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# 27-day variation of galactic cosmic ray intensity by PAMELA experiment. Relationship with heliospheric parameters

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**Abstract.** We analyzed the dynamics of the 27-day variation of galactic cosmic rays (GCR) using PAMELA data in the solar cycle 24 covering the period of 2006-2015. We studied the time line of the proton and helium spectra for different rigidities measured by PAMELA and compared with neutron monitor (NM) observations. We studied the relationship between the 27-day variations of GCR and heliospheric parameters: solar wind velocity and heliospheric magnetic field (HMF). We found that the 27-day variation observed by PAMELA was changing over the solar cycle 24. Near the solar minimum in the 2007-2008 it was observed the stationary 27-day variation with stable amplitude and time of maximum for almost ~8 solar rotations. Solar wind velocity and Bx component of the HMF also showed the same clear 27-day periodicity. The recurrent changes of solar wind velocity were in strong antiphase with changes of GCR. In contrary in the rising phase of the solar cycle 24 the period of quasi-recurrent GCR variations was much more variable in time and in duration, in average 27-days, but also with the strong contamination of the higher harmonics. The antiphase relation between GCR and solar wind is not so clearly pronounced. Moreover, in the rising phase of the solar cycle 24 we established in all analyzed parameters some wave packages, periodically enhanced, taking place averagely each 1.5-2 years, suggesting the occurrence of the quasi biannual oscillations (QBOs).

## 1. Introduction

Flux of galactic cosmic ray (GCR) intensity contains various quasi-periodic changes with different time scales (from hours to several years), see e.g. [1,2] and references therein. On the background of the long term solar modulation: 22 years and 11 years, connected with the global heliospheric magnetic field (HMF) and the sun spot activity cycle, respectively, the short term modulation effects - sporadic (Forbush decreases) and recurrent (periodic) -also take place.

The 27-day GCR variation is connected with the heliolongitudinal asymmetry of heliospheric conditions during the solar rotation. The 27-day GCR variation is generally more typical and longer in duration during the minimum and near minimum epochs of solar activity. The amplitudes of the 27-day variations, and other GCR variations (e.g. Forbush decreases and solar diurnal anisotropies) in the



range between few hours and few months vary, in general, in phase with the solar activity cycle, i.e. they reach the maximum values during solar activity maximum [3]. The 27-day variations of GCR are observed not only by ground based neutron monitors (NMs) [4], near Earth at L1 point by space missions (*SOHO*, *Stereo*, *ACE*, *WIND*, etc.) [5], in the inner heliosphere out of the ecliptic plane on *Ulysses* [6] and even on the *Voyager* spacecraft [7] in the outer heliosphere confirming them to be ubiquitous.

In spite of the progress has been made from the experimental (e.g. [8]) and theoretical (e.g. [9]) points of view in understanding the modulation processes governing the 27-day variation of the GCR intensity, it still remains much necessity to find new properties of the 27-day variation of GCR. Especially, up to now the relationship between the 27-day variation of GCR intensity and the heliospheric phenomena seems to be changeable over the solar cycle and is not completely understood requiring further investigation.

