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Hale cycle and long-term trend in variation of galactic cosmic rays related to solar rotation

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ABSTRACT

Context. Galactic cosmic ray (GCR) intensities around solar minimum times are modulated by magnetic drifts that depend on the overall solar polarity. GCR intensities reach a higher but more narrow peak during negative minima than during positive minima. However, despite these higher intensities, the variation of GCRs over timescales of solar rotation is smaller during negative minima than during positive minima.

Aims. We study the variation of GCR intensity over the 27-day synodic solar rotation and over the 14-day half-rotation, in particular the long-term trend and cyclic pattern of this variation, and propose a unifying explanation for the observations.

Methods. We used two high-latitude neutron monitors, Oulu and Apatity, which are most sensitive to the low-energy part of the GCR spectrum and thereby more strongly affected by the changes in the conditions of the local heliosphere. We calculated the yearly mean amplitudes of the GCR intensity variation during the full solar rotation (A_{27}) and half-rotation (A_{14}) in 1964–2016.

Results. We verify that the A_{27} and A_{14} amplitudes exhibit a clear 22-yr Hale cycle during solar minima at both stations, with larger amplitudes in positive minima. We find that the mean amplitude of the Hale cycle is about 30–45% of the mean amplitude for A_{14}, while is only about 15–30% for A_{27}. We also find that all amplitudes depict a declining long-term trend, which we suggest is due to the weakening of solar polar magnetic fields during the last four solar cycles and the ensuing latitudinal widening of the heliospheric current sheet (HCS) region. An exceptionally wide HCS region during the last solar minimum, when A_{14} reached its all-time minimum, is demonstrated by Ulysses probe observations.

Conclusions. Our results emphasize the effect of polarity-dependent drift and the properties of the HCS in modulating the variation of GCR intensity during solar rotation in solar minimum times. The second rotation harmonic yields a larger Hale amplitude than the first because it is more probable for the Earth to be outside the HCS only once during the rotation than twice or more, which more strongly reduces A_{14} during negative polarity times than A_{27}. With the HCS region widening from minimum to minimum, the decrease in A_{14} is relatively faster than in A_{27}.

Key words. Sun: general – Sun: rotation – Sun: heliosphere

1. Introduction

Periodicities of about 27 days that are due to the synodic rotation of the Sun are observed in several parameters of solar activity, such as sunspot numbers, or solar UV or radio fluxes, and in the solar wind (SW). The variation in galactic cosmic ray (GCR) intensity with solar rotation was first studied by Forbush (1938) using a network of ionization chambers (for reviews, see Kudela et al. 2010; Richardson 2004; Vernova et al. 2003, and references therein). Richardson et al. (1999) showed based on observations by space probes and neutron monitors in 1954–1998 that the amplitude of the 27-day variation of GCRs depicts the 22-yr Hale cycle. The Hale cycle consists of two successive 11-yr solar activity cycles (also called Schwabe cycles) of opposite magnetic field polarities (Hale et al. 1919). Alania and coauthors (Alania et al. 2001; Gil & Alania 2001) confirmed that the 27-day amplitude of GCR variation is larger during positive-polarity minima ($A > 0$, magnetic field lines directed outward from the northern pole) than negative ($A < 0$, magnetic field lines directed outward from the southern pole), in contradiction to the expectation (e.g., Kota & Jokipii 1991) that the 27-day variation is the same for both polarities.

Kota & Jokipii (2001) used a non-stationary three-dimensional model of GCR transport that included a southward-shifted heliospheric current sheet and corotating interaction regions (CIRs) to demonstrate the polarity dependence of rotation-related quasi-periodic variations of GCR intensity. Iskra et al. (2004) suggested that the 27-day variation of GCR intensity has a larger amplitude during $A > 0$ minima because the drift stream has the same direction as the convection stream during these times, but they are oppositely directed during $A < 0$. They attributed the 27-day variation of GCR intensity to the heliolongitudinal asymmetry of the SW in the inner heliosphere. Modzelewska & Alania (2013) used simulations to show that the product of the SW speed and the strength of the heliospheric magnetic field (HMF) plays an important role in creating the 27-day GCR intensity variation. GCR intensity variation and SW parameters are also known to have a higher correlation during positive minima than during negative minima (Singh & Badruddin 2007; Sabbah 2007).

