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An Unusual Pattern of Cosmic-Ray Modulation During Solar Cycles 23 and 24

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Abstract By means of an analysis of data from eight neutron monitor (NM) stations with different geomagnetic cutoff rigidities, we found an unusual latitudinal effect observed in the cosmic-ray (CR) modulation during the last solar cycles. Since the beginning of the ground-based cosmic-ray monitoring, it is known that the solar-cycle modulation is more evident in data from high latitude than from the medium and low latitudes, showing an expected geomagnetic cutoff rigidity effect. However, a more detailed look shows a new latitudinal effect in cycle 24: while the magnitude of the solar modulation in the low-latitude data remains the same for the last three solar minima, the last solar minimum caused a more intense peak in the polar NM data than in the previous cycles. After correcting the data for the geomagnetic changes of the period, we found an anomalous solar modulation in the last cycle. This suggests a weaker heliospheric modulation at low-energy particles (responsible for the NM counting in polar sites) now than in the previous cycles, while there is no significant difference of the modulation for the more energetic part of the CR spectrum. Our result can be associated with changes of the solar wind turbulence, which would corroborate some recent studies about the last solar minimum phase, and indicates that this new solar modulation feature is still present in the current solar maximum stage.

Keywords Cosmic rays, galactic · Solar cycle, observations

1. Introduction

Ground-based measurements of galactic cosmic-ray (GCR) flux are possible because their interaction with Earth's atmosphere creates the hadronic component of the atmospheric cas-

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cade, also known as atmospheric shower, that reaches the terrestrial surface in a detectable flux. Before its interaction with Earth's atmosphere, a charged particle of GCR experiences two main modulation processes: the solar (or heliospheric) modulation, which is related to the interplanetary magnetic field (IMF) and solar wind conditions, and the local geomagnetic shielding, often quantified in terms of the cutoff rigidity (P_c), which is a local threshold of the cosmic-ray (CR) energy spectrum that can penetrate the atmosphere at a certain geographical site. Therefore, studying many years of CR measurements from ground-based stations of different latitudes enables using the geomagnetic field as a giant spectrometer, gathering information concerning the CR energy spectra changes over the years, or, in other words, information about the solar modulation.

The dominant solar modulation of GCR is related to the 11-year (yr) solar activity cycle, which can be seen in ground-based neutron monitor (NM) data from all latitudes (more pronounced in high-latitude regions). The inverted 11 yr cycle observed in the flux of CR in the inner heliosphere is a result of the stronger IMF shielding and solar wind scattering of the CR particles during solar maxima periods. In addition, a 22 yr Hale cycle is also imprinted on CR time series as a modulation of the shape of the cycles (alternating sharp and flat peaks during consecutive solar minimum phases). This flat-sharp pattern in the CR data can be associated with the 22 yr polarity reversal of the solar magnetic field. In a series of articles, Jokipii and coworkers (*e.g.*, Jokipii and Thomas, 1981) modelled the drift effect due to the wavy heliospheric current sheet (HCS) on the GCR transport in the heliosphere, explaining the differences in the shape of the NM counts for solar cycles with opposite polarities. For the "negative" polarity solar minimum periods, with $A < 0$ (which is the case of the minimum between cycles 23 and 24), positively charged GCRs drift inwards to the heliopshere mostly through the equatorial regions along the wavy HCS. Thus, in these cases, the solar modulation is usually higher for the GCR low-energy component than the modulation in $A > 0$ minimum periods, producing harder GCR energy spectra during these $A < 0$ periods (Potgieter, 2013). Some other solar features can be noted in higher time-resolution data as short-term modulations, and they are mainly related to the solar transient structures such as flares or coronal mass ejections.