## 2. Data and methods

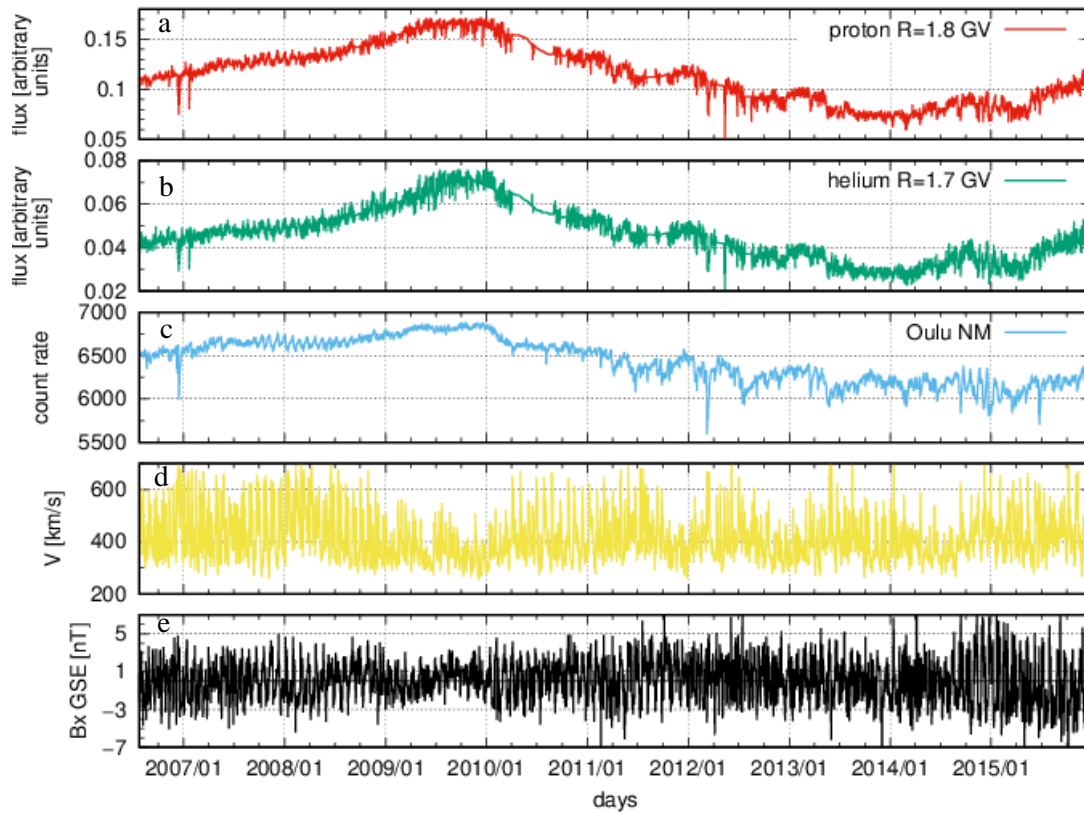
In this paper we study the dynamics of the 27-day variation of the GCR intensity in the period of 2006-2015 covering the main part of the solar cycle 24 and the minimum between the solar cycles 23 and 24 on the base of the PAMELA experiment [10]. PAMELA fills the largely unexplored energy gap between the particles detected in space (below few hundreds of MeV) and particles detected on the Earth (above few GeV). PAMELA data allow for the first time to study the time line of the 27-day variation of GCRs observed directly in space in a wide rigidity  $R$  range. Because of high statistics of PAMELA measurements and good enough accuracy it is possible to investigate the time- and rigidity-profile for different GCR particle species: proton and helium. Moreover it gives the possibility to discuss the relation of periodic GCR variations with heliospheric parameters through the solar cycle.

Here we use the daily proton and helium fluxes measured by PAMELA experiment:

- 17 rigidity bins for protons: 0.43 GV; 0.51 GV; 0.59 GV; 0.69 GV; 0.81 GV; 0.95 GV; 1.1 GV; 1.4 GV; 1.8 GV; 2.3 GV; 2.9 GV; 3.8 GV; 4.8 GV; 6.2 GV; 8.7 GV; 12.9 GV; 19.1 GV;
- 6 rigidity bins for helium: 0.89 GV, 1.2 GV, 1.7 GV, 2.4 GV, 3.4 GV, 4.7 GV

Since the main source of the 27-day GCR variation is the corotating interaction region (CIR), we also analyze the significant solar wind parameters: daily solar wind velocity  $V$  and the radial  $B_x$  component of the HMF. Figure 1 from top to bottom presents the daily proton ( $R=1.8$  GV, Fig. 1a) and helium fluxes ( $R=1.7$  GV, Fig. 1b) measured by PAMELA, Oulu NM count rate (geomagnetic rigidity cut-off  $R_c=0.8$  GV, Fig. 1c), daily solar wind velocity  $V$  (Fig. 1d) and the radial  $B_x$  component of the HMF (Fig. 1e) for 2006-2015. As far the GCR intensity displays the long period trend connected with the solar activity, we normalize to the average of 29 days and exclude a long period trend by 29-days smoothing. Results are presented in Figure 2 for the PAMELA proton, helium fluxes and the Oulu NM, respectively. It allows to study the time line of the short period (27-days) GCR variation for 2006-2015.