Dunzlaff et al. (2008) proposed that coronal hole structures differ in $A > 0$ and $A < 0$ minima, leading to a 22-yr variation in CIRs. Abramenko et al. (2010) found that the area occupied by the near-equatorial coronal holes (±40°) was larger in the recent ($A < 0$) minimum between solar cycles 23 and 24 than in the minimum before. Alania et al. (2008) studied the phase distribution of the 27-day variation in SW speed and found more stable and long-lived heliolongitudinal structures during $A > 0$ minima, possibly affecting the amplitude of 27-day variation of GCR intensity and causing the observed Hale cycle dependence. Burger et al. (2008) used a Fisk-type hybrid field in modeling the GCR intensity variation and also found a larger 27-day variation during positive-polarity minima.

Here we calculate the amplitudes of the GCR intensity variation during the full synodic solar rotation period (A_{27}) and half-rotation period (A_{14}) in 1964–2016. We find that both amplitudes depict a strong 22-yr Hale cycle in addition to the dominant 11-yr solar cycle, with both amplitudes being larger during positive than during negative minima. We show that both A_{27} and A_{14} display a declining trend during solar minima, which is most likely related to the weakening of the solar polar magnetic fields during the last four solar cycles. The paper is organised as follows: Sect. 2 presents the data and methods. In Sect. 3 we present and discuss our results. In Sect. 4 we give our conclusions.

2. Data and methods

Since the amplitude of the rotation related GCR intensity variation is more pronounced in the lower cutoff-rigidity stations (Fonger 1953; Simpson 1954) and neutron monitors measure cosmic rays with a lower energy of between 1–50 GeV (Nagashima et al. 1989; Simpson 2000), we analyse cosmic ray measurements by two high-latitude neutron monitors, Apatity (latitude 67.57° N, effective vertical cutoff-rigidity of 0.65 GV; data retrieved from `pgia.ru` and `nmdb.eu`) and Oulu (65.05° N, 0.8 GV; `cosmicrays.oulu.fi`). We consider the time interval from 1964 to 2016 (only half a year in 2016), and study not only the 22-yr variability, but also the long-term trend in the rotation-related variation of the cosmic ray intensity. Using daily data from the two above detectors, we computed the two harmonic amplitudes A_{27} and A_{14} as follows (see e.g. Xue & Chen 2008): for each consecutive 27-day period we calculated the amplitude for the first ($k = 1$) and second ($k = 2$) harmonics:

$$H_k = \sqrt{a_k^2 + b_k^2}, \tag{1}$$

where

$$a_k = \frac{1}{T/2} \sum_{n=1}^{T} x(t_n) \cos \frac{\pi k t_n}{T/2} \tag{2}$$

and

$$b_k = \frac{1}{T/2} \sum_{n=1}^{T} x(t_n) \sin \frac{\pi k t_n}{T/2} \tag{3}$$

are the coefficients of the Fourier series

$$\begin{aligned} x(t_n) &= \frac{a_0}{2} + \sum_{k=1}^{T/2} \left(a_k \cos \frac{2\pi k t_n}{T} + b_k \sin \frac{2\pi k t_n}{T} \right) \\ &= \frac{a_0}{2} + \sum_{k=1}^{T/2} \left(A_k \sin \left(\frac{2\pi k t_n}{T} + \varphi_k \right) \right), \end{aligned} \tag{4}$$

and $x(t_n)$ denotes the daily NM count rates ($T = 27$ days). From now we call the amplitudes of the full solar rotation period $H_1 = A_{27}$ and of the half-rotation period $H_2 = A_{14}$. After calculating the amplitudes for each rotation, we excluded from further consideration all solar rotations that are affected by Forbush decreases (Cane et al. 1996; Richardson & Cane 2011; Musalem-Ramirez et al. 2013). After this, to emphasize the long-term evolution and to eliminate short-term disturbances, we calculated the yearly means of the two amplitudes and smoothed them with a three-year running mean.

