Recurrence of galactic cosmic-ray intensity and anisotropy in solar minima 23/24 and 24/25 observed by ACE/CRIS, STEREO, SOHO/EPHIN and neutron monitors

Fourier and wavelet analysis

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ABSTRACT

Aims. We studied the 27-day variations of galactic cosmic rays (GCRs) based on neutron monitor (NM), ACE/CRIS, STEREO, and SOHO/EPHIN measurements in the solar minima 23/24 and 24/25, which are characterized by the opposite polarities of solar magnetic cycle. We used the opportunity to reanalyze the polarity dependence of the amplitudes of the recurrent GCR variations in 2007–2009 for the negative A < 0 solar magnetic polarity and to compared it with the clear periodic variations related to solar rotation in 2017–2019 for positive A > 0.

Methods. We used the Fourier analysis method to study the periodicity in the GCR fluxes. Because the GCR recurrence is a consequence of solar rotation, we analyzed not only GCR fluxes, but also solar and heliospheric parameters to examine the relations of the 27-day GCR variations and heliospheric as well as solar wind parameters.

Results. We find that the polarity dependence of the amplitudes of the 27-day variations of the GCR intensity and anisotropy for NMs data is kept for the last two solar minima: 23/24 (2007–2009) and 24/25 (2017–2019), with greater amplitudes in the positive A > 0 solar magnetic polarity. ACE/CRIS, SOHO/EPHIN, and STEREO measurements are not governed by this principle of greater amplitudes in the positive A > 0 polarity. The GCR recurrence caused by the solar rotation for low-energy (<1 GeV) cosmic rays is more sensitive to the enhanced diffusion effects, resulting in the same level in 27-day amplitudes for the positive and negative polarities. In contrast, the high-energy (>1 GeV) cosmic rays that are registered by NMs are more sensitive to the large-scale drift effect, which leads to the 22-year Hale cycle in the 27-day GCR variation, with the larger amplitudes in the A > 0 polarity than in A < 0.

Key words. Sun: general – Sun: activity – Sun: heliosphere – solar wind – Sun: rotation

1. Introduction

The galactic cosmic-ray (GCR) spectrum observed near Earth is considerably controlled by solar activity. The transport of GCRs in the heliosphere is governed by the solar wind and the combination of the regular and turbulent heliospheric magnetic field (HMF). Through the interaction of GCRs with solar wind and the HMF, the GCR spectrum below a few dozen GV is modulated with respect to the local interstellar spectrum (LIS; Potgieter 2013). The GCR flux is subject of solar modulation that produces various quasi-periodic changes on different timescales (from hours to several years), see, for example, Usoskin (2017), Kudela & Sabbah (2016), Chowdhury et al. (2016), Bazelevskaya et al. (2014) and references therein. The most prominent periodic variations are the 22-year, 11-year, 27-day and the solar diurnal variation (24 hours). On the background of the long-term solar modulation of 22 years and 11 years, which is connected with the global HMF and the solar activity cycle, respectively, the short-term sporadic (Forbush decreases) and recurrent (periodic) modulation effects also take place.

The 27-day variation of the GCR intensity and anisotropy, which is related to the solar rotation, is the main topic of this paper. This phenomenon is connected with the heliolongitudinal asymmetry of the heliospheric parameters, which are affected by corotating interaction regions (CIRs); for a review, see (Richardson 2004, 2018). The Sun rotates at different rates depending on the heliolatitudes, which is called differential rotation. The equator and near equatorial regions of the Sun rotate on its axis with a period of about 25–26 days. This is called the solar sidereal rotation period. For an observer on Earth, this periodicity equals 27–28 days because of the orbital motion of Earth. This is called the solar sinodial rotation period. At its polar regions, the period value of the solar rotation is about 36 days. The recurrent GCR variations with a period of ~27 days are generally more typical and longer during and near solar minimum. The amplitudes of the 27-day variations and of other GCR variations (e.g., Forbush decreases and solar diurnal anisotropies) in a range of a few hours and a few months in general vary in phase with the solar activity cycle, that is, they reach maximum values during solar activity maximum (e.g., Bazelevskaya 2000). Recurrent structures in GCR fluxes with a period of ~27 days are observed on Earth by neutron monitors (NMs; Modzelewska & Alania 2013), in space by Advanced Composition Explorer (ACE; Leske et al. 2011), for instance, out of the ecliptic plane by Ulysses (Mckibben et al. 1995), and even in the distant heliosphere by the Voyager spacecraft (Decker et al. 1999).

