



Study of the 27-day variations in GCR fluxes during 2007-2008 based on PAMELA and ARINA observations

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Using measurements from the PAMELA and ARINA spectrometers onboard the RESURS DK-1 satellite, we have examined the 27-day intensity variations in galactic cosmic ray (GCR) proton fluxes in 2007-2008. The PAMELA and ARINA data allow for the first time a study of time profiles and the rigidity dependence of the 27-day variations observed directly in space in a wide rigidity range from ~ 300 MV to several GV. We find that the rigidity dependence of the amplitude of the 27-day GCR variations cannot be described by the same power law at both low and high energies. A flat interval occurs at rigidity $R = <0.6-1.0>$ GV with a power law index $\gamma = -0.13 \pm 0.44$ for PAMELA, whereas for $R \geq 1$ GV the power-law dependence is evident with index $\gamma = -0.51 \pm 0.11$. We have revisited the data of PAMELA and ARINA measurement and confirmed our previous results. We hope that the model of the GCR transport will explain the physical nature of the change in the shape of the rigidity spectrum of the 27-day GCR variation in the framework of a realistic picture of the CIR formation in the heliosphere.

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1. Introduction

The recurrent variations of the galactic cosmic ray (GCR) intensity and anisotropy which are due to the passage through the point of measurement of the solar wind (SW) and heliospheric magnetic field (HMF) structures rotating with the Sun, have been studied for more than 60 years [1]. According to the modern concept, the source of these structures is the longitudinal gradient of the SW velocity in the heliosphere near the Sun, connected in turn with the geometry of the flux-tube from the coronal holes into the heliosphere [2, 3]. As a result, in the inner heliosphere ($r < 1$ AU) the stream interaction regions (SIRs) are formed between the low-velocity stream and the overtaking fast-velocity stream originating from coronal holes on the Sun. The interaction region due to the rotation of the Sun, is twisted approximately into a Parker spiral. Due to the long-lived coronal holes rotating with the Sun, this structure is seen by an observer as a periodic corotating interaction region (CIR) [4]. CIRs are especially prominent during the declining phase of the solar cycle and occur usually at low latitudes, where the HMF has a well-established sector structure and coronal holes spread to low helio-latitudes. Such a situation is characteristic of periods near solar cycle minima. Consequently, the 27-day GCR variations are generally more evident and typical with longer duration during the minimum and near minimum epochs of solar activity.

The rigidity dependence of amplitude of the 27-day variation of GCR (A27) was studied in a sequence of publications by Gil and Alania [5-8], showing that the spectrum was a power-law vs. rigidity R . Gil and Alania [8] demonstrated that the power-law rigidity spectrum of the recurrent variations of the GCR intensity is harder during maximum epochs, and softer during the minimum epochs of solar activity. It was suggested that this phenomenon could be related to the changes in the effective size of the modulation region of the recurrent variations of the GCR intensity in different epochs of solar activity. The effective size of the modulation region of the GCR recurrence is smaller during minimum epochs than in maximum epochs. However, these studies concerned only the energy range covered by observations with NMs, that is, for rigidities $R > 10$ GV.

The study of GCR recurrent variations during 1992-1993 onboard Ulysses revealed a maximum in the rigidity dependence of A27 around 1 GV [9]. The recurrent GCR variations were seen from the equatorial to high helio-latitudes; and a linear relationship between the GCR latitudinal gradient and A27 was reported by [10]. This implies the existence of a modulation mechanism controlling both the global latitudinal distribution and the short-term temporal variation of GCR fluxes. Paizis et al. [11] described the rigidity dependence of A27 observed by Ulysses in 1992-1993.

It has become clear that the prominent 27-day GCR variations near the minimum of cycle 23 developed in 2007-2008, after the period of 2005-2006 analyzed by Dunzlaff et al. [12]. Owing to the wide energy range of GCRs provided by the PAMELA mission [13-15] we now have an opportunity to retrieve the rigidity spectrum of the amplitude of the recurrent GCR variations in 2007-2008 and to compare it with the result obtained by Ulysses in 1992-1993.