3. Results and discussion

Figure 1 depicts the amplitudes of the first (A_{27}) and second (A_{14}) harmonics of GCR intensity variation for the Oulu and Apatity neutron monitors. Figure 1 illustrates the dominant 11-yr cycle in A_{27} and A_{14} with maxima around solar maxima and minima around solar minima (Meyer & Simpson 1954). However, in addition to this 11-yr cycle, there is a systematic 22-yr variation in the level of both amplitudes around solar minima, verifying the above-discussed polarity dependence (Richardson et al. 1999; Gil & Alania 2001). The amplitudes of the two harmonics of the GCR intensity variation are larger during each positive-polarity minimum than the corresponding amplitudes during the previous or the following negative-polarity minima. During maximum times of solar activity, the 22-yr cycle in A_{27} or A_{14} amplitude is not as systematic as during solar minima because other factors more important than drifts, in particular the merged interaction regions (Balogh & Erdõs 2013; Burlaga et al. 2003; Burlaga & Ness 1994), affect the variation of GCRs at these times.

The upper panels of Figs. 2 and 3 present the lowest values of A_{27} and A_{14}, respectively, for the two stations for all solar minima included in Fig. 1. They further visualise the systematic 22-yr cycle of GCR variation around solar minima. In addition, they show evidence of a systematic decreasing trend in both A_{27} and A_{14}, which is seen for both stations. We have calculated the best-fit lines to the available five points in each case and include them in the upper panels of Figs. 2 and 3. The fits are fairly highly correlated with the observations (the correlation coefficients for the four cases are given in Table 1), but the small number of data points reduces the statistical significance.

The lower panels of Figs. 2 and 3 show the detrended values of A_{27} and A_{14}, which further clarify the Hale cycle. We estimated the mean amplitude of the 22-yr variation by fitting a 22-yr sine function to the five points in each of the lower panels of Figs. 2 and 3. The amplitudes and correlation coefficients of the sine fits are also included in Table 1 (we also tested other close-by periods and found fairly similar high correlations). We found very high correlation coefficients (above 0.97) for all other cases except for A_{27} of Apatity, where it was high, but considerably lower than for the other cases. This is due to the rather high value of A_{27} of Apatity during the last solar minimum, which clearly contrasts the evolution observed in Oulu, for example (see Fig. 2).

The sine amplitudes for A_{27} and A_{14} are about 0.04–0.07 and 0.06–0.09, respectively. (We note that for A_{27} of Apatity and A_{14} of Oulu, for which the two maxima have rather different levels, the three-parameter sine fit tends to yield excessively large amplitudes. Amplitudes in Table 1 for these cases (given in parenthesis) are obtained by fixing the fit phase, unlike in the other cases, where it was left as a free parameter.) Comparing these to the typical 22-yr amplitudes for the mean minimum time levels, the relative variations are roughly 15−30% for A_{27} and 30−45% for A_{14}. Accordingly, the 22-yr cycle is considerably stronger in the amplitude of the second harmonic than in the first harmonic. We also note that the amplitudes for these high-latitude stations (Oulu and Apatity) follow the common polarity rule even during

