Boezio et al., 1999, 2003; Menn et al., 2000; Seo et al., 1991, 2001; Shikaze et al., 2007; Wang et al., 2002; Webber et al., 1991).

3. Fitting of the Data With Model Spectra

Each measured spectrum of protons (Tables 1 and 2) was fitted with the force-field model to define the corresponding modulation potential ϕ . The force-field model links the energy spectrum of GCR particles of a given type (protons, α -particles, etc.) near Earth, J , with their reference intensity outside the heliosphere, called the local interstellar spectrum (LIS) J_{LIS} :

$$J_i(T, \phi) = J_{\text{LIS}_i}(T + \Phi_i) \frac{T(T + 2T_r)}{(T + \Phi_i)(T + \Phi_i + 2T_r)} \quad (1)$$

where T is the kinetic energy per nucleon, $T_r = 0.938$ GeV is the proton's rest mass, $\Phi_i = \phi \cdot (eZ_i/A_i)$ is the mean energy loss of the GCR particle inside the heliosphere, and Z_i and A_i are the charge and mass numbers of the nucleus of type i . The force-field approximation is obtained as an analytical solution (in the form of characteristic curves) of the heavily simplified GCR transport equation (Caballero-Lopez & Moraal, 2004; Gleeson & Axford, 1968), where all the modulation effects are reduced to a single parameter ϕ called the modulation potential. Although it has little physical sense because of the heavy simplified assumptions (spherical symmetry, steady state, and adiabatic changes), the force-field model provides a very good and useful parameterization of the near-Earth GCR spectrum (e.g., Vainio et al., 2009). The exact value of the modulation parameter depends on the reference LIS (Asvestari et al., 2017; Herbst et al., 2010; Usoskin et al., 2005). Here we used a recent estimate of the proton LIS by Vos and Potgieter (2015), who provided a parameterization of LIS using recent data:

$$J_{\text{LIS}} = 2.7 \cdot 10^3 \frac{T^{1.12}}{\beta^2} \left(\frac{T + 0.67}{1.67} \right)^{-3.93}, \quad (2)$$

where $\beta = v/c$ is the ratio of the proton's velocity to the speed of light, J and T are given in units of ($\text{m}^2 \text{sr GeV/nuc}$) $^{-1}$ and GeV/nuc, respectively. This LIS is shown as the dashed curve in Figure 2.

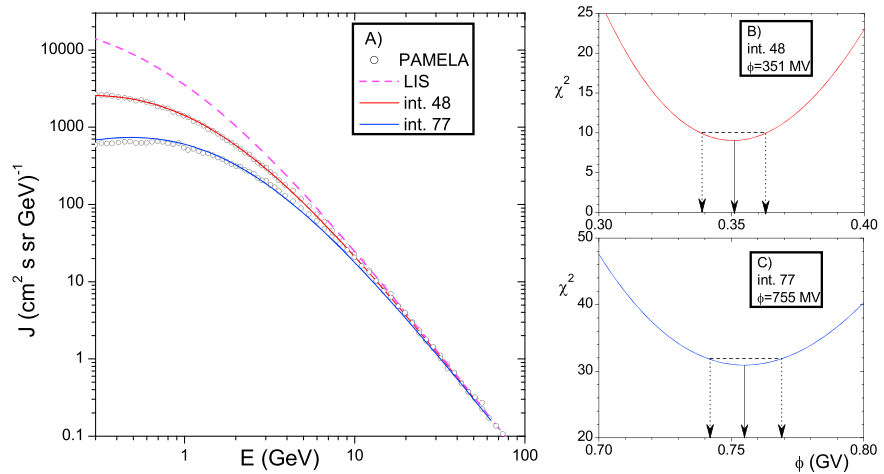


Figure 2. Examples of the fitting of a force-field model to the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) proton spectrum for periods 48 (3–30 January 2010) and 77 (11 June to 8 July 2013); see Table 1. (a) The best fit spectra are shown as the red and blue curves, respectively. The dots represent the corresponding PAMELA data points. The purple dashed curve represents the proton local interstellar spectrum (LIS; Vos & Potgieter, 2015). (b) The χ^2 statistics of the force-field model fitting to the PAMELA data for the Interval 48 as shown in panel A. The best fit value of $\phi = 351$ MV, corresponding to the minimum $\chi^2_{\min}$, and the 68% confidence interval, corresponding to $\chi^2_{\min} + 1$, shown by the solid and dashed arrows, respectively. (c) Similar to (b) but for Interval 77 (the best fit value $\phi = 755$ MV).

