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Force-field parameterization of the galactic cosmic ray spectrum: Validation for Forbush decreases

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Abstract

A useful parametrization of the energy spectrum of galactic cosmic rays (GCR) near Earth is offered by the so-called force-field model which describes the shape of the entire spectrum with a single parameter, the modulation potential. While the usefulness of the force-field approximation has been confirmed for regular periods of solar modulation, it was not tested explicitly for disturbed periods, when GCR are locally modulated by strong interplanetary transients. Here we use direct measurements of protons and α-particles performed by the PAMELA space-borne instrument during December 2006, including a major Forbush decrease, in order to directly test the validity of the force-field parameterization. We conclude that (1) The force-field parametrization works very well in describing the energy spectra of protons and α-particles directly measured by PAMELA outside the Earths atmosphere; (2) The energy spectrum of GCR can be well parameterized by the force-field model also during a strong Forbush decrease; (3) The estimate of the GCR modulation parameter, obtained using data from the world-wide neutron monitor network, is in good agreement with the spectra directly measured by PAMELA during the studied interval. This result is obtained on the basis of a single event analysis, more events need to be analyzed.

Keywords: Cosmic rays; Heliosphere; Forbush decrease

1. Introduction

Galactic cosmic rays (GCRs) are always present in the vicinity of Earth, and their intensity varies as a result of modulation in the heliosphere by solar magnetic activity. While a theory of the heliospheric transport and modulation of GCR is well developed (see, e.g., a review by Potgieter (2013)), a simple parametrization of the energy spectrum of GCR near Earth (e.g., Vainio et al., 2009) is required for many practical purposes, without referring to physics behind. Such parameterizations are widely used in many practical applications, for example studying atmospheric effects of cosmic rays, production of cosmogenic radionuclides, long-term variability of solar activity, etc. (e.g., Bazilevskaya et al., 2008; Beer et al., 2012; Usoskin, 2013). One such parametrization is based on the force-field approximation and describes the spectrum of GCRs with good precision, using a single parameter.

Although the force-field approximation is derived using a physical basis (Gleeson and Axford, 1968; Caballero-Lopez and Moraal, 2004), the modulation potential has no clear physical meaning. Moreover, the physical assumptions used to derive the approximation, such as quasi-steadiness of the solar wind, spherical symmetry, etc, are apparently invalid for short time scales and disturbed heliospheric conditions. In fact, they are not fully valid even for the regular condition (Caballero-Lopez and Moraal, 2004). Thus, no one expects that physics of the force-field model would be applicable during a major Forbush decrease (FD). However, the force-field formalism was found to provide a very useful and comfortable mathematical parametrization of the GCR spectrum in the energy range from a few hundred MeV up to 100 GeV, irrespective of the (in) validity of physical assumptions behind the force-field model. The GCR differential energy spectrum is formally described by the force-field model with one variable parameter, the modulation potential ϕ, and the prescribed shape of the local interstellar spectrum (LIS) (see formalism in Usoskin et al. (2005)). This parametrization works better and uses fewer parameters than, e.g., a power-law in rigidity or other formal parameterizations. It has been shown (Usoskin et al., 2005, 2011) that the GCR spectrum parameterized in this way agrees quite well (within $\approx$5%) with direct measurements of GCR spectrum performed by balloon- and space-borne detectors for the monthly time scale. The value of ϕ is usually obtained empirically from the data of the worldwide network of neutron monitors. The exact value of the modulation potential depends on the employed LIS, but they can be easily recalculated between each other (Usoskin et al., 2005; Herbst et al., 2010).

Sometimes the flux and spectrum of cosmic rays near Earth are greatly modified by solar/interplanetary transient phenomena, such as solar energetic particle (SEP) events or Forbush decreases. FD is a sudden suppression of GCR intensity near the Earth, caused by interplanetary transients such as a shock or magnetized ejecta of coronal mass ejections (Cane, 2000). While the force-field parametrization is obviously unable to describe the SEP spectrum, the question of its applicability to fit the GCR spectrum during FDs has never been explicitly considered because of the lack of direct measurements of GCR spectra up to high energy during a strong FD. The shape of the GCR spectrum during a FD was not directly measured and left room for speculations. E.g., Ahluwalia and Fikani (2007) speculated, using data from the ground-based NM data, that it can be still described by the force-field model but it was hardly possible to confirm or disprove that. Although FDs are known as suppressions of the ground-based detector count rates since long (Forbush, 1954), direct measurements of GCR energy spectra during FDs were not performed until the launch of PAMELA

(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) instrument in 2006 (Adriani et al., 2011). PAMELA is installed onboard a low orbiting satellite Resurs-DK1 with a quasi-polar (inclination 70°) elliptical orbit (360–640 km). With PAMELA, energy spectra of GCR have been measured in full detail for a major FD studied here, thus allowing for a careful study of the GCR spectrum parametrization also during transient events. Although the force-field model is expected to fail in the FD conditions (no steady state, no spherical symmetry), the question on the applicability of the formal parametrization during FDs was open. Short-term variability of cosmic rays and spectral parametrization is important for practical applications such as the cosmic ray induced ionization (Calisto et al., 2011; Semeniuk et al., 2011; Usoskin et al., 2011) or production of short-living cosmogenic isotopes, such as ^{7}Be, used as tracers for the large-scale air mass dynamics (Kulan et al., 2006; Leppänen et al., 2010).

