Is the Highest Cosmic-Ray Flux Yet to Come?

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Abstract The recent 2009 solar-minimum period was characterized by a record-setting high Galactic cosmic-ray flux observed at Earth. This, along with the unexpected low heliospheric magnetic-field magnitude, caused this period to be characterized as unusual compared with previous minimum epochs. In this work, selected solar-activity proxies and corresponding cosmic-ray observations for the past five solar cycles are compared with each other, and we identify those that showed unusual behaviour during the 2009 solar-minimum modulation period. Using a state-of-the-art numerical-modulation model, the proton-intensity spectra for the past solar minima are reproduced to establish which of the transport processes might be considered the main cause of this unusually high cosmic-ray flux. It is found that diffusion was more prominent during 2009 so that drift effects on the modulation of cosmic rays in the heliosphere were less evident than during previous solar-polarity epochs. However, particle drifts still occurred and because of these drift effects, the proton spectrum is predicted to be even higher during the coming $A > 0$ solar-minimum period.

1. Introduction

The recent solar-minimum activity epoch was characterized by Galactic cosmic-ray (CR) intensities at Earth reaching record-breaking high levels at the end of 2009 (Heber *et al.*, 2009; Mewaldt *et al.*, 2010; McDonald, Webber, and Reames, 2010; Ahluwalia and Ygbuhay, 2011; Potgieter *et al.*, 2014). Using a comprehensive modulation model in comparison with observations, we investigate solar-modulation processes to establish what might have been responsible for these unusually low levels of CR modulation and the subsequent high CR intensities. The roles played by, especially, diffusion and drifts are evaluated and discussed, and then predictions are made for the next solar-minimum period.

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2. The Recent Unusual Solar Minimum Conditions

Various measurements of heliospheric modulation parameters spanning the previous five solar-minimum epochs are depicted in Figure 1. Panel a shows the neutron monitor (NM) counting rate, normalized to March 1987, of the Hermanus NM in South Africa; panel b shows the yearly averaged sunspot number (taken from the Solar Influences Data Analysis Center: sidc.oma.be); panel c shows the highest latitudinal excursion of the heliospheric current sheet (HCS), as the average of the *new* and *classical* HCS models (taken from the Wilcox Solar Observatory: wso.stanford.edu), and panel d shows the heliospheric magnetic field (HMF) magnitude at Earth (taken from cohoweb.gsfc.nasa.gov). The well-known 11-year cycle is evident in all of these proxies, with the NM counts anti-correlated with solar activity. Above panel a, the HMF polarity cycles are indicated by $A < 0$ and $A > 0$, respectively. As a distinct feature of drift effects (*e.g.* Strauss, Potgieter, and Ferreira, 2012; Potgieter, 2013), the NM counts show a sharp maximum during $A < 0$ cycles, while a flattish plateau was observed during $A > 0$ solar-minimum times, exhibiting the 22-year cycle in CR modulation. As an indication of the energy contained in the turbulent HMF at Earth (*i.e.* a proxy of the level of turbulence), panel e shows the yearly statistical variance of the HMF, calculated using hourly values and normalized to unity in 2009 (see also Strauss and Potgieter, 2010).

Before attempting to establish which processes might have been mainly responsible for the high CR levels in 2009, it is useful to identify which of the quantities shown in Figure 1 can be considered as showing *unusual* behaviour during this period. The HCS tilt angle and HMF variance appear to be *normal* compared with the values obtained in previous solar cycles, although the tilt angle took longer than before to reach a minimum value. In contrast, the sunspot number and HMF magnitude were significantly lower than previously. The former does not have any causal relationship with CR modulation, however, so that the quantity that influences the CR modulation, which was significantly lower in 2009, is the HMF magnitude. The unexpected decrease in the HMF magnitude, well below the expected "floor" levels, is well documented (*e.g.* Cliver and Ling, 2011). Another prominent feature of the recent solar-minimum period was its duration; compared with previous solar-minimum periods, the recent one lasted at least twice as long.