Richardson et al. (1999) showed for the first time that the amplitude of the recurrent GCR variation is larger when A > 0.

* Dedicated to the memory of Michael Alania.
(A is the global direction of the HMF) than during adjacent minima when \( A < 0 \). The polarity dependence of the amplitude of the 27-day variation of the GCR intensity has so far mainly been considered quantitatively by NM observations (Alania et al. 2001; Gil & Alania 2001; Vernova et al. 2003). It was also confirmed using mathematical modeling of GCR heliospheric transport (e.g., Iskra et al. 2004). Later, Alania et al. (2005, 2008), Gil et al. (2005) showed that the amplitudes of the 27-day variation of the GCR anisotropy are also polarity dependent at solar minimum, with greater values when \( A > 0 \) than in the \( A < 0 \) polarity period. The polarity dependence of the 27-day amplitude of the GCR intensity registered by NMs has recently been confirmed experimentally by Gil & Marsula (2017), who explained it by a combination of the drift effect and solar wind convection.

In this paper we extend the quantitative study of the 27-day variations of the GCR intensity for the lower part of the energy spectrum using spacecraft data of SOHO/EPHIN, STEREO, and ACE/CRIS. We can now reanalyze the polarity dependence of the recurrent variations related to solar rotation in the solar minimum 23/24 in 2007–2009 when \( A < 0 \) and compare it with the clear periodic variations related to solar rotation in the solar minimum 24/25 in 2017–2019 when \( A > 0 \). Because the GCR recurrence is a consequence of solar rotation, we analyze not only GCR fluxes, but also solar and heliospheric parameters to examine the relation between the 27-day GCR variations and heliospheric as well as solar wind parameters.

The paper is organized as follows: in Sect. 2 we describe the data we analyzed and the methods we used in this paper. In Sect. 3 we study the polarity dependence of the amplitudes of the 27-day GCR variations. In Sect. 4 we analyze the relation of the periodic GCR variation with heliospheric parameters. In Sect. 5 we discuss the results. In Sect. 6 we conclude.

2. Data and methods

We analyzed the daily data of the GCR proton flux for SOHO/EPHIN and for STEREO A and B for the solar minimum 23/24 when \( A < 0 \) in 2007–2009 and for the solar minimum 24/25 when \( A > 0 \) in 2017–2019. STEREO B data are not available in 2017–2019. We also did this for ACE/CRIS GCR fluxes of carbon, nitrogen, oxygen, neon, silicon, and iron. Additionally, we updated the calculations for the daily GCR intensity and anisotropy for NMs with different cutoff rigidities, from 0.65 GV to 4.58 GV located at Hermanus, Newark, Kerguelen, Oulu, and Apatity.