Here we perform an analysis of a strong FD that took place in mid-December 2006, as measured by PAMELA instrument (Adriani et al., 2011). In particular, we study whether the energy spectrum of GCR during a FD can be still parameterized by the force-field empirical model, and whether it agrees with the data of the world-wide network of neutron monitors (NMs).

2. Analyzed period

December 2006 was chosen for the analysis as the most perturbed (in the sense of cosmic ray variations) month during the entire period of PAMELA observations. There is a gap in the data between 06-Dec and 11-Dec-2006. Cosmic ray variability, as recorded by the ground-based subpolar Oulu neutron monitor (NM) (65°N 25.5°E, see http://cosmicrays.oulu.fi) during that period, is shown in Fig. 1. One can see that the cosmic ray flux was fairly stable during the first six days of the month, then a moderate suppression (4–5%) of the count rate of a polar NM took place. On the day of 13-Dec-2006 a major ground level

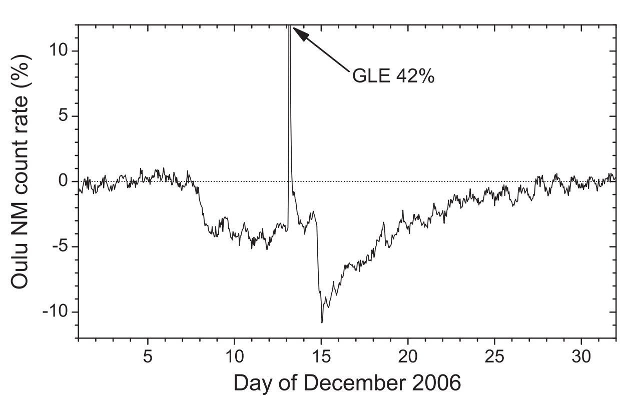

Fig. 1. Relative changes of pressure-corrected hourly count rate of Oulu NM (http://cosmicrays.oulu.fi) for December 2006. The GLE event of 13-Dec-2006 was 42% (outside the plot bounds).

enhancement (GLE) of cosmic rays occurred. It was GLE #70, which was among the greatest solar energetic particle events (Plainaki et al., 2009), as observed by Oulu NM at the level of 42% in hourly data and 92% in 5-min data. One day later, an interplanetary shock, led by a CME ejecta arrived at Earth triggering a classical strong FD of about 10% magnitude (difference in the hourly data between the pre-event level and the minimum intensity) on the day of 15-Dec-2006. The recovery phase of the FD was typical (Usoskin et al., 2008) and took about two weeks with a clearly observed diurnal variations of a few percent magnitude.

As the reference period we chose the period of January through March 2008, when the cosmic ray flux, as recorded by ground-based NMs was fairly stable, within ±1%. That period was characterized by quite low solar activity, the modulation potential ϕ was remaining within a narrow range of 360–367 MV (in the definition of Usoskin et al. (2011)).

3. Fitting of GCR spectrum measured by PAMELA

Here we use the force-field parametrization of the GCR energy spectrum, following formalism described elsewhere (Webber and Higbie, 2003; Usoskin et al., 2005, 2011). We used LIS as described by Burger et al. (2000) for both protons and α-particles. We note that this LIS may be outdated in the low energy part below several hundred MeV/nuc, and does not consider recent data from Voyager spacecraft (Stone et al., 2013; Webber and McDonald, 2013). However, the values of ϕ can be directly recalculated between different LIS models (Usoskin et al., 2005; Herbst et al., 2010).