3. Unusually High Cosmic-Ray Spectra

A compilation of Galactic CR proton spectra observed at or near Earth during the previous five solar-minimum epochs is shown in Figure 2. Data symbols for $A > 0$ cycles are coloured blue, with red symbols for the $A < 0$ observations. These observations are taken from Fan, Gloeckler, and Simpson (1966), Balasubrahmanyan *et al.* (1965), Ormes and Webber (1968), Webber and Yushak (1979), von Rosenvinge *et al.* (1979), Evenson *et al.* (1983), McDonald, Lal, and McGuire (1998), and Adriani *et al.* (2013). A striking feature is that the two $A < 0$ spectra of 1965 and 1987 have similar levels at lower energies, whereas the two $A > 0$ spectra of 1977 and 1996 have similar levels on their part. Evidently, these two $A > 0$ spectra are consistently higher than the two $A < 0$ spectra at kinetic energies lower than 500 MeV. This splitting of Galactic CR spectra observed during opposite-polarity cycles is well understood in terms of heliospheric-drift effects (Jokipii and Thomas, 1981), and is as such another manifestation of the consequent 22-year modulation cycle (see also Potgieter, 2013). Despite these differences in CR-proton spectra caused by the way particles drift in consecutive polarity cycles, the modulation conditions, to first order, seem to
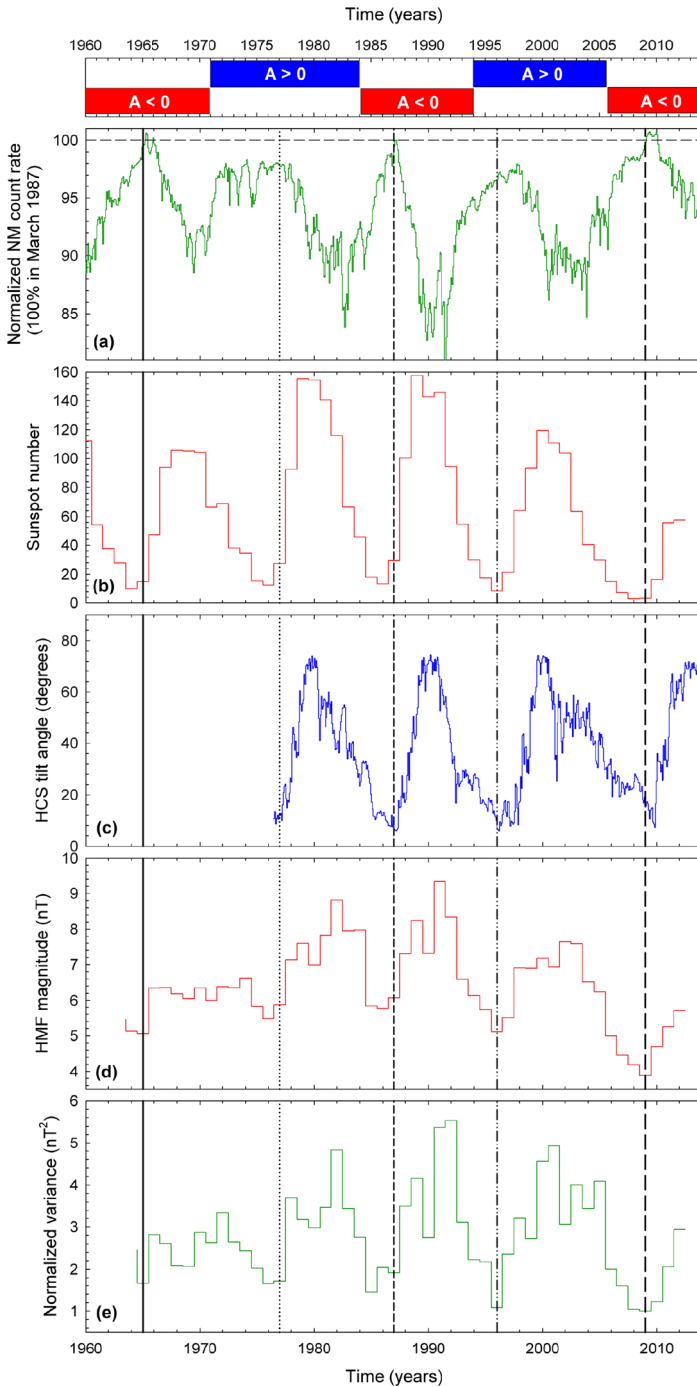
Figure 1 The top panel shows normalized NM counts as a function of time with subsequent panels showing various observed or inferred heliospheric quantities indicative of changing solar activity. The vertical lines indicate approximate times of solar-minimum modulation. The alternating HMF polarity periods are indicated above the top panel.
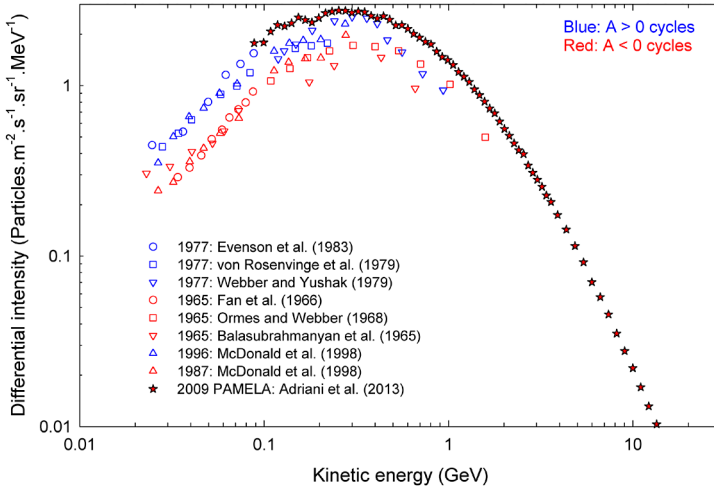
Figure 2 Galactic proton spectra observed over the past five decades during solar-minimum activity, that is, spanning five solar cycles. The $A < 0$ observations are indicated by red symbols and $A > 0$ observations by blue symbols. References to the data sets are given in the text. The PAMELA spectrum for the end of 2009 is indicated by the stars.