We studied the dynamics of the recognized periodicity connected with solar rotation using the Lomb periodogram (Lomb 1976) and adapted the procedure from (Modzelewska & Alania 2013). We calculated the power of the periodic variation connected with solar rotation for a period of 27 ± 2 days with a 95% confidence level. This high period from the Lomb periodogram indicates the main period of the recurrent GCR variations in the analyzed time series. As an example, panel a in Fig. 1 presents STEREO A daily proton fluxes for a kinetic energy of 40–60 MeV and 60–100 MeV for the solar minimum 23/24 when \( A < 0 \) in 2007–2009. Panel b in Fig. 1 presents the normalized and detrended (by excluding the 29-day running average) GCR intensity. The time line of the power of the recurrent variations lasts 25–29 days, and the recognized main period for each Bartel rotation (BR) are displayed in panels c and d of Fig. 1, respectively. Figure 2 presents data and Lomb analysis results of STEREO A for the solar minimum 24/25 when \( A > 0 \) in 2017–2019. Figures 1 and 2 demonstrate the existence of the periodic variations in GCR intensity related to solar rotation for the last two solar minima with opposite solar magnetic polarity: 23/24 in 2007–2009, and 24/25 in 2017–2019. The high power of the very famous episode in the 27-day variation when \( A < 0 \) in 2007–2008 (Fig. 1) is clearly visible, as are clear periodic variations when \( A > 0 \) in 2017–2018 (Fig. 2) for both energy bins. The same data processing was applied to STEREO B, SOHO/EPHIN, ACE/CRIS, and NMs data, and it revealed similar results.
3. Polarity dependence of the amplitudes of the 27-day variations

First we studied the polarity dependence of the amplitude of the 27-day variation using NMs data from locations in Hermanus, Newark, Kerguelen, Oulu, and Apatity. We updated the calculations for the 27-day variation of the GCR anisotropy \(A27A\) (Modzelewska & Alania 2018) and intensity \(A27I\) (Gil & Mursula 2017) for the solar minima 23/24 and 24/25. The average amplitudes of \(A27A\) and \(A27I\) for the last two solar minima are presented in Fig. 3 and Table 1. The average of \(A27A\) and \(A27I\) is polarity dependent, with greater amplitudes when \(A > 0\) in 2017–2019 for the solar minimum 24/25 than for \(A < 0\) in 2007–2009 for the solar minimum 23/24.

\[
\begin{array}{lll}
A27A[\%] & A < 0 & A > 0 \\
Apatity & 0.13 \pm 0.01 & 0.15 \pm 0.01 \\
Kerguelen & 0.13 \pm 0.01 & 0.15 \pm 0.01 \\
Newark & 0.12 \pm 0.01 & 0.17 \pm 0.02 \\
Oulu & 0.13 \pm 0.01 & 0.16 \pm 0.02 \\
Hermanus & 0.11 \pm 0.01 & 0.13 \pm 0.01 \\
\end{array}
\]

\[
\begin{array}{lll}
A27I[\%] & A < 0 & A > 0 \\
Apatity & 0.41 \pm 0.04 & 0.64 \pm 0.05 \\
Kerguelen & 0.34 \pm 0.04 & 0.48 \pm 0.05 \\
Newark & 0.34 \pm 0.04 & 0.54 \pm 0.07 \\
Oulu & 0.42 \pm 0.05 & 0.52 \pm 0.05 \\
Hermanus & 0.25 \pm 0.02 & 0.43 \pm 0.05 \\
\end{array}
\]

Figure 4 and Table 2 present the average \(A27I\) of the GCR proton intensity for SOHO/EPHIN and STEREO A and B for the \(A > 0\) and \(A < 0\) polarities. The average amplitudes of \(A27A\) and \(A27I\) are shown in Fig. 4 and Table 2 and are consistent with the results presented in Table 1.

\[
\begin{array}{llll}
A27I[\%] & A < 0 & A > 0 \\
SOHO/EPHIN & & \\
25–40.9 & 3.94 \pm 0.00 & 3.04 \pm 0.36 \\
40.9–53 & 4.25 \pm 0.00 & 3.44 \pm 0.37 \\
STEREO A & & \\
40–60 & 2.17 \pm 0.20 & 2.65 \pm 0.20 \\
60–100 & 1.61 \pm 0.20 & 1.83 \pm 0.10 \\
STEREO B & & \\
40–60 & 2.80 \pm 0.30 & \\
60–100 & 1.40 \pm 0.10 & \\
\end{array}
\]

Figure 4. Same as in Fig. 3 for the 27-day variation of the GCR proton intensity recorded by SOHO/EPHIN and STEREO A and B.