Using this parametrization we fitted the GCR spectra as measured by PAMELA. Fits were performed by fitting spectra in the energy range from 0.3 to 100 GeV/nuc by the χ^2 method, separately for protons and α-particles, for every day of observations, which may include a few tens of orbits. During the days when the lower energy part of the spectrum was contaminated by SEPs, the lower bound of the fitting range was increased up to the energy when the contribution of SEPs becomes negligible (see Fig. 2(B)). During the day of GLE, 13-Dec-2006, no fitting was done because SEPs were essential up to the energy of several GeV/nuc making a robust fitting impossible. An example of the fit is shown in Fig. 2. The shown error bars account only for statistical uncertainties. The normalization efficiency was obtained using fitting to the high-energy range of data. This may lead to additional small uncertainties below 10%. One can see that the measured spectrum for a quiet day (panel a) can be perfectly fitted by the force-field parameterization ($\chi^2 \approx 70$ for 50 degrees of freedom) as expected from earlier studies (Usoskin et al., 2005). A new fact is that spectra of both protons and α-particles can be well parameterized by the force-field model also for the deep phase of the FD ($\chi^2 = 21$ for 39 degrees of

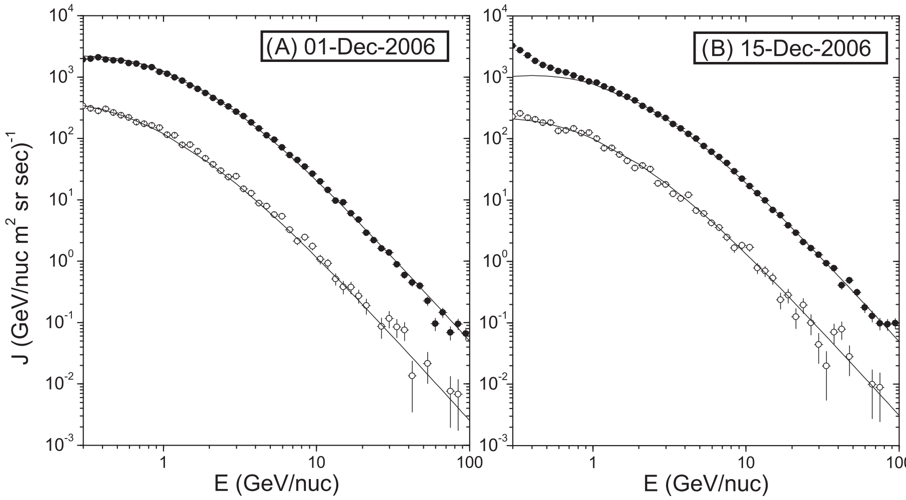

Fig. 2. Energy spectra of cosmic rays for a quiet day (01-Dec-2006, panel A) and the deepest phase of the Forbush decrease (15-Dec-2006, panel B). Solid (open) dots represent PAMELA measurements of protons (α-particles), along with uncertainties. Curves denote the best-fit force-field approximation. The excess of protons (<700 MeV) in panel B is due to solar energetic particles.

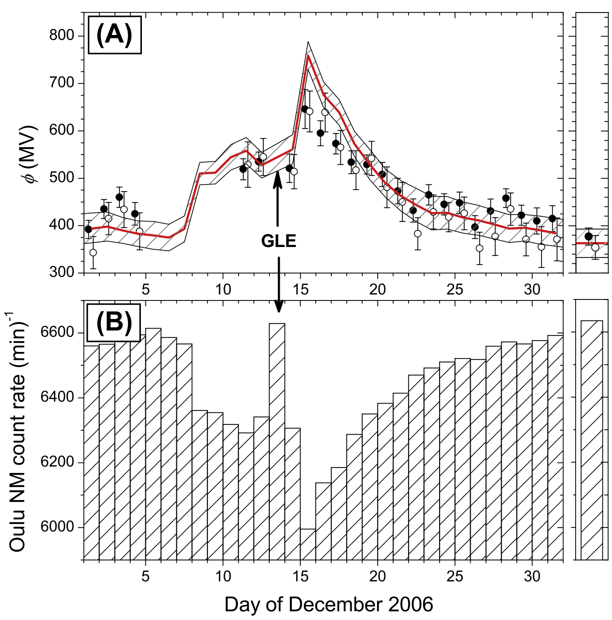

Fig. 3. (A) Modulation potential ϕ as reconstructed from the world-wide neutron monitor network (red line with 1σ uncertainties hatched) and from PAMELA data fitting for protons/α-particles (black/open dots with 1σ uncertainties). The right-hand panel shows the mean values for the quiet period of Jan–Mar 2008. (B): Daily averaged count rate of the Oulu neutron monitor. The day of GLE is indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

freedom, as shown in panel b). This forms a solid ground to the practical use of the parameterization also for the period of a FD.

Daily values of thus estimated modulation potential ϕ for protons and α-particles are shown in Fig. 3(a) as solid and open dots, respectively, along with 1σ uncertainties. One can observe that, although protons and α-particles were fitted independently, the values of ϕ always agree within the error bars. The GCR spectrum during the deep phase of the FD appears much harder than during the quite time, in agreement with earlier estimates using the neutron monitor data (Lockwood, 1971; Sakakibara et al., 1987; Lockwood et al., 1991).