The measured proton spectra were fitted by the force-field model (equations (1) and (2)) using the χ^2 method. For a value of ϕ the merit function χ^2 was calculated as

$$\chi^2 = \sum_j \left(\frac{J_{\text{mod}}(T_j) - J_{\text{meas}}(T_j)}{\sigma_j} \right)^2, \quad (3)$$

where T_j is the mean value of the energy in the j th bin in the spectrum, modeled and measured mean intensities in this energy bin are $J_{\text{mod}}(T_j)$ and $J_{\text{meas}}(T_j)$, respectively, and σ_j is the uncertainty of the measured intensity. Here we fitted the spectra in the energy range 1–30 GeV, which includes $n = 42$ energy bins. Accordingly, the number of degrees of freedom (DoFs) is $(n - 1) = 41$. Two examples of the fit are shown in Figure 2. One example is for the Interval 48 (see Table 1) with the lowest value of the modulating potential (351 MV). The other example is for the Interval 77 with the highest value of ϕ (755 MV). The corresponding dependences

of the merit function χ^2 on values of ϕ are shown in panels b and c. The best fit values of the modulation potential are taken as those corresponding to the minimum value of $\chi^2_{\min}$ as shown by vertical arrows in the panels. The 68% confidence interval of the modulation potential is defined in a standard way as that bounded by values of ϕ corresponding to $\chi^2 = (\chi^2_{\min} + 1)$, as illustrated in the figure by dotted arrows. Thus, the values of $\phi = 351 \pm 12$ and 755 ± 12.5 MV are defined and enter Table 1 for Intervals 48 and 77, respectively.

The values of $\chi^2_{\min}$ appear to be 9.4 and 30.9 for the Intervals 48 and 77, respectively. When normalized per DoF, it yields 0.23 and 0.75 per DoF, respectively. A histogram distribution of the $\chi^2_{\min}$ values for all the 83 intervals is shown in Figure 3. One can see that the median of the distribution lies close to 16 (the mode ≈ 12), which corresponds to about 0.4 per DoF, and is reasonably described by a lognormal distribution (the red curve). Such low (below unity per DoF) values and the smooth distribution of $\chi^2_{\min}$ suggest that, while the fit is correct, the uncertainties of PAMELA data are likely overestimated, in a sense that the real spread of data points is smaller than expected from the official error bars. On the other hand, the formal uncertainties of the spectra, provided by PAMELA data, include two types

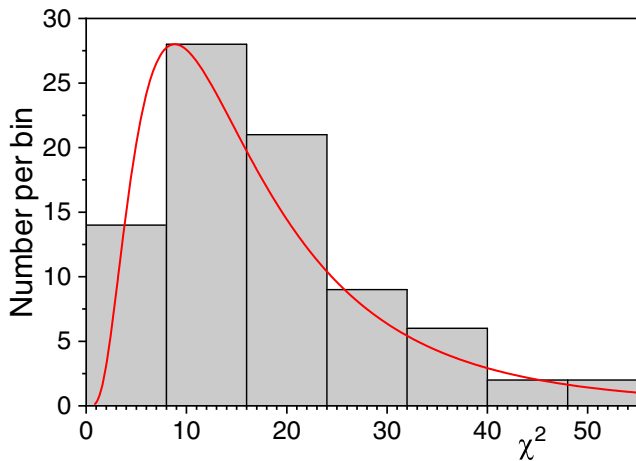


Figure 3. Distribution of the $\chi^2_{\min}$ values of the PAMELA spectrum fitting for the 83 intervals listed in Table 1. The best fit lognormal distribution is shown in red.