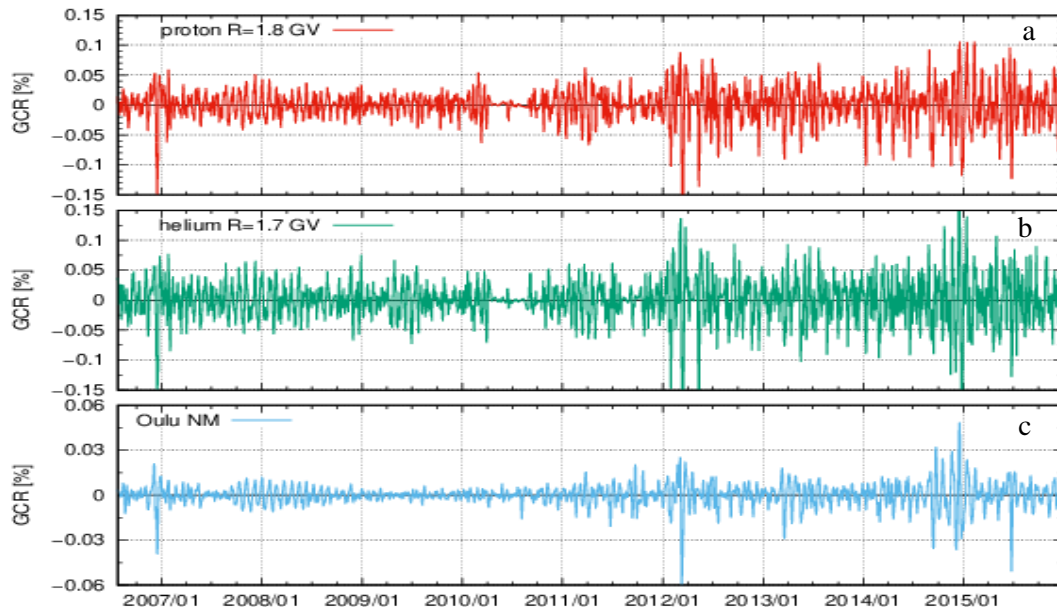
For studying the periodic character of the data series we use the Cross Wavelet Transform (XWT) [11]. This method allows to study causal relationships in time-frequency space between two time series  $X$  and  $Y$  with corresponding continuous wavelet transform for each series:  $WX_n(f)$  and  $WY_n(f)$ . Regions of high common power and consistent phase connection suggest causal relation between  $X$  and  $Y$ . The statistical significance of the Cross Wavelet Spectrum was estimated following [12] and [11].



**Figure 1.** Daily PAMELA proton ( $R=1.8$  GV), helium ( $R=1.7$  GV) fluxes, Oulu NM ( $R_c=0.8$  GV) GCR intensity count rates, solar wind velocity  $V$  and  $B_x$  component of the HMF for 2006-2015.