The calculations for the 27-day variation of the GCR anisotropy \(A27A\) (Modzelewska & Alania 2018) and intensity \(A27I\) (Gil & Mursula 2017) for the solar minimum 23/24 and 24/25. The average amplitudes of \(A27A\) and \(A27I\) for the last two solar minima are presented in Fig. 3 and Table 1. The average of \(A27A\) and \(A27I\) is polarity dependent, with greater amplitudes when \(A > 0\) in 2017–2019 for the solar minimum 24/25 than for \(A < 0\) in 2007–2009 for the solar minimum 23/24.

The average amplitudes of \(A27A\) and \(A27I\) for the last two solar minima are presented in Fig. 3 and Table 1. The average of \(A27A\) and \(A27I\) is polarity dependent, with greater amplitudes when \(A > 0\) in 2017–2019 for the solar minimum 24/25 than for \(A < 0\) in 2007–2009 for the solar minimum 23/24.

\[
\begin{array}{llll}
A27A[\%] & A < 0 & A > 0 \\
Apatity & 0.155 \pm 0.007 [\%] \\
Kerguelen & 0.125 \pm 0.004 [\%] \\
Newark & 0.520 \pm 0.030 [\%] \\
Oulu & 0.350 \pm 0.030 [\%] \\
\end{array}
\]
for the GCR flux of high-mass nuclei registered by ACE/CRIS remain on the same level for both polarities for all considered species.

4. Periodic GCR variations and heliospheric parameters

We considered daily data of solar and heliospheric parameters, such as the sunspot number (SSN), the solar radio flux (SRF), the solar wind speed (SWs), the temperature (SWT), the density (SWd), the HMF strength ($B$), and the components ($B_x$, $B_y$, $B_z$). First, we used a cross-wavelet transform to trace a possible coherence between cosmic rays and the above-mentioned time series around the time of solar rotation. We performed the cross-wavelet spectrum and the wavelet coherence analysis for each of the above data in the pair with the GCR flux from the Oulu NM for the two solar minima. The cross-wavelet analysis is built on the basis of a continuous wavelet transform. It consists of two wavelet transforms. The signal is decomposed into a scaled and a shifted version of a wavelet that is a function of two variables: translation and scale. The wavelet transform is localized in the time and frequency domain. In our calculations we followed Torrence & Webster (1999) using tools developed by Jevrejeva et al. (2003) and Grinsted et al. (2004). From a comparison of the solar minima 23/24 and 24/25 it is clear that in all of the studied parameters, the 27-day variation was prevalent in both time intervals, although it was more constantly visible during the first minimum (e.g., Modzelewska & Alania 2013; Gil & Mursula 2018; Jian et al. 2019).

The relations in time-frequency domain around the solar rotation period between the GCR and other studied time series were analyzed using the cross-wavelet transform (XWT). Figure 7a shows the cross-wavelet analysis results for the cosmic rays and sunspot number. The cosmic-ray changes were mostly led by the SSN of $\sim$135–150 deg. This behavior was much weaker in the SRF performance. Figure 7c shows that SWs and GCR were in antiphase in June 2019 to September 2019. During other time intervals when GCR and SWs had high common power, from February to June 2017 or from September 2018 to January 2019, SWs led the GCR of $\sim$120–135 deg.
Similar changes were observed in the case of SWT, but the opposite direction in phase distribution was true in the case of Swd (Fig. 7d). Tracing the time evolution of the high mutual power of the HMF strength $B_x$ and the GCR (Fig. 7b), they were in antiphase in May 2019 to June 2019. In February to March 2017, $B_y$ and GCR were in phase. A much stronger common power was observed between the HMF components $B_x$, $B_y$ and $B_z$ and the GCR.