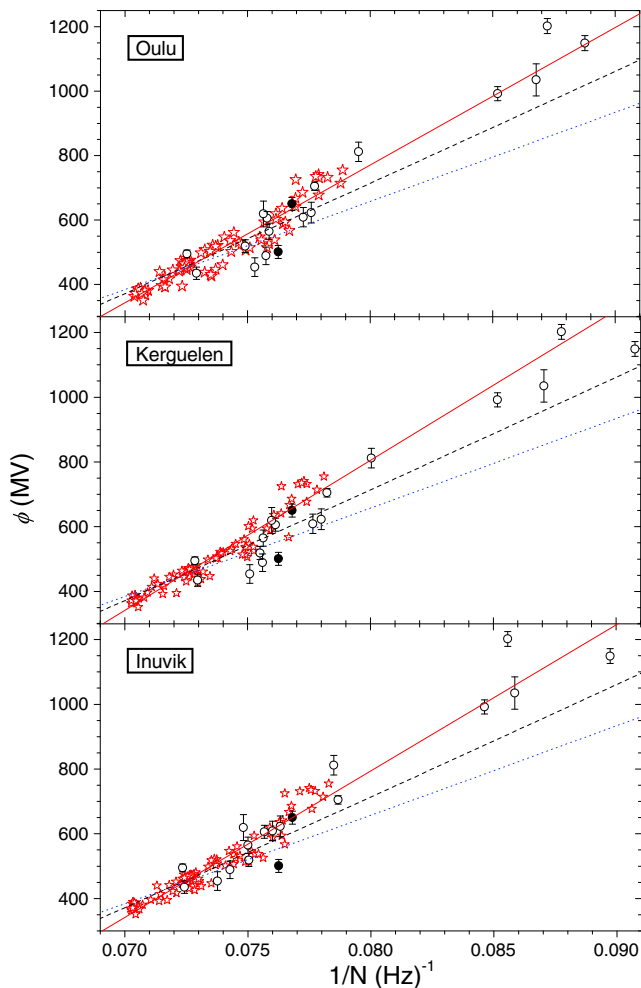


Figure 4. Relation between the modulation potential ϕ and inverted, per counter, count rate ($1/N$) of neutron monitors analyzed here: Oulu, Kerguelen, and Inuvik. Red stars represent the PAMELA data periods (see Table 1); open and black dots—various balloon-borne and spaceborne cosmic ray measurements, as listed in Table 2, respectively. The red solid line is the best fit linear regression only for the PAMELA-based data points (red stars; black dots were not used for fitting), while black dashed Mi13 and blue dotted Ma16 lines depict theoretical models based on the NM yield functions by Mishev et al. (2013) and Mangeard, Ruffolo, Sáiz, Madlee, and Nutaro (2016), respectively. PAMELA = Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics.

of errors, statistical and systematic, which are comparable to each other. The latter was estimated in a conservative manner leading to quite a conservative error estimate. However, this does not undermine the way of the definition of best fit values of ϕ and does not affect the present analysis.

Spectra for all other PAMELA intervals as well as for other data were fitted in the same way, and the best fit modulation potentials were defined along with its 68% confidence interval. The corresponding values were gathered in Tables 1 and 2.

4. Comparison With NM Data

In Figure 4 we show a scatter plot of the fitted modulation potential ϕ for all PAMELA intervals and balloon flights as a function of the (inverted) count rate N of the three selected NMs for the same time intervals. Since an approximately linear relation $\phi = A/N + B$ between these variables is expected (Santiago et al., 2018; Usoskin et al., 2017), we plot, as X axis, the inverted count rate per counter. One can see that PAMELA data sets (red stars), balloon-borne data (open circles), and AMS data (filled circles) all lie along a nearly linear dependence (the best fit linear dependence was built using only PAMELA data), which is shown by the red line. Red stars lie much more compact than other data points, because they were obtained by the same instrument, similarly presented and fitted, while isolated balloon-borne data lead to a large scatter.

We also depict in Figure 4 theoretically expected relations between ϕ and N . The theoretically expected NM count rate at given time t and atmospheric depth h was computed as (see, e.g., Usoskin et al., 2017)

$$N(T, h) = \frac{1}{\kappa} \sum_i \int_{T_{c,i}}^{\infty} J_i(T, t) \cdot Y_i(T, h) \cdot dT, \quad (4)$$

where the summation is over different types of primary CRs (protons, α particles, etc.), J_i is the spectrum of these particles in the near-Earth space outside the atmosphere and magnetosphere, Y_i is the yield function, and κ is a scaling factor (typically in the range 0.8–1.25) correcting for the “nonideality” (local surrounding, exact electronic setup, efficiency of counters, etc.; see Mangeard, Ruffolo, Sáiz, Madlee, & Nutaro, 2016) of each NM. Scaling factors κ were adopted from our previous work (Usoskin et al., 2017) as 1.121, 1.254, and 1.078 for Oulu, Inuvik, and Kerguelen NMs, respectively. NM yield functions were adopted from two recent models: Mishev et al. (2013, called Mi13 henceforth) and Mangeard, Ruffolo, Sáiz, Nuntiyakul, et al. (2016, Ma16), both built on a full Monte Carlo simulation of the CR-induced nucleonic cascade in the atmosphere.

It is important to consider also α particles (effectively including heavier species because of the similar A/Z ratio) separately from protons since they are modulated differently and contribute 30–50% to the overall count rate of a NM (Caballero-Lopez & Moraal, 2012; Usoskin et al., 2011). For α particles (including the heavier species) we used the same LIS form as for protons (equation (2)) but with the weight of 0.3 (in the number of nucleons) similarly to Usoskin et al. (2011).