### 3. Analysis

First we crosscheck the normalized GCR intensity from Figure 2 measured by PAMELA with NMs data for 2006-2015. We use the NM observations with different geomagnetic cut-off rigidities  $R_c$ : Oulu ( $R_c=0.8$  GV), Apatity ( $R_c=0.65$  GV), Nain ( $R_c=0.3$  GV), Moscow ( $R_c=2.43$  GV), Rome ( $R_c=6.32$  GV) and Potchefstroom ( $R_c=7$  GV) NMs. In Figure 3ab we present the correlation coefficients vs rigidity  $R$  between NMs data and PAMELA each rigidity bin for 2006-2015 for proton and helium fluxes, respectively. Figure 3ab show that the correlation coefficients between PAMELA data and NMs observations are relatively high ( $\sim 0.60 \pm 0.01$ ) for protons and a bit lower but still high ( $\sim 0.55 \pm 0.02$ ) for helium for the rigidity interval from  $\sim 1$  GV up to  $\sim 5$  GV. It seems that PAMELA data in this rigidity interval are in good correspondence to the GCR modulation effect registered by NMs. At the same time for rigidities below 1 GV the correlation coefficients for both, proton and helium, are relatively lower. It could suggest different contamination of solar cosmic rays in PAMELA data and in NMs. Time lines of the 27-day variations (Figure 2) observed by PAMELA proton ( $R=1.8$  GV), helium ( $R=1.7$  GV) fluxes and Oulu NM ( $R_c=0.8$  GV) are similar in shape. However Figure 3ab show that the 27-day GCR intensity measured by PAMELA only for few rigidity bins between  $\sim 1$  GV and  $\sim 5$  GV is comparable with the ground-based NMs data with effective rigidity  $\sim 15$ -20 GV responsible for solar modulation. Nevertheless it should be noted that we compare the differential GCR intensity as measured by PAMELA with an integrated GCR flux above the magnetic rigidity threshold typical for each NM.

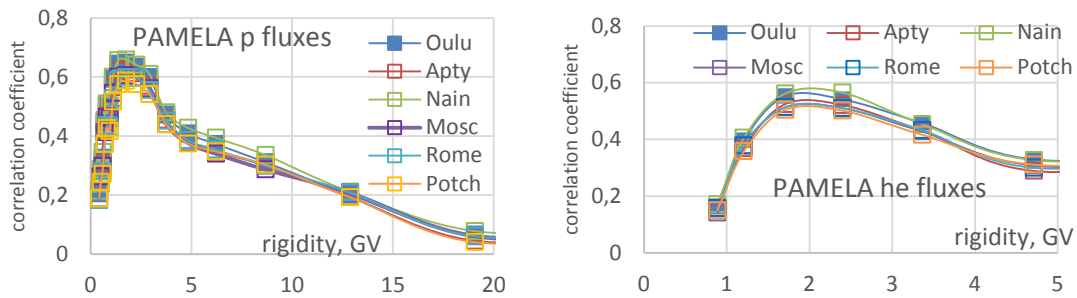


**Figure 2.** Daily PAMELA proton ( $R=1.8$  GV), helium ( $R=1.7$  GV) fluxes and Oulu NM ( $R_c=0.8$  GV) GCR intensity normalized and detrended over 29 days smoothing for 2006-2015.