The paper is devoted to the well-known episode of the 27-day GCR variations in 2007-2008, near the minimum of solar cycle 23, the period exclusively favorable for the development of the pronounced and long-lived recurrent GCR variations. This episode was extensively studied based

on observations with NMs, e.g., [16, 8, 17] and space probes, e.g. [18-21]. All authors emphasized the very stable period of ~ 27 days and a strong negative correlation between the 27-day waves in GCRs and SW velocity. Correlations with the HMF strength and its components were less prominent, however. Also, for 2007-2008, Leske et al. [19] reported particle enhancements, accelerated by CIRs, observed at 1 AU during the long and deep solar minimum of 2007-2009, practically free of solar energetic particle (SEP) contamination.

Here, we present the results of the 27-day variation in GCR protons with rigidities from ~ 0.3 GV to ~ 10 GV, (kinetic energy, KE, from ~ 0.05 to ~ 10 GeV) as observed by the space-borne instruments PAMELA and ARINA in 2007-2008 (Figure 1). PAMELA observations fill the largely unexplored energy gap between the GCR particles detected in space (below a few hundred MeV) and particles detected on the Earth (KE > 10 GeV). PAMELA and ARINA data allow for the first time to study the rigidity dependence of the 27-day variation of GCRs observed directly in space over a wide rigidity range so that it is possible to investigate the time and rigidity profiles of these GCR intensity variations.

2. PAMELA and ARINA experiments

The spectrometers PAMELA [14] and ARINA [22] situated on the same spacecraft Resurs DK1, had been operational for almost 10 years since June 2006. In 2007-2008, the satellite orbit was elliptical (altitude varying between 355 and 584 km) with an inclination of about 70° and a period of about 94 minutes. The instrument allowed the measurement of protons, electrons, their antiparticles, and light nuclei in the KE interval from several tens of MeV up to several hundreds of GeV. The instrument consisted of a magnetic spectrometer with a silicon tracking system, a time-of-flight system shielded by an anticoincidence system, an electromagnetic calorimeter and a neutron detector. The data treatment is described in detail by Munini et al. [23].

The ARINA telescope was a multilayer scintillation detector consisting of 10 plates arranged as a truncated pyramid. Particles were identified by the energy loss in each detector and the path until stopping measured in the number of plates (dE/dX vs E method). The instrument detected electrons with energies of 3-30 MeV and protons with energies of 30-110 MeV. The energy resolution of the ARINA spectrometer was 10-15%. The aperture of the device was ~ 10 cm² sr. For the extraction of the galactic component, events with energy higher than the geomagnetic cutoff were selected at each registration point, on L-shells no less than 8.