The role of drift as the dominant solar modulation during solar minima periods (and diffusion by the solar wind dominating the solar maxima modulation) had been verified by observations (ground- and space-based) for the last solar cycles and became an accepted conceptual paradigm. The standard theory of transport of charged particles in the heliosphere includes several main processes involved in CR modulation in addition to the diffusion and the HCS drifts: regular drifts (gradient and curvature), convection, and adiabatic energy losses. A good review of the physical basis of all the four solar modulation processes and current theoretical models can be found in Potgieter (2013) and references therein.

However, as expressed by Potgieter (2013): "the latest prolonged solar minimum brought additional insight in how this interplay [between the four solar modulation mechanisms] can change as the Sun keeps on surprising us". The solar minimum between cycles 23 and 24 was quite unusual, and the present solar maximum is the smallest sunspot cycle since cycle 14 (which peaked in 1906). Yet it is not a Grand-Minimum type of solar activity, but rather a moderate cycle (Usoskin, 2013).

In addition to the frequently reported changes in the solar and heliospheric conditions for the last solar minimum (*e.g.*, Gibson *et al.*, 2011) (especially its longer duration, weaker IMF, and the different decrease rate of the HCS tilt angle compared with the previous $A < 0$ minimum of 1987), three main anomalies observed in GCR modulation can be highlighted here:

i) Record-breaking high intensities of GCR flux were measured at the end of 2009 for ground- and space-based instruments (*e.g.*, Heber *et al.*, 2009; Starodubtsev and Grigoryev, 2011; Potgieter *et al.*, 2014; Strauss and Potgieter, 2014; Ahluwalia, 2014).
ii) There was a long time-delay between sunspot number minimum and NM count maximum (*e.g.*, Kane, 2011; Paouris *et al.*, 2012).
iii) A softer energy spectrum of GCR than expected even for the $A > 0$ period was recorded (*e.g.*, Oh *et al.*, 2013; Potgieter *et al.*, 2014).

An association of models and data enables studying the origin of these new features observed in GCR data during the latest solar minimum. For example, from comparing the HCS tilt angles with the NM counts of one ground-based station (Newark), Cliver, Richardson, and Ling (2013) first suggested (already in 2011) that the drift of charged GCR was not a dominant factor in the minimum of cycle 24, contrary to expectations. Recent studies found an association between the 2009 anomalous peak and higher values of the diffusion coefficient (*e.g.*, Alania, Modzelewska, and Wawrzynczak, 2014; Nuntiyakul *et al.*, 2014). Other studies also found evidence of the remission of the drift process in the solar modulation during the last minimum and suggested that changes in the solar wind turbulence might produce a diffusion-dominated solar modulation period (*e.g.*, Starodubtsev and Grigoryev, 2011; Potgieter *et al.*, 2014).

In fact, the solar modulation scenario looks different in the last solar cycle, and it is a challenge to understand the relative importance of the four mechanisms associated with GCR modulation during a very weak solar cycle. It has been proposed, for instance, that during periods of very weak solar activity (like the Maunder Minimum), the relation between solar activity and CRs might be inverted (Owens, Usoskin, and Lockwood, 2012).

This study aims to analyse the solar modulation imprints over the past 35 years of NM measurements from high-, mid-, and low-latitude stations, discussing not only the peculiarities of the last solar minimum, but also the curious features found in the current solar maximum stage.

The geomagnetic field continuously changed during the studied period. Accordingly, to obtain a really homogeneous series of CR intensity from an NM, its count rates need to be corrected for the geomagnetic change. Thus, we first corrected the data according to the recent changes in the geomagnetic field, which cannot be neglected when using NM data from high cutoff rigidities (or low latitudes) (Smart and Shea, 2009; Herbst, Kopp, and Heber, 2013), and then the GCR modulation was investigated for each solar cycle.

2. Data: Geomagnetic Correction and Normalization

We used here data from eight stations from the worldwide network of neutron monitors (available at www.nmdb.eu) from the last four cycles (cycles 21 to 24, 1977 throughout 2012). Table 1 contains the geographical locations of the selected stations and also the nominal geomagnetic rigidity cutoff (P_c) computed for the 1995 epoch (Shea and Smart, 2001).