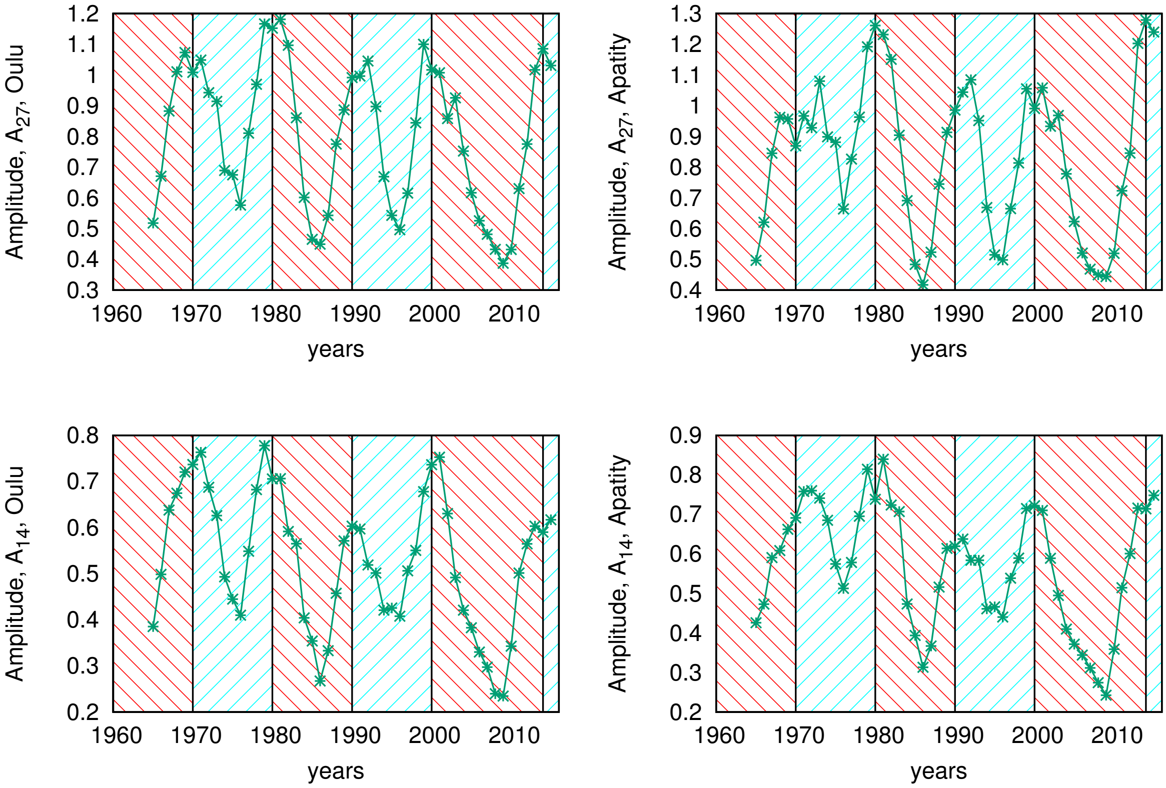

Fig. 1. Three-year running means of yearly averaged amplitudes of the first (A_{27}, *upper panels*) and the second (A_{14}, *lower panels*) harmonics of GCR for the Oulu (*left panels*) and Apatity (*right panels*) neutron monitor count rates in 1964–2016 during $A > 0$ epochs (cyan boxes with upward lattice) and $A < 0$ epochs (red boxes with downward lattice).