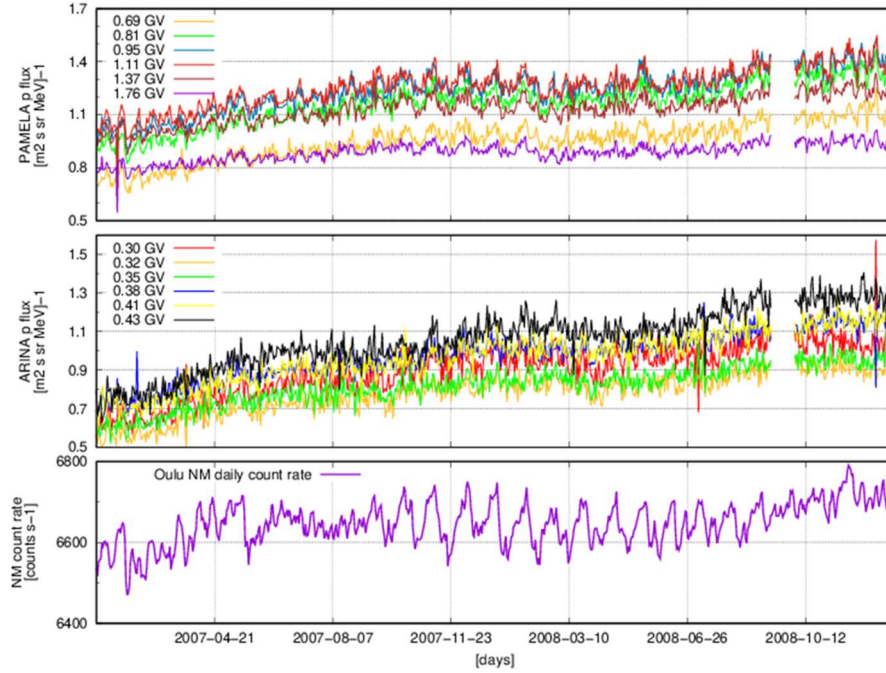


Figure 1: Daily proton fluxes for a selected range of rigidities for PAMELA (upper panel), and for ARINA (middle panel), and the Oulu NM (cutoff rigidity 0.8 GV) daily count rate (lower panel), in 2007-2008, Figure from [21].

3. Rigidity dependence of the 27-day GCR variation

We study the rigidity dependence of the amplitude of the 27-day GCR variation (A_{27}) for proton fluxes measured by the PAMELA and ARINA instruments for 2007-2008. Detailed analyses are performed for five Bartel rotations (BRs) 2377-2381 corresponding to 30 September 2007 – 11 February 2008 of the stable 27-day GCR periodicity. The A_{27} for PAMELA, ARINA, SOHO and STEREO proton fluxes as a function of rigidity R in 2007-2008 are presented in Figure 2. Figure 2 manifests a non-monotonous form of the A_{27} rigidity spectrum. For $R \geq 1$ GV it is a power-law with index $\gamma = -0.51 \pm 0.11$ for PAMELA protons. However, it flattens significantly when $R < 1$ GV which is described in the interval $R = < 0.6 - 1 > \text{GV}$ with a power-law index $\gamma = -0.13 \pm 0.44$. In addition, one can see a local minimum at $R < 0.6$ GV in the PAMELA and ARINA results. The growth of A_{27} at $R < 0.4$ GV which is seen in SOHO, STEREO, and ARINA data is probably caused by the particles accelerated by the CIR-connected shock. Analyzing the rigidity spectrum of the 27-day GCR variation on the basis of NM observations, Gil and Alania [8] found $\gamma = -1.79 \pm 0.09$ in 2007-2008 which does not agree with our finding.

It should be noted that a direct quantitative comparison between the results obtained with NM and PAMELA observations is not correct. In particular, it is not clear to what energy the NM results relate because NMs are integral energy detectors, whereas PAMELA measurements deal with differential energy bins. Moreover, it should be underlined that although the determination of the effective rigidity of NM was discussed in the literature, e.g. [24], it is not a simple issue, because the effective rigidity should be different for GCR variations with different rigidity dependence. This means that the effective rigidity of a NM for these 27-day variations may be well ~ 15 -20 GV, and the spectrum of the 27-day GCR variation may be softer at these rigidities.

To prove that a change in the spectral form indeed occurs, it is important to validate its behavior at $R < 1$ GV against other observations. Leske et al. [19, 25] studied the recurrent variations of GCRs and anomalous cosmic rays (ACRs) in the range from 10 to several hundred MeV/n and reported a flatter dependence on energy around 100 MeV/n as in Fig. 5 by Leske et al. [19] and in Fig. 4 by Leske et al. [25], which is consistent with our results. Moreover, we have examined the A27 for protons by the SOHO ERNE HED experiment [OMNI] [26] for five energy bins from 40-130 MeV/n and STEREO A and B HET observations [http://www.srl.caltech.edu/STEREO/Public/HET_public.html] for two energy bins from 40-100 MeV/n [27]. The results are shown in Fig. 2. Evidently, the presented 27-day amplitudes for SOHO ERNE and STEREO are consistent with PAMELA and ARINA measurements for overlapping energy intervals. For more details see [21].