4. Comparison with NM data

For the same days of December 2006, the modulation potential ϕ was reconstructed also using data from the world-wide NM network. We applied the same procedure as used by Usoskin et al. (2011), but only using daily count rates of the neutron monitors instead of monthly values. The reconstruction (along with its $\pm 1\sigma$ uncertainties) is shown in Fig. 3(a) as the hatched curve. One can see that the modulation potential forms a mirror image of the NM count rate.

Two observations are important:

(1) The ϕ values obtained for PAMELA α-particles are systematically lower by 30–50 MV than those for protons, although remaining within the error bars. This may indicate a not perfect scaling of the LIS for the two species.
(2) The ϕ values reconstructed from the NM network (Usoskin et al., 2011) are in good agreement with those obtained from a direct fit to the spectra measured by PAMELA, both for the quiet period (beginning and end of December 2006 and the reference period of 2008) and for the disturbed period (mid-December 2006). The only discrepancy slightly exceeding the error bars is observed for the very deep phase of the FD. This agreement suggests that the indirect method of the estimate of the modulation potential based on the NM network data works well.

We also compared the latitudinal dependence of the modeled FD effect with that obtained from the worldwide

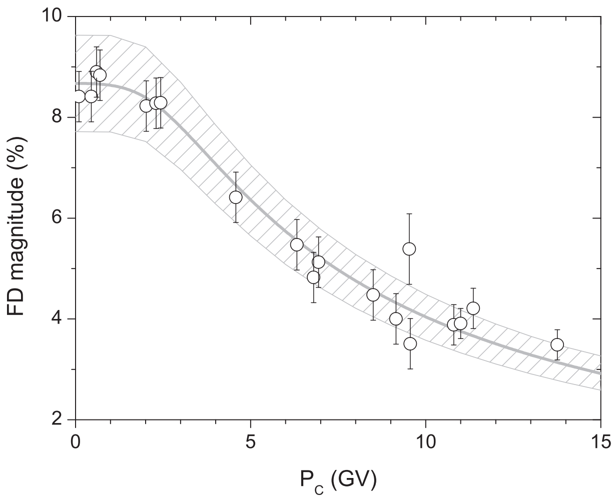

Fig. 4. Latitudinal dependence of the Forbush decrease effect (Eq. 1) for ground based neutron monitors, presented as a function of the geomagnetic cut-off rigidity P_C. The error bars are related to ambiguity of the definition of the pre-event level. The thick gray line with hatched area depicts the modeled dependence (see text) with its $\pm 1\sigma$ uncertainties. The dots represent individual neutron monitor data (left to right Barentsburg, Cape Schmidt, Apatity, Oulu, Newark, Kiel, Moscow, Hermanus, Rome, Tbilisi, Potchefstroom, Athens, Tsumeb, Mexico, Beijing, ESOI, Santiago, Mt.Norikura, Tibet).

NM network, as shown in Fig. 4. The effect is defined as the percentage decrease of the average NM count rate for the day of 15-Dec-2006 with respect to that for the day of 30-Dec-2006:

$$D = \left(1 - \frac{N_{15.12.2006}}{N_{30.12.2006}}\right) \times 100\%. \quad (1)$$

The model dependence (thick gray line with uncertainties) was computed for the values of ϕ shown in Fig. 3(a), using the method described in Usoskin et al. (2011) and the NM yield function provided by Mishev et al. (2013). One can see a very good agreement between the modeled and the observed dependencies in the entire range of geomagnetic cut-off rigidities up to 14 GV. This confirms the validity of the used approach.

5. Conclusions

We have analyzed spectra of galactic protons and α-particles in the energy range from 0.3 to 100 GeV/nuc as recorded by PAMELA experiment in December 2006 and conclude that:

- The force-field model parametrization works very well in mathematically describing the energy spectra of protons and α-particles directly measured by PAMELA mission outside the Earths atmosphere during the studied time interval. Protons and α-particles are modulated in a similar way, yielding very close values of the modulation potential. The fact that the values of ϕ obtained for α-particles are systematically slightly smaller than those for protons, possibly indicates inaccuracy of the local interstellar spectrum approximation used here.
- It is shown for the first time that the energy spectrum of GCR can be well parameterized by the force-field model also during the deep phase of a strong Forbush decrease, even though physical assumptions on the steadiness and spherical symmetry of the solar wind are obviously violated.
- Estimates of the GCR modulation parameter, based on data from the world-wide neutron monitor network, appear in good agreement with the directly measured spectra, implying that this method works well also during the periods of greatly disturbed GCR intensity.

We have analyzed the strongest Forbush decrease observed by PAMELA during first six years of its operation. Other FDs were weak (<3%) and not worth of a detailed analysis. Since this result is based on a single event analysis, an analysis of other strong FD events, provided they are covered by direct spectrum measurements, is necessary to confirm the present conclusion globally.

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