Before studying the NM count temporal variations, we applied a correction for the P_c changes in the entire selected data-series, although for polar regions these changes can be neglected. For that, we computed the geomagnetic cutoff rigidity (P_c values) for each station considering an eccentric dipole approximation, using the International Geomagnetic Reference Field (IGRF) coefficients for the epochs from 1975 to 2010. All the formalism for the P_c computation can be found in the Appendix of Usoskin *et al.* (2010). This method gives reasonable accuracy values of the cutoff rigidity compared with the full model computations (Nevalainen, Usoskin, and Mishev, 2013).

Table 1 NM stations along with their geographic coordinates and nominal P_c for the 1995 epoch (corresponding to the period 1995 – 2000).

Station	P_c [GV] for 1995	Lat/Long
Apatity	0.55	67.5N 33.3E
Oulu	0.77	65.1N 25.5E
Kerguelen	1.14	49.4S 70.3E
Kiel	2.36	54.3N 10.2E
Moscow	2.3	55.5N 37.3E
Rome	6.27	41.9N 12.5E
Potchefstroom	6.85	26.7S 27.1E
Tsumeb	9.06	19.2S 17.6E

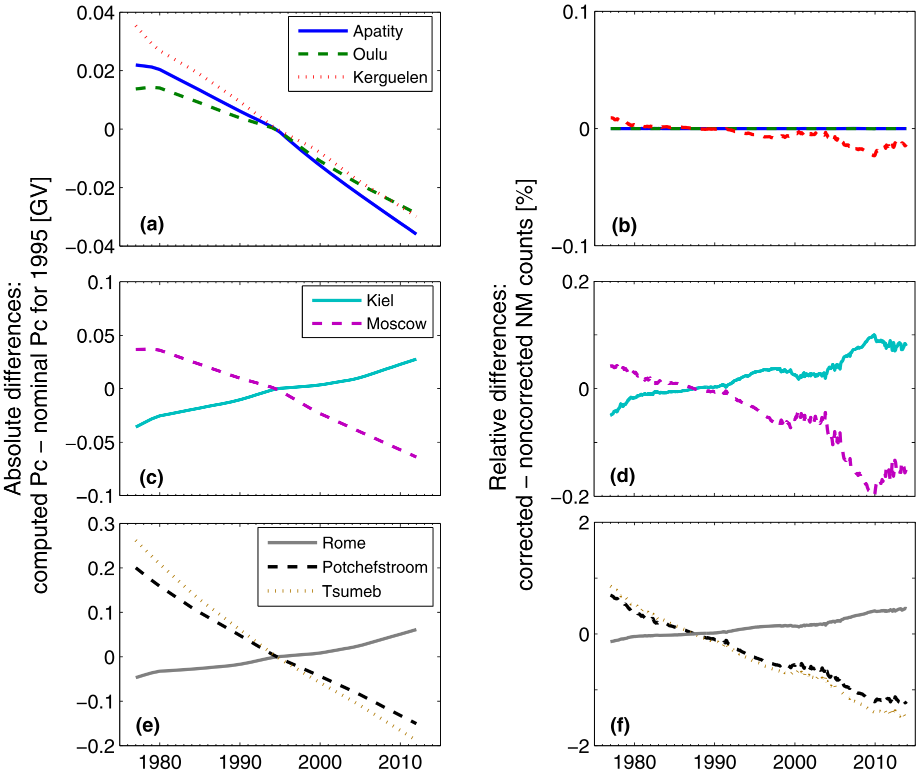

Figure 1 Left column: differences between the computed P_c for each year and the nominal values (fixed for the 1995 epoch); right column: relative differences between the actual NM counts and those corrected for changes in P_c.