The corresponding theoretical dependencies are shown in Figure 4 as black dashed and blue dotted lines for the models Mi13 and Ma16, respectively. Although both models predict a nearly linear relation between ϕ and $1/N$, the slopes are different for the two models, and they both differ from the empirical relation, shown by the red line. The result based on Mi13 is more or less consistent with the data for weak activity with $\phi < 500$ MV. This led Usoskin et al. (2017) to a conclusion that the Mi13 yield function is fully consistent with the early PAMELA data covering the solar minimum 2006–2009. However, a significant divergence can be observed at higher activity ($\phi > 600$ MV). In order to illustrate this, we show (Figure 5) time profiles of the modulation

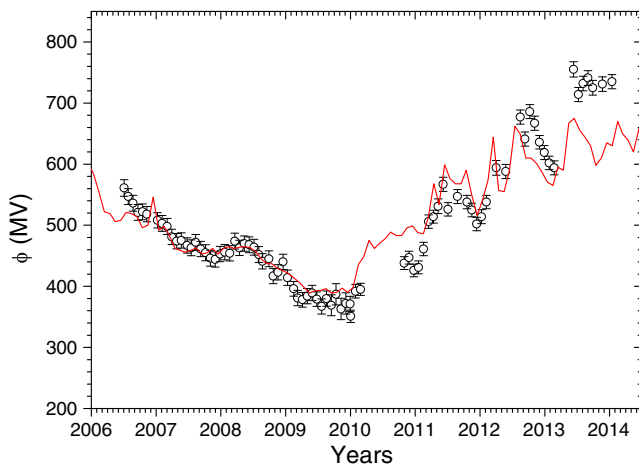


Figure 5. Time profiles of the modulation potential ϕ for the period covered by PAMELA data. Dots with error bars represent the fit to PAMELA data (Table 1), while the red curve is based solely on NM data (Usoskin et al., 2017). PAMELA = Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics.

potential obtained here from the PAMELA data (dot with error bars) and that reconstructed by Usoskin et al. (2017) from NM data using the Mi13 yield function (red curve). One can see that, indeed, the first period of PAMELA data 2006–2009 depicts good agreement, but the NM-based reconstruction seems to underestimate the modulation potential systematically by up to 100 MV (or 10%) during higher activity periods. The results based on Ma16 yield function diverge even greater (up to 200 MV or 20%, not shown here). This pattern is persistent for all the three NMs considered here.

The results shown in Figures 4 and 5 imply that there is a discrepancy between the energy spectra of GCR protons directly measured in space and those formally reconstructed from ground-based NM data. The discrepancy is not large (being within the full range of 100 MV) but systematic. The observed relation between the modulation potential ϕ and the inverted NM count rate appears systematically weaker (the slope is steeper) than expected from the numerical models. We found that both used yield function models disagree with the data, but the results based on Mi13 lie closer to the experimental data than those based on Ma16. Although the exact reason for the discrepancy is unknown, we may speculate on three possible sources. One possibility is related to a possible

degradation of the PAMELA sensitivity with time, leading to an overestimated modulation potential during the late years. However, considering the thoroughness of the PAMELA team work and the fact that the spectral shape is not distorted, this option looks unlikely, which is consistent with independent balloon-borne data. Other, more likely possibilities, are related to the modeled yield function of NM. Since the observed dependence on the modulation potential is weaker than the modeled one (i.e., the NM count rate is less sensitive to changes of the modulation than expected from the models), it can be either an underestimate of the NM yield function at the high-energy tail or its overestimate in the low-energy range. On the other hand, reconstructions of the energy spectra of solar energetic particles from NM data (e.g., Kocharov et al., 2017; Mishev & Usoskin, 2016) suggest that the low-energy part of the NM yield function by Mishev et al. (2013) is more or less correct.

At present we are not able to identify the source of the discrepancy between the modeled and measured spectra for periods of high solar activity but can speculate that a likely reason for the discrepancy is an underestimate of the NM yield function in high-energy range. More investigation is needed, which is planned for further research.

5. Conclusions

In this work we have compared GCR proton spectra directly measured by the PAMELA experiment during 83 time intervals covering the period 2006–2014 with the data of polar neutron monitors for the same time intervals. The following conclusions have been made:

1. The GCR proton spectra measured by PAMELA were parameterized by the force-field model. The parameterization works well within the range of the modulation potential values from 350 to 750 MV for the LIS by Vos and Potgieter (2015).
2. The obtained values of the modulation potential are in good agreement with those calculated from the data of the world neutron monitor network (Usoskin et al., 2017) for the period of low solar activity 2006–2012 but diverge during the maximum of solar cycle 24 around 2013–2014.
3. The empirical relation between the modulation potential and the (inverted) NM count rate appears somewhat steeper than the modeled one. The discrepancy is not big (up to 10–20% during periods of high activity) but systematic. The results based on the NM yield function by Mishev et al. (2013) lie closer to the experimental points than those based on the results by Mangeard, Ruffolo, Sáiz, Nuntiyakul, et al. (2016).
4. The reason for the discrepancy is unclear. We speculate that a likely reason is a possible underestimate of the NM yield function in the high-energy range. A systematic error in PAMELA data is less likely. More investigation is needed with the use of an independent data set, for example, GCR spectra measured by the AMS experiment (Aguilar et al., 2015).

Acknowledgments

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