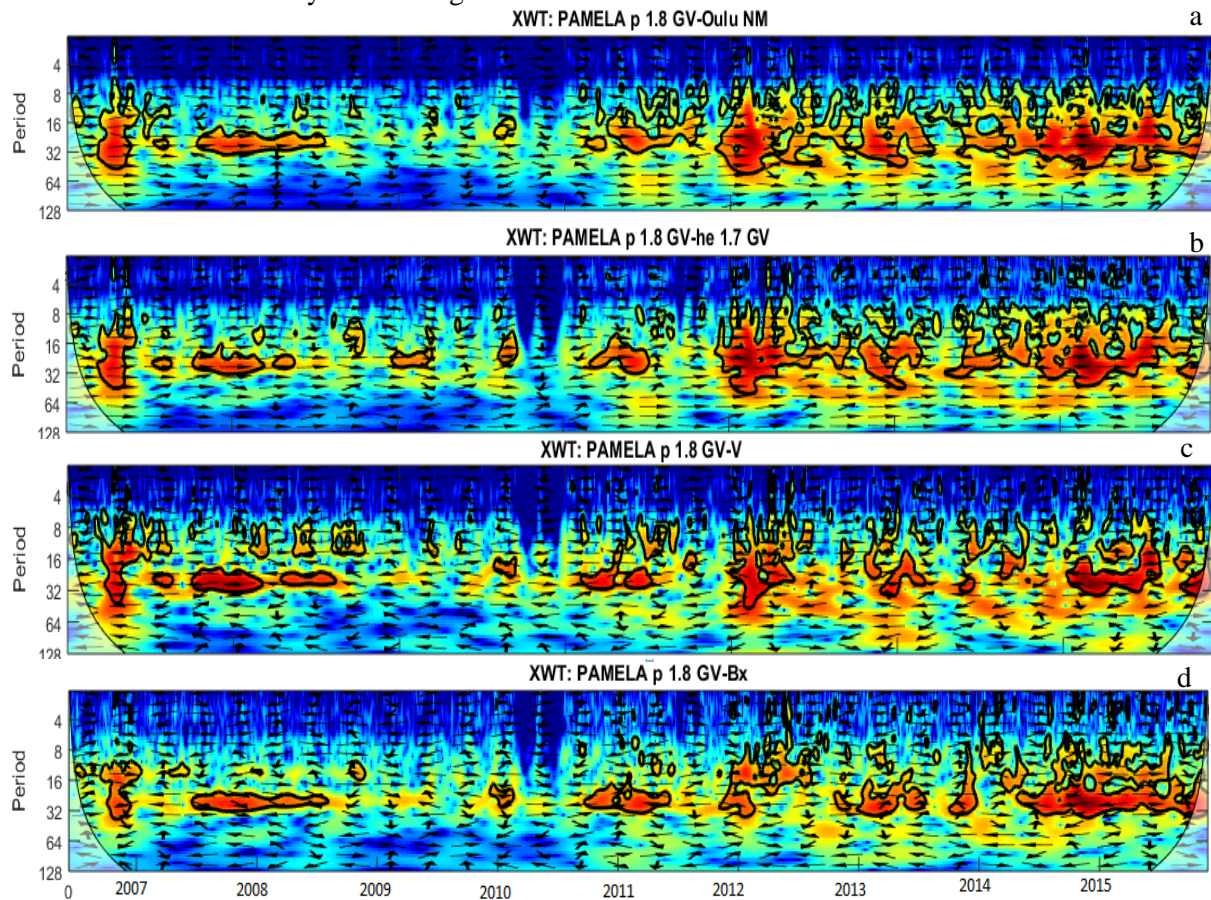
Next we analyze the relationship of quasi-periodic variations of GCR intensity and heliospheric parameters using the cross-wavelet time-frequency method (Grinsted et al., 2004). In Figures 4 we present the cross wavelet transformation XWT between (a) the PAMELA proton fluxes for  $R=1.8$  GV and the Oulu NM data, (b) the PAMELA proton fluxes for  $R=1.8$  GV and the PAMELA helium fluxes for  $R=1.7$  GV, (c) the PAMELA proton fluxes for  $R=1.8$  GV and solar wind velocity  $V$  and (d) the PAMELA proton fluxes for  $R=1.8$  GV and  $B_x$  component of the HMF for 2006-2015. The line corresponds to the 95% confidence level of the wavelet spectra. The color-bar indicates the power of a period range (from blue-low power to red-high power). The arrows indicate the phase relationship between the data series in time-frequency space: (1) arrows pointing rightward mean the in-phase behavior of the two data series; (2) arrows pointing leftward indicate antiphase behavior; (3) arrows pointing downward indicate that the first dataset phase is shifted relative to the second one by 90 degrees. Figures 4 present the time-frequency variations of GCR intensity and solar wind parameters in the main part of the solar cycle 24 and prolonged solar minimum between solar cycles 23 and 24. Figures 4abc confirm the high positive correlation between PAMELA proton and helium fluxes and both with Oulu NM for the whole interval. In the time interval of 2006-2015 one can see two different modes of behaviors of the quasi-periodic variations, plotted in Figures 4. Mainly the first period 2007-2008 corresponds to the part of the prolonged solar minimum between solar cycles 23 and 24. During this period the stationary 27-day variation of GCR was observed with stable amplitude and phase for almost  $\sim 8$  solar rotations. Heliospheric parameters: solar wind speed  $V$  and  $B_x$  component of the HMF also showed the same clear 27-day periodicity. The recurrent changes of solar wind velocity were in strong antiphase with changes of GCR. It is well known that this recurrent variation of solar wind speed are formed at CIR when a high speed solar wind stream overtakes and interacts with a slow speed stream, which was a case in 2007-2008. CIRs are especially prominent during the declining phase of the solar cycle and occur usually only at low latitudes, where the HMF has a well established sector structure and coronal holes spread to low latitudes (for a review see [13]).