The absolute differences between the computed changing P_c and the nominal P_c for 1995 epoch (listed in Table 1) are shown in Figure 1 for each station, in Figure 1(a) for the stations with low P_c, in Figure 1(c) for stations with medium P_c, and in Figure 1(e) for stations with high P_c. Owing to the geomagnetic pole migration, stations in the same P_c interval (*e.g.* Rome and Potchefstroom) can depict different temporal changes. The differences found for the low P_c stations are negligible, but can reach 0.3 GV for high P_c ones.

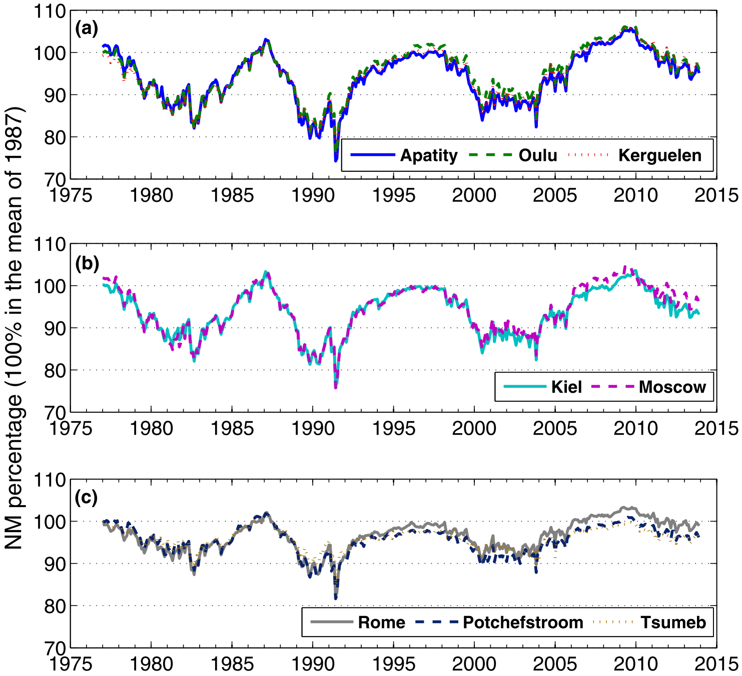

Figure 2 NM counts normalized for 100 % in the mean of 1987, and corrected for P_c changes.

To take this geomagnetic effect into account, the response of each NM station was computed using a full Monte Carlo simulation of the atmospheric cascade (describe in Mishev, Usoskin, and Kovaltsov, 2013) considering the P_c variations in time. Thus, it was possible to apply a correction for the geomagnetic changes that occurred in the studied period in the entire studied NM database. Figures 1(b), 1(d), and 1(f) present the relative differences between the NM counts measured for each station (corrected for pressure and efficiency) and those corrected also for changes in P_c. For low-latitude stations (with high P_c values), the changes can reach 1 % for the last solar cycle, which is significant compared with the 5 – 10 % solar cycle variability.

Figure 2 shows the corrected data, normalized for 100 % to the mean value of the year 1987. As expected, the solar modulation is more pronounced for high latitude stations with low P_c. However, the well-documented NM count peak of 2009 is not seen at low-latitude stations, suggesting a softer GCR energy spectrum than that in 1987 (the last solar minimum with the same polarity $A < 0$), corroborating the observations reported by Oh *et al.* (2013). In fact, a softer GCR spectrum together with a lower geomagnetic cutoff rigidity (Figure 1(e)) in 2009 compared with 1987 can explain the reduction of counts measured by Tsumeb and Potchefstroom stations. Moreover, the NM count rate during the current solar maximum is much higher than in previous maxima, and this pattern is more evident for low P_c stations as well.