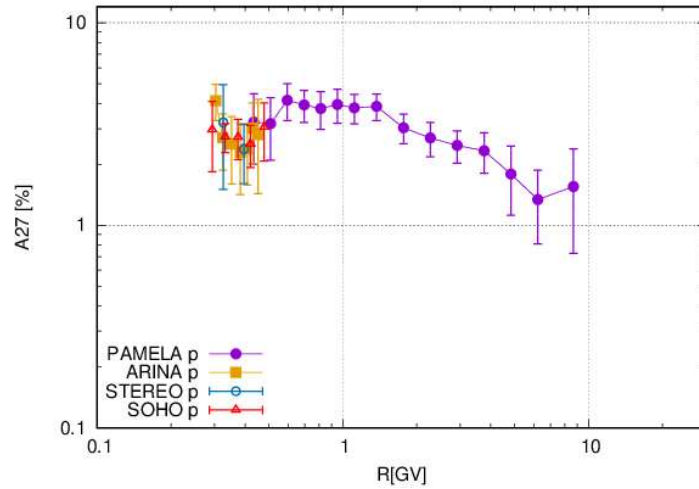


Figure 2: The A27 for *PAMELA*, *ARINA*, *SOHO* and *STEREO* proton fluxes as a function of rigidity R in 2007-2008. The solid lines through the *PAMELA* and *ARINA* data points are to guide the eye.

A clear maximum in A27 around $R \sim 1$ GV was initially observed in 1992-1994 during the out-of-ecliptic journey of the *Ulysses* spacecraft [9]. At that time, the spatial and rigidity dependences of the recurrent GCR modulation and the latitudinal GCR gradient showed remarkable similarity [28].

4. Summary

We have studied the rigidity dependence of the amplitude of the 27-day variation (A27) of the GCR intensity observed directly in space in a wide rigidity range from ~ 0.3 GV to ~ 10 GV as observed by the space-borne instruments *PAMELA* and *ARINA*. The rigidity dependence of A27 (GCR) cannot be described by the same power law at both low and high rigidities. The rigidity spectrum of A27 (GCR) manifests a non-monotonous form; for $R \geq 1$ GV a power-law dependence is noticeable with index $\gamma = -0.51 \pm 0.11$ for *PAMELA* protons; for $R = <0.6-1>$ GV the rigidity dependence becomes flatter with $\gamma = -0.13 \pm 0.44$ for *PAMELA* protons. According to *PAMELA* and *ARINA* results, a local minimum in the rigidity dependence for $R < 0.6$ GV is present. Such a flatter dependence of A27 (GCR) on energy around 100 MeV/n is also found for *SOHO* ERNE and *STEREO*, being consistent with *PAMELA* and *ARINA* measurements for overlapping rigidity intervals. We hope that the model of the GCR transport [29] will explain the

physical nature of the change in the shape of the rigidity spectrum of the 27-day GCR variation in the framework of a realistic picture of the CIR formation in the heliosphere.