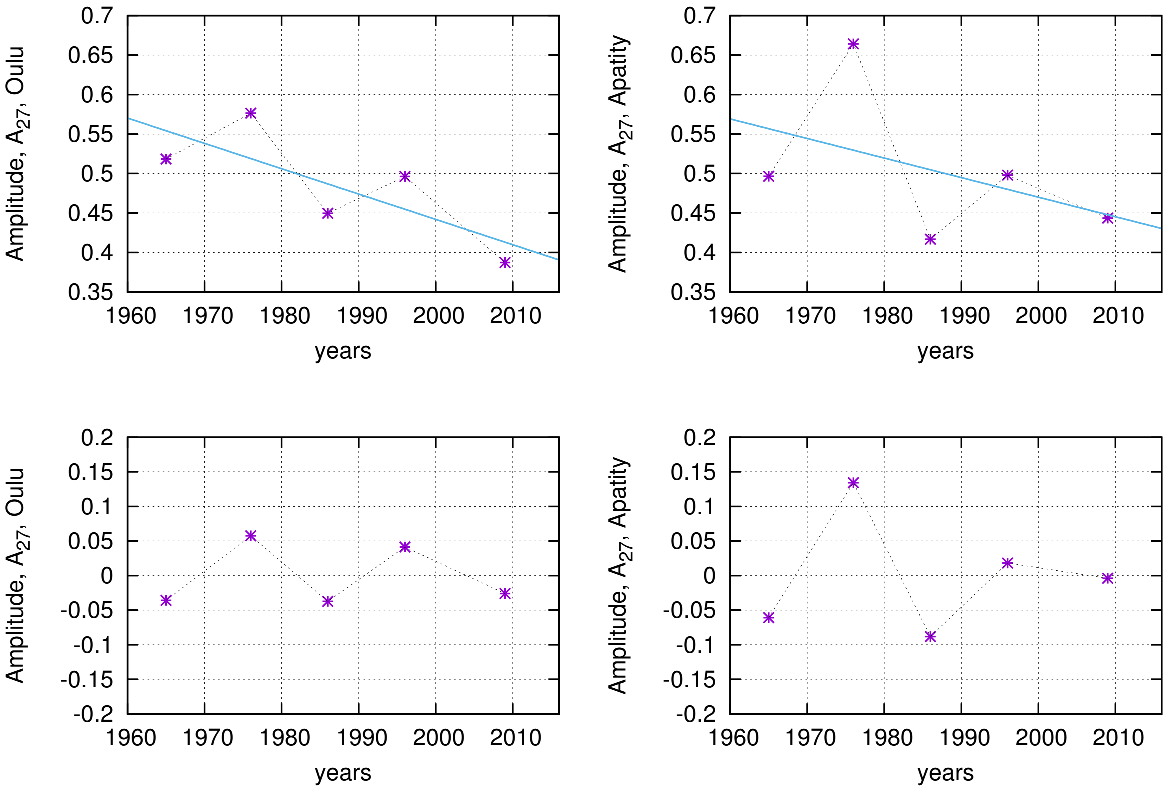

Fig. 2. Three-year means of amplitude of the first (A_{27}) harmonic of GCR for the last five solar minima with linear trend (*upper panels*) and detrended (*lower panels*) for the Oulu (*left panels*) and Apatity (*right panels*) neutron monitor count rates.