The second period 2011-2015 represents the conditions of the rising phase of the solar cycle 24. Contrary to 2007-2008, in this period the quasi-recurrent GCR variations were much more variable in time and in duration, in average 27-days, but also with the strong contamination with the higher harmonics. The quasi-periodic GCR variations seem to be nonstationary [14]. The antiphase relation between GCR and solar wind  $V$  is not so clearly pronounced. Recently Gil and Mursula [15]

compared the two 2007-2008 and 2014-2015 episodes of the 27-day variation using NMs data. They suggested that in both cases the source of periodic variations was a coronal hole, but the coronal holes in the two intervals were located quite differently: a strongly north-south asymmetric polar coronal hole existed in 2014-2015 and a transequatorial coronal hole governed the periodic variations during 2007-2008. Moreover, Figures 4 show that in the rising phase of the solar cycle 24 (2011-2015) one can observe in all parameters some wave packages with the periodic enhancements of the amplitude taking place averagely each 1.5-2 years. It suggests the existing of the knowing in literature the quasi biannual oscillations (QBOs) (for review see [2]). However this topic is out of the scope of this paper.



**Figure 3ab.** Correlation coefficient between the Oulu, Apatity, Nain, Moscow, Rome and Potchefsroom NMs data and the PAMELA each rigidity bin for proton and helium fluxes normalized and detrended over 29 days smoothing for 2006-2015.



**Figure 4.** Cross wavelet transformation between (a) PAMELA proton spectra ( $R=1.8$  GV) and Oulu NM data, (b) PAMELA proton spectra ( $R=1.8$  GV) and helium spectra ( $R=1.7$  GV), (c) PAMELA proton spectra ( $R=1.8$  GV) and V and (d) PAMELA proton spectra ( $R=1.8$  GV) and Bx for 2006-2015.

#### 4. Discussion and conclusion

We studied the dynamics of the 27-day GCR variation observed by PAMELA over the main part of the solar cycle 24 and the solar minimum between solar cycles 23 and 24. We analyzed the relationship between the PAMELA proton and helium fluxes and the NMs data (normalized and detrended over 29 days smoothing) and found the high correlation for the rigidity interval  $\sim 1$  GV– $\sim 5$  GV. We showed that the time lines of the 27-day variations observed by PAMELA protons, helium and NMs are similar in shape. We studied the relationship between PAMELA data and solar wind velocity and heliospheric magnetic field over the main part of the solar cycle 24. We established that the 27-day variation observed by PAMELA was changing over the solar cycle 24. Near the solar minimum in the 2007-2008 the stationary 27-day variation was observed with stable amplitude and time of maximum for almost  $\sim 8$  solar rotations. Solar wind velocity and Bx component of the HMF also showed the same clear 27-day periodicity. The recurrent changes of solar wind velocity were in strong antiphase with changes of GCR. In contrary, in the rising phase of the solar cycle 24 the period of quasi-cycling GCR variations was much more variable in time and in duration, in average 27-days, but also with the strong contamination with the higher harmonics. The antiphase relation between GCR and solar wind is not so clearly pronounced. Moreover, in the rising phase of the solar cycle 24, we found in all analyzed parameters some wave packages, with the periodic enhancements, taking place averagely each 1.5-2 years, suggesting the presence of the quasi biannual oscillations (QBOs).

#### Acknowledgments

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