3. Solar Modulation Changes

Using the datasets corrected for P_c changes and normalized for the mean value or 1987 as described above, it is possible to study changes of the solar modulation during the four

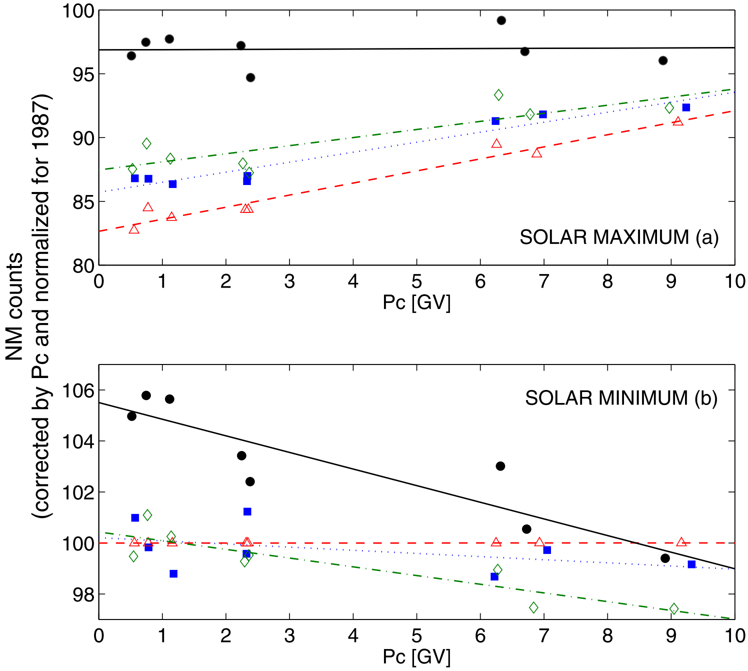

Figure 3 NM counts *vs.* P_c [GV] for years of maxima and minima of solar cycles 21 (1980 and 1977, respectively, represented by blue squares), 22 (1990 and 1987, red triangles), 23 (2000 and 1996, green diamonds), and 24 (2013 and 2009, black circles). The best linear fits are shown (cycle 21: dotted lines; cycle 22: dashed lines; cycle 23: dash-dotted lines; cycle 24: solid lines).

last solar cycles. Figure 3 shows the NM counts for each station as a function of the corresponding P_c values for the years of solar maximum (Figure 3(a)) and minimum activity (Figure 3(b)), along with their best linear fits. Solar maximum and minimum years were defined according to the inclination of the HCS (computed with the radial model[1]): HCS tilt angles $> 70°$ (1980, 1990, 2000, and 2013) and $< 10°$ (1977, 1987, 1996, and 2009), respectively. Since the solar modulation depends on the energy of GCR particles, these plots can be understood as follows: the more negative the slope of the linear fit, the larger the low-energy component of the GCR flux that reaches Earth compared with a reference year (1987, in this study), indicating a softer GCR energy spectrum. The temporal evolution of the slope values is presented in Figure 4.

As expected, the solar minimum years with $A > 0$ (1977 and 1996) present negative slopes (showing more low-energy particles of the GCR flux reaching Earth than for the 1987 flux). However, contrary to the values expected for another $A < 0$ year, the 2009 linear fit (represented by the black line that fits the black circles in Figure 3(b)) presents the most negative slope among all of the four solar minima. Figure 4 shows that the GCR spectra have systematically softened since the onset of solar cycle 23, and the most negative slopes of the NM era were found in the period between 2006 and 2010. Moreover, this period also corresponds to the highest levels of NM counts for low-P_c stations (with the 2009 level as

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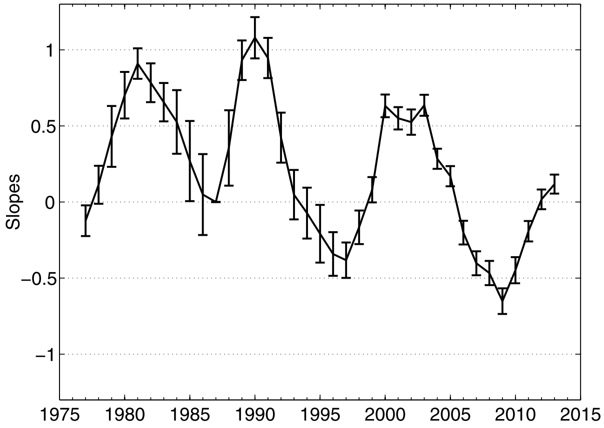
[1] http://wso.stanford.edu.