Figure 8a presents results of the coherence analyses between the cosmic-ray flux measured by the Oulu NM and the solar activity level expressed by its proxy, that is, the SSN. In some time intervals, the SSN leads the GCR on average by $\sim 27$ days between cosmic rays and the solar wind velocity (Modzelewska & Alania 2012), and the GCR WTC. Figure 8c displays a significant coherence at a period of $\sim 70–100$ deg. Between January and March 2018, a period of a phase agreement and GCR (Fig. 7b), they were in antiphase in May 2019 to June 2019. In February to March 2017, $B_y$ and GCR were in phase. A much stronger common power was observed between the HMF components $B_x$, $B_y$ and $B_z$ and the GCR.

Table 3. Amplitude of the 27-day variation of the GCR intensity for carbon, nitrogen, and oxygen by ACE/CRIS for the $A > 0$ and $A < 0$ polarities.

<table>
<thead>
<tr>
<th>A27I[%]</th>
<th>$A &lt; 0$</th>
<th>$A &gt; 0$</th>
<th>E[MeV/n]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_x$</td>
<td>47.8–61.2</td>
<td>3.06 ± 0.26</td>
<td>3.00 ± 0.24</td>
</tr>
<tr>
<td>$B_y$</td>
<td>62.6–84.0</td>
<td>3.33 ± 0.30</td>
<td>3.30 ± 0.27</td>
</tr>
<tr>
<td>$B_z$</td>
<td>103.6–119.2</td>
<td>4.31 ± 0.32</td>
<td>3.91 ± 0.36</td>
</tr>
<tr>
<td>$B_{total}$</td>
<td>148.6–161.1</td>
<td>4.17 ± 0.36</td>
<td>3.84 ± 0.34</td>
</tr>
</tbody>
</table>

Table 4. Amplitude of the 27-day variation of the GCR intensity for neon, silicon, and iron by ACE/CRIS for the $A > 0$ and $A < 0$ polarities.

<table>
<thead>
<tr>
<th>A27I[%]</th>
<th>$A &lt; 0$</th>
<th>$A &gt; 0$</th>
<th>E[MeV/n]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_x$</td>
<td>51.4–65.8</td>
<td>4.67 ± 0.53</td>
<td>6.93 ± 0.54</td>
</tr>
<tr>
<td>$B_y$</td>
<td>67.3–90.4</td>
<td>5.55 ± 0.46</td>
<td>5.24 ± 0.49</td>
</tr>
<tr>
<td>$B_z$</td>
<td>91.5–110.6</td>
<td>7.25 ± 0.64</td>
<td>6.13 ± 0.50</td>
</tr>
<tr>
<td>$B_{total}$</td>
<td>145.3–159.4</td>
<td>7.52 ± 0.69</td>
<td>7.94 ± 0.78</td>
</tr>
</tbody>
</table>

5. Discussion

The polarity dependence of the 27-day variation of the GCR has so far been explained by several approaches, for example, polarity-dependent diffusion coefficients (Richardson et al. 1999; Richardson 2004), the helio-latitudinal asymmetry of the solar wind velocity (Modzelewska & Alania 2012), and a combination of solar wind convection and drift effects (Gil & Mursula 2017). Richardson et al. (1999) suggested that the response of the cosmic rays to the solar wind speed enhancements seems to be diminished in $A < 0$. Furthermore, they interpreted it in the sense of an $A$-dependence of the transport coefficients (Chen & Bieber 1993), especially by a decrease in radial diffusion coefficient that may increase the effect of the solar wind convection during $A > 0$. It has to be underlined that