References

- [1] J.A. Simpson, *Space Sci. Rev.*, 83, (1998) 169, doi: https://doi.org/10.1007/978-94-017-1189-0_15
- [2] Y.-M. Wang and N. R. Jr. Sheeley, *Astrophys. J.*, 355, (1990) 726, doi: 10.1086/168805
- [3] C. N. Arge and V. J. Pizzo, *J. Geophys. Res.*, 105, (2000) 10465, doi: <https://doi.org/10.1029/1999JA000262>
- [4] I.G. Richardson, *Living Rev. Solar Phys.*, 15, (2018) 1, doi: <https://doi.org/10.1007/s41116-017-0011-z>
- [5] A. Gil and M.V. Alania, *Adv. Space Res.*, 45, 3, (2010) 429, doi: <https://doi.org/10.1016/j.asr.2009.09.021>
- [6] A. Gil and M.V. Alania, *J. Atmospheric and Solar-Terrestrial Phys.*, 73, 2-3, (2011) 294, doi: <https://doi.org/10.1016/j.jastp.2010.01.013>
- [7] A. Gil and M.V. Alania, *Solar Phys.*, 283, 2, (2013) 565, doi: <https://doi.org/10.1007/s11207-012-0204-5>
- [8] A. Gil and M.V. Alania, *Solar Phys.*, 291, (2016) 1877, doi: <https://doi.org/10.1007/s11207-016-0924-z>
- [9] R.B. Mckibben, J.A. Simpson, M. Zhang, S. Bame, A. Balogh, (1995) In: Marsden R.G. (eds) *The High Latitude Heliosphere*. Springer, Dordrecht, doi: https://doi.org/10.1007/978-94-011-0167-7_67
- [10] M. Zhang, *Astrophys. J.*, 488, (1997) 841
- [11] C. Paizis, B. Heber, A. Raviart, et al., *Proc. 25th Inter. Cosmic Ray Conf.*, 2, (1997) 93
- [12] P. Dunzlaff, B. Heber, A. Kopp, et al., *Ann. Geophys.*, 26, (2008) 3127
- [13] P. Picozza, A. M. Galper, G. Castellini, et al., 27, (2007) 296, doi: <https://doi.org/10.1016/j.astropartphys.2006.12.002>
- [14] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, et al., *Phys. Reports*, 544(4), (2014) 323, doi: <https://doi.org/10.1016/j.physrep.2014.06.003>
- [15] M. Martucci, R. Munini, M. Boezio, et al. (PAMELA collaboration), *Astrophys. J. Lett.*, 854, (2018) L2:1-8, doi: 10.3847/2041-8213/aaa9b2
- [16] R. Modzelewska and M V. Alania, *Solar Phys.*, 286, (2013) 593, doi: <https://doi.org/10.1007/s11207-013-0261-4>
- [17] A. Gil and K. Mursula, *J. Geophys. Res.*, 123, (2018) 6148, doi: <https://doi.org/10.1029/2018JA025523>
- [18] J. Gieseler, N. Dresing, P. Dunzlaff, at al., *Proc. 31st Inter. Cosmic Ray Conf.*, (2009) 1
- [19] R. Leske, A.C. Cummings, R.A. Mewaldt, et al., *Proc. 32nd Inter. Cosmic Ray Conf.*, 11, (2011) 194, doi: 10.7529/ICRC2011/V11/0721
- [20] M.B. Krainev, G.A. Bazilevskaya, I.K. Borkut, et al., *Physics of Atomic Nuclei*, 81(9), (2018) 1355, doi: <https://doi.org/10.1134/S1063778818090156>

- [21] R. Modzelewska, G.A. Bazilevskaya, M. Boezio et al., *Astrophys. J.*, 904, (2020) 3(13), <https://doi.org/10.3847/1538-4357/abbdac>
- [22] A.V. Bakaldin, A.G. Batishchev, S.A. Voronov, et al., *Cosmic Research*, 45, 5, (2007) 445, doi: <https://doi.org/10.1134/S0010952507050085>
- [23] R. Munini, V. M. di Felice, M.Boezio, et al., *Proc.35th Inter. Cosmic Ray Conf.*, PoS(ICRC2017) (2017) 091
- [24] A. Gil, E. Asvestari, G.A. Kovaltsov, I. Usoskin, *Proc. 35th Inter. Cosmic Ray Conf.*, Busan, Korea, *Proc. of Sci.* 301, (2017) 32
- [25] R. Leske, A.C. Cummings, R.A. Mewaldt, et al., *Proc. 36th Inter. Cosmic Ray Conf.*, ICRC2019, (2019) 1105
- [26] V. Domingo, B. Fleck, and A.I. Poland, *Solar Phys.*, 162, (1995) 1, doi: <https://doi.org/10.1007/BF00733425>
- [27] T.T. Rosenvinge, D.V. Reames, R. Baker, et al., *Space Sci. Rev.*, 136, (2008) 391, doi: [10.1007/s11214-007-9300-5](https://doi.org/10.1007/s11214-007-9300-5)
- [28] C. Paizis, B. Heber, Ferrando, et al., *J. Geophys. Res.*, 104, (1999) 28241, doi: [10.1029/1999JA900370](https://doi.org/10.1029/1999JA900370)
- [29] X. Luo, M. Zhang, X. Feng, et al. *Astrophys. J.*, 899, 90, (2020) doi: <https://doi.org/10.3847/1538-4357/aba7b5>