Figure 4 Temporal changes in the slopes found for the best linear fits of the NM counts *vs.* P_c [GV] relationship, compared with the 1987 behaviour. The uncertainties (1σ) of the slopes are also presented.



the highest ever), indicating a higher flux of the low-energy GCR in the heliosphere during this period, in agreement with the GCR energy spectra modelled for the primary GCR measurements from 100 MeV to 50 GeV by the *Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics* (PAMELA; Adriani *et al.*, 2014) experiment between 2006 and 2009 by Potgieter *et al.* (2014).

Based on different approaches, recent studies suggested that this new solar modulation pattern observed in the latest solar minimum cannot be explained by the "drift-dominated" paradigma and proposed the "diffusion-dominated" scenario for heliospheric modulation observed in solar cycle 24. Using numerical models, Strauss and Potgieter (2014) were only able to reproduce the GCR spectrum measured in 2009 (by space-based instrument PAMELA) when the diffusion coefficients were increased by a factor of two, although the drift was still present in the simulation. Alania, Modzelewska, and Wawrzynczak (2014) also had to apply a higher diffusion coefficient (30 % higher) for 2009 to reproduce observational data from NM. Changes in the interplanetary GCR diffusion coefficient were also reported by Nuntiyakul *et al.* (2014) as a possible drive of the curious patterns observed in latitudinal surveys of GCR between 1994 and 2007. Using solar wind *in situ* data (from the OMNI[2] database), Starodubtsev and Grigoryev (2011) found a sharp change in the residual solar wind turbulence level already after the onset of cycle 23, indicating a decrease of CR scattering in the inner heliosphere. Based on interplanetary scintillation observations between 1998 and 2008, Bisoi *et al.* (2014) reported a decrease of 8 % in the density modulation index in the inner heliosphere that might be related to the decrease in solar wind turbulence. Our results presented here support the evidence of a new dominant process that overcomes the drift in the last solar minimum.

Moreover, our analysis also includes the current solar maximum years. Figure 3(a) shows the solar modulation features during solar maximum years. The 2013 linear fit is also higher than the previous solar maximum years, and its slope is also softer. The slope found for 2013 is similar to solar minimum conditions of 1987 (Figure 4). These results indicate that the flux of GCR in the near-Earth environment is still higher than usual and the solar modulation suffered by the lower energetic ones continues to be less efficient than the modulation of previous cycles.

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[2] http://omniweb.gsfc.nasa.gov/.

4. Concluding Remarks

Thus, on the basis of the analysis of a data from eight ground-based NM stations from different latitudes (corrected by the geomagnetic temporal changes), we can conclude the following:

– More GCR particles have reached Earth in the last years, indicating that solar cycle 24 has a different and less efficient solar modulation than previous cycles during both maximum and minimum phases;

– In both maximum and minimum phases of solar cycle 24, low-energy GCR are not experiencing the same modulation as in the previous periods, which causes the differences in the counts detected by NM stations from different cutoff rigidities. This processes had started already at the onset of cycle 23 and is probably related to the reduced IMF turbulence, from spacial scales of a few hundred km (Bisoi *et al.*, 2014) up to 10^7 km (Starodubtsev and Grigoryev, 2011), which affects the GCR propagation in the inner heliosphere.

These results, obtained using NM data alone, agree with recent studies that used models and *in situ* observations of solar wind conditions and supports the idea that there is a new balance between the four solar modulation processes observed in the present solar cycle.

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