Similar changes were observed in the case of SWT, but the opposite direction in phase distribution was true in the case of Swd (Fig. 7d). Tracing the time evolution of the high mutual power of the HMF strength $B_x$ and the GCR (Fig. 7b), they were in antiphase in May 2019 to June 2019. In February to March 2017, $B_y$ and GCR were in phase. A much stronger common power was observed between the HMF components $B_x$, $B_y$ and $B_z$ and the GCR.
Richardson et al. (1999) did not show any remarkable differences in solar wind structures between \( A > 0 \) and \( A < 0 \). In contrast, Modzelewska & Alania (2012), Alania et al. (2008) showed that the heliolongitudinal distribution of the phase of the 27-day variation of the solar wind velocity demonstrated that a long-lived (\( \sim 22 \) years) active heliolongitude exists on the Sun preferentially for the \( A > 0 \), which is the source of the long-lived 27-day variation of the solar wind velocity. It could later be considered as the general source of the 27-day variations of the GCR intensity and anisotropy. Moreover, Modzelewska & Alania (2012) showed that the amplitudes of the 27-day variation of the solar wind velocity were about twice as high for the \( A > 0 \) epochs than for the \( A < 0 \). As a consequence, it was shown by Alania et al. (2008), Gil et al. (2005), Modzelewska & Alania (2012) that recurrent changes of the solar wind velocity were crucial in the modulation mechanism of the 27-day variation of GCR in the minimum epoch of solar activity. In a sequence of papers, Alania et al. (2010, 2011), Modzelewska & Alania (2013) therefore studied this theoretically and successfully reproduced the 27-day variation in the GCR observed by NMs during 2007–2008. This model was based on the Parker transport equation that incorporates the recurrent changes in solar wind speed and consistent divergence-free HMF with a full 3D anisotropic diffusion tensor (Alania 1978, 2002). In contrast, Kota & Jokipii (2001) used a nonstationary transport model that incorporated the southward displacement of the heliospheric current sheet (HCS) and CIRs effect in order to reproduce the polarity dependence of the 27-day variation.

The polarity dependence of the 27-day amplitude of GCR has recently been confirmed experimentally by Gil & Mursula (2017), who explained it as a combination of the drift effect and solar wind convection. Gil & Mursula (2017) based on the computed amplitudes of the first two harmonics of the recurrent variation of GCR intensity during 1964–2016 showed for the first time that the mean values of amplitudes in the solar minima show a clear declining trend. Gil & Mursula (2017) stated that this may be due to the weakening of the polar magnetic fields during the previous four solar activity cycles (Smith & Balogh 2008) and
the subsequent growth, in the heliolatitudes, of the HCS range (e.g., Virtanen & Mursula 2010). This means that the Earth has spent more time within the HCS in conditions of the slow solar wind in the last solar minimum, leading to a significant decrease in the amplitudes of the two harmonics. Moreover, the relative damping of the second harmonic was stronger because it was more probable that the Earth was outside the HCS once, than twice, and even more times during a single solar rotation (Gil & Mursula 2017).

Recently, Leske et al. (2019) and Ghanbari et al. (2019) compared the 27-day variations of GCRs in the solar minima 23/24 and 24/25 based on ACE data. Leske et al. (2019) stated that the amplitude of the GCR variations is similar during the last two minima 23/24 (2007–2009) and 24/25 (2017–2019), even though the anomalous cosmic-ray (ACR) variation is substantially weaker in 2017–2019 than in the previous minimum in 2007–2009. They proposed that the cause of the recurrent variations is not only the polarity of the HMF by the bidirectional latitudinal gradient near the HCS (even when the HCS is crossed more than once per solar rotation, the clear 27-day variation still persists). Moreover, they found that the direction of HCS intersections is not a crucial factor, but it seems more important whether the observer changes position during HCS intersections, that is, the observer leaves the area below the dominant coronal hole or enters it. Ghanbari et al. (2019) proposed that the convection of the solar wind does not play a significant role in the vicinity of CIRs and indicated that the GCR intensity is inversely proportional to the perpendicular diffusion coefficient around CIR.

Engelbrecht & Wolmarans (2020) studied the values for the several hemispheric turbulence quantities significant for the GCR modulation such as magnetic variances, squared HMF magnitudes, as well as the parallel and perpendicular proton mean free path at Earth as a result of the cosmic-ray long-term modulation model and concluded that the diffusion and drift coefficients of GCR protons do not deviate much from each other during the previous minima. The need of including turbulence analysis when GCR characteristics is investigated was also underlined (Engelbrecht & Wolmarans 2020). Zhao et al. (2018) and Caballero-Lopez et al. (2019) used the spacecraft observations and analyzed the turbulence properties versus solar cycle, and subsequently found the solar cycle dependence of cosmic-ray diffusion coefficients derived from the quasilinear and nonlinear theories.