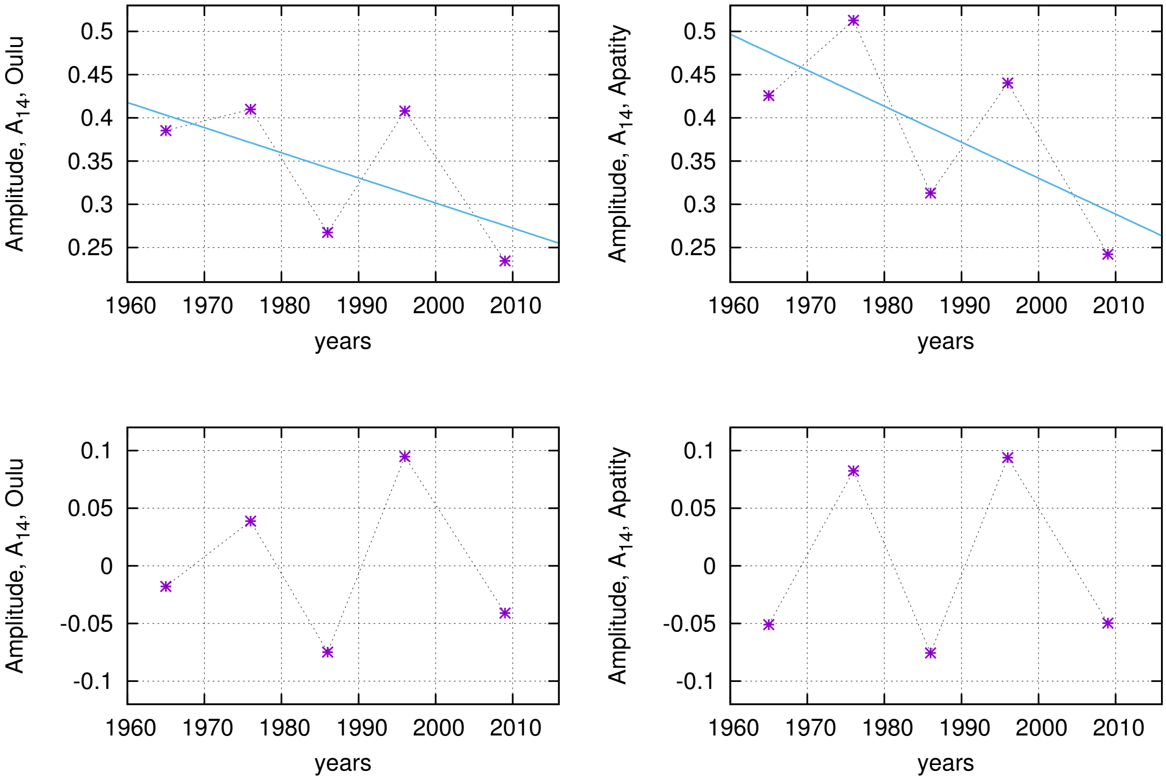

Fig. 3. Three-year means amplitude of the second (A_{14}) harmonic of GCR for the last five solar minima with linear trend (*upper panels*) and detrended (*lower panels*) for the Oulu (*left panels*) and Apatity (*right panels*) neutron monitor count rates.

Table 1. Correlation coefficients (cc) for linear fits of observational points and sine fits of detrended data.

Amplitude	Line fit cc	Sine fit cc	Sine fit amplitudes
A27 for Oulu	0.77	0.98	0.04
A27 for Apatity	0.44	0.73	(0.07)
A14 for Oulu	0.59	0.97	(0.06)
A14 for Apatity	0.66	0.99	0.09

the recent minimum, contrary to the Kiel and Moscow stations (Gil et al. 2012; Modzelewska & Alania 2012), where the amplitudes during the previous (negative-polarity) minimum were at the same level as during the (positive-polarity) minimum in the 1990s.

Figures 1 and 3 show that the (undetrended) A_{14} amplitudes experienced their all-time lowest values during the last prolonged solar minimum. This behaviour can be explained by the specific structure of the heliospheric current sheet (HCS) during the last solar minimum. Figure 4 shows the SW speed measured by Ulysses during the first (Smith et al. 1995) and the third (Ebert et al. 2009) fast latitude scan. The extent of the HCS region (the slow SW speed region around the solar equator) in 05.2007–11.2007 ($A < 0$) clearly was considerably larger than in 12.1994–05.1995 ($A > 0$) (e.g. Virtanen & Mursula 2010). During the first scan in 1994–1995, Ulysses showed clearly separate areas of slow and fast SW, but during 2007, the boundary between the slow and fast SW regions was less sharp. Table 2 shows the maximal northern and southern extents of the HCS region during seven Carrington rotations around the first scan in 12.1994–05.1995 (upper panel of Table 2) and around the third scan in 05.2007–11.2007 (lower panel)[1]. The extent of the HCS region in 2007 is much broader than in 1994–1995. The large extent of the HCS region in 2007 is connected to the weak polar fields in the declining phase of cycle 23 (e.g. Smith & Balogh 2008). Thus, the Earth spent more time deep inside the HCS region of the slow SW during the last solar minimum, leading to rather constant heliospheric conditions and a significant decrease in A_{27} and A_{14}. Moreover, the relative damping of A_{14} is stronger because it is more probable that the Earth is outside of the HCS region.

Table 2. Maximal northern and southern extents of the HCS region during seven Carrington rotations of 1994–1995 and seven Carrington rotations of 2007[1].