This paper showed that the 27-day variations in GCR anisotropy and intensity observed by NMs are larger in A > 0 than in A < 0 polarity. The same was recently reanalyzed for IMP8 for the previous solar cycles (Shen et al. 2020), confirming the results of Richardson et al. (1999). This effect may be naturally linked to the A-dependent drift effect in the global HMF. However, the 27-day variations of lower energy (<1 GeV) GCR protons registered by STEREO A and B and SOHO/EPHIN and high-mass species by ACE/CRIS observed in the solar minima 23/24 and 24/25 remain at the same level and seem not to be polarity dependent. The solar minima 23/24 and 24/25 are characterized by the highest GCR intensity of any of the previous A > 0 and A < 0. At the same time, we can observe the diminishing trend in the 27-day amplitudes by IMP8 (Shen et al. 2020) and NMs (Gil & Mursula 2017), most probably due to a weakening of the solar polar fields. As a consequence, the GCR particle drifts may be suppressed by diffusion (turbulence) in the background weakening B; this mechanism has been suggested previously by e.g. Minnie et al. (2007). de Simone et al. (2011) found that the value of the bidirectional latitudinal gradient measured for low-energy protons by Ulysses and PAMELA is lower than expected from theories.

Recent variations connected with the solar rotation for low-energy (<1 GeV) cosmic rays are more sensitive to the enhanced diffusion effects, leading to the same level of the 27-day amplitudes for A > 0 and A < 0 polarities. High-energy (>1 GeV) cosmic rays observed by the NMs with an effective energy 10–15 GeV are more sensitive to the large-scale drift effect, resulting in a larger amplitude of the 27-day GCR variations in the A > 0 polarity than in the A < 0. This agrees with theoretical expectation of the drift-reduction factor in terms of the rigidity caused by turbulence reported by Engelbrecht et al. (2017). Moloto & Engelbrecht (2020) employed this reduction factor and found that long-term GCR modulation effects can be explained by the solar-cycle-dependent interplay of drift and diffusion, which were moderated by the solar-cycle-dependent effect of turbulence on the GCR drift coefficient.

In spite of the progress that has been made from the experimental and theoretical point of view in understanding the modulation processes governing the 27-day variation of the GCR intensity and anisotropy, the problem is not entirely solved to date. Because the GCR modulation around CIR is so complex, more sophisticated numerical models (e.g., Luo et al. 2020; Guo & Florinsky 2016; Wiengarten et al. 2016; Wawrzynczak et al. 2015) should be tested on this problem in the future.

6. Conclusions

We confirmed the polarity rule in the behavior of the amplitudes of the 27-day variations of the GCR anisotropy and intensity observed by NMs in the solar minima 23/24 (2007–2009) and 24/25 (2017–2019). Larger amplitudes are observed for the A > 0 polarity epoch.

The amplitudes of the 27-day variations of the GCR intensity observed by ACE/CRIS, STEREO A and B, and SOHO/EPHIN in the solar minima 23/24 and 24/25 remain at the same level and do not seem to be polarity dependent.

Recent variations connected with the solar rotation for low-energy (<1 GeV) cosmic rays are more sensitive to the enhanced diffusion effects, leading to the same level of the 27-day amplitudes for A > 0 and A < 0 polarities. In contrast, high-energy (>1 GeV) cosmic rays observed by NMs are more sensitive to the large-scale drift effect, resulting in the 22-year Hale cycle of the 27-day GCR variations, with larger amplitudes in the A > 0 polarity than in A < 0. Nevertheless, processes around CIR are more complex and need further study, for example, because modulation and acceleration of cosmic rays around stream interaction regions compete.


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