CR	Starting day	North	South
1890	1994-12-03	18.1	–28.3
1891	1994-12-31	17.6	–26.5
1892	1995-01-27	14.8	–27.2
1893	1995-02-23	16.8	–22.0
1894	1995-03-23	20.4	–31.3
1895	1995-04-19	19.4	–31.3
1896	1995-05-16	16.5	–31.6
2057	2007-05-24	29.2	–37.9
2058	2007-06-21	28.6	–35.4
2059	2007-07-18	28.3	–32.4
2060	2007-08-14	30.1	–32.6
2061	2007-09-10	27.1	–32.5
2062	2007-10-08	26	–32.2
2063	2007-11-04	23.6	–37.2

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

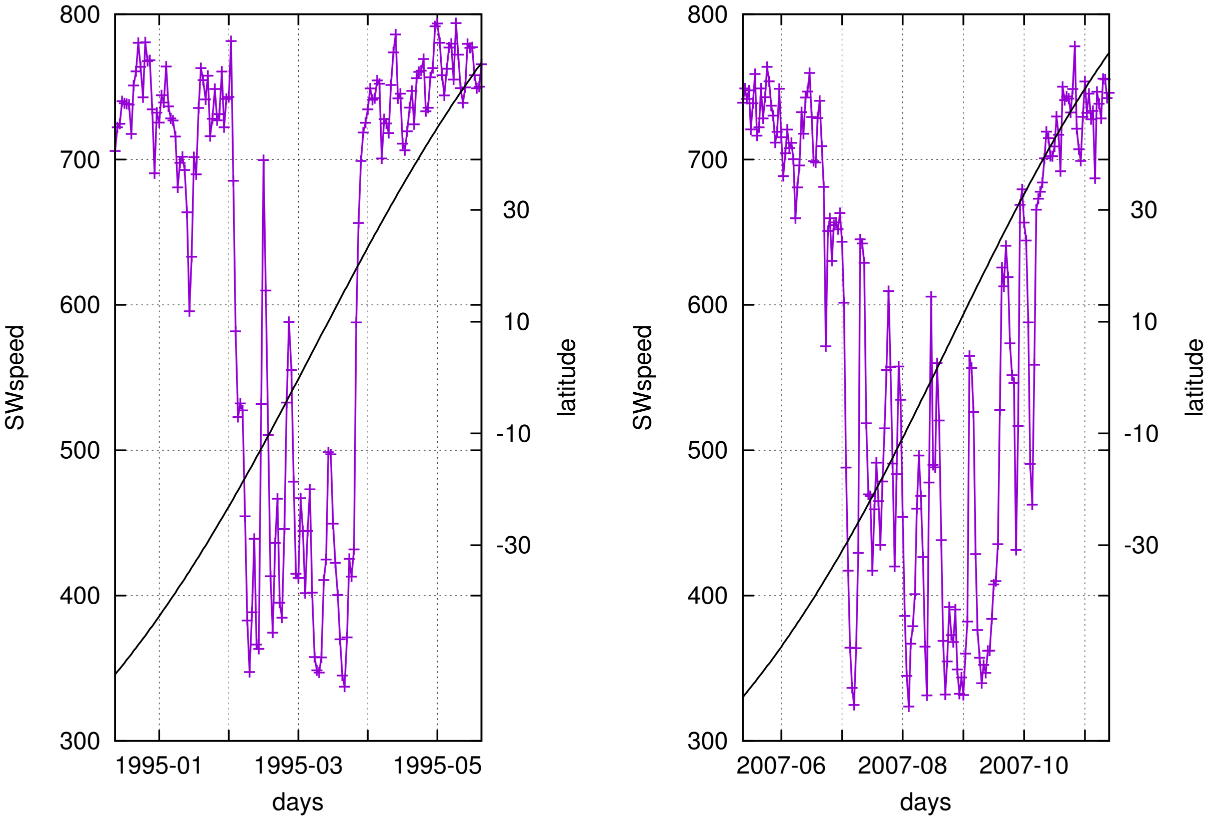

Fig. 4. Daily SW speed measured by Ulysses during the first (12.1994–05.1995, *left panel*) and the third (05.2007–11.2007, *right panel*) fast latitudinal scan. The black dash-dotted curve (y-axis on the right) illustrates the latitudinal position of the space probe during that period.

Owing to the drift pattern during negative polarity minima (Jokipii & Thomas 1981), the GCR particles preferentially drift inward along the HCS at low heliolatitudes, where the SW speed is low, and therefore the effect of convection remains small. Instead, the properties of the HCS, in particular its extent, play a dominant role at this time. On the other hand, during $A > 0$, GCRs drift over a wider range of heliolatitudes, and they also meet a faster SW, which increases convection. Thus, GCRs arriving at Earth have experienced quite different SW conditions during one solar rotation at these times. This increases the rotational variability amplitudes during positive-polarity times. These differences in GCR conditions during positive and negative polarity times lead to the Hale cycle in the rotation amplitude of GCR variation. Accordingly, the related Hale cycle is due to the different drift patterns of GCRs and the different causes of modulation during the two polarity times: during $A < 0$, the properties of the HCS play the dominant role, during $A > 0$, the latitudinal variation of SW is important. Figure 5 schematically presents the directions of convection and drift during $A > 0$ and $A < 0$. With the long-term decrease in solar polar fields (during the last four solar cycles) and the related widening of the HCS region, the A_{14} amplitude is relatively more affected than A_{27} during the negative-polarity times, leading to a larger Hale cycle in A_{14}.

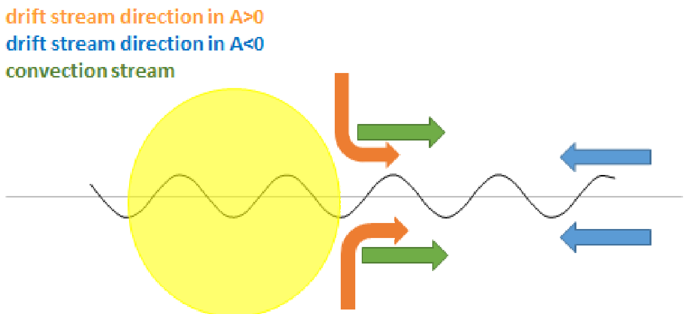

Fig. 5. Directions of convection and drift during $A > 0$ and $A < 0$ (adapted from Moraal & Mulder 1985).

4. Conclusions

We studied in detail the variation in solar-rotation-related amplitudes A_{27} and A_{14} of the GCR intensity. We quantified the Hale cycle in A_{27} and A_{14} during the last five solar minima in a robust way and offered a physical explanation of earlier concepts based on the influence of drift on the GCR intensity at 1 AU. We find that the mean amplitude of the Hale cycle is about 30–45% of the mean amplitude for A_{14}, but only about 15–30% for A_{27}. We conclude that the observed Hale cycle in the solar-rotation-related variation of GCRs is due to the different drift patterns and different causes of GCR modulation during the two polarity periods: during $A < 0$, the heliospheric current sheet plays the dominant role, while during $A > 0$, the heliolatitudinal change in SW is more important. We find that the A_{27} and A_{14} amplitudes during the solar cycle minima depict a declining trend, which can be associated with the weakening in the solar polar magnetic fields during the last four solar cycles (e.g. Smith & Balogh 2008). The weakening polar fields lead to a widening of the HCS region, which causes Earth to spend more time within the slow SW region and decreases A_{27} and A_{14} during negative-polarity times. The weakening of fields culminated during the last solar minimum and decreased the A_{14} amplitude in particular to record low levels, thus increasing the related Hale cycle in A_{14}. Ulysses observations verified that the slow SW (and HCS) region was considerably larger during the last solar minimum than during the previous minimum. The widening of the HCS is relatively more important for the amplitude of the second harmonic (A_{14}) because it is more likely that the Earth is outside the HCS region only once per solar rotation than twice or more often.

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