be quite similar for these solar-minimum periods. But what about the proton spectrum during the recent $A < 0$ minimum? This 2009 *Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics* (PAMELA) spectrum, indicated with star symbols, is higher for the energies shown than all previous observations, and more importantly, it is even higher than the previous $A > 0$ spectra. This is a clear deviation from the pattern as described and seems contradictory to the expected drift effects. We interpret this as indicative of quite different solar-modulation conditions during the 2009 minimum than experienced for the previous minimum periods. This aspect is further investigated, from a modelling point of view, in the next section. A preliminary report was presented by Potgieter *et al.* (2013).

4. What Was Different in 2009? A Modelling Approach

In this section, the unusual high proton spectrum of 2009 and the spectra for the previous five solar-minimum epochs are compared with computations. The numerical modulation model of Strauss *et al.* (2011a, 2011b), based on stochastic differential equations (SDEs), is used to solve the Parker (1965) transport equation

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V}_{sw} + \boldsymbol{v}_d) \cdot \nabla f + \nabla \cdot (\mathcal{K} \cdot \nabla f) + \frac{P}{3} \nabla \cdot \boldsymbol{V}_{sw} \frac{\partial f}{\partial P} \qquad (1)$$

in four-dimensional phase space, with f the omni-directional CR distribution function and P the particle rigidity. From left to right, the terms describe temporal changes, convection by the solar-wind, drifts, spatial diffusion, and adiabatic energy changes. As input to the model, a value of $\boldsymbol{V}_{sw} = 400$ km s^{-1} was used for the solar-wind speed, with a drift field $\boldsymbol{v}_d$ as described by Strauss *et al.* (2012b) along with an HCS tilt of 10°. The parameters that were changed in the model to obtain these simulations are the HMF magnitude (normalized to a reference value B_e at Earth), its polarity, and the magnitude of the diffusion tensor $\mathcal{K}$, which is discussed in subsequent sections, all taken from Strauss *et al.* (2012a).
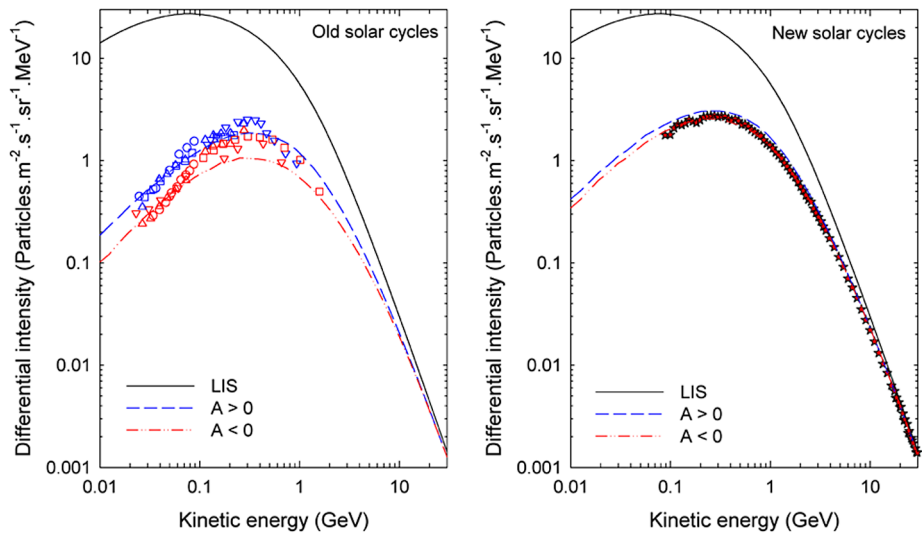
Figure 3 A comparison between proton spectra observed during the previous four (left panel) and the recent (right panel) solar-minimum epochs and corresponding computed spectra for the $A < 0$ and $A > 0$ polarity cycles. The computations are based on an assumed local interstellar spectrum (LIS) as indicated. To reproduce the 2009 PAMELA spectrum in the right panel, the diffusion coefficients had to be almost doubled, as shown in Figure 4.

Figure 3 shows solutions for the previous four solar-polarity cycles (left panel; referred to as *old solar cycles*) and separately for the 2009 solar minimum (right panel; referred to as *new solar cycles*). Proton spectra are shown at Earth with respect to an unmodulated local interstellar spectrum (LIS), specified at the heliopause at a distance of 120 AU from the Sun. When examining the old solar cycles, we note that by simply using the same set of diffusion coefficients with the same value of $B_e = 5$ nT and changing only the HMF polarity, reasonably good agreement can be achieved with these observations at the lower energies. This is interpreted to indicate that the modulation conditions in these four solar cycles were basically similar, apart from the different drift-velocity directions. Obviously, the modulation parameters need to be fine-tuned in the applied model to reproduce the spectra equally well at all the energies. The crossing of consecutive minimum proton spectra at higher energies was described in detail by Reinecke and Potgieter (1994), Langner, Potgieter, and Webber (2003), and Ngobeni and Potgieter (2008). See also the review by Potgieter (2013). This subtle aspect is not addressed again in this work since it is not crucially important for what we present here.

For the new solar cycles, where $B_e = 4$ nT is now used, the computed $A < 0$ spectrum is again comparable with observations. Compared with the old solar cycles, the diffusion coefficients need to be almost doubled, indicating that solar modulation became significantly weaker during this period. An interesting point is that if solar-modulation conditions were similar in ≈ 2020, when the next $A > 0$ minimum period is expected, the CR flux would then even be higher than observed in 2009 because of drift effects. As mentioned above, for similar modulation-minimum conditions, the $A > 0$ proton spectra are always higher than their $A < 0$ counterparts at energies below 500 MeV.

The diffusion coefficients used for this comparative study are shown in Figure 4 as different length-scales in AU as a function of particle rigidity. For the parallel and perpendicular

Figure 4 The computed mean
free paths (MFPs) and drift scales
used in this study, shown as a
function of particle rigidity. The
length scales used to simulate the
old solar cycles are shown in
blue, while the red lines show the
2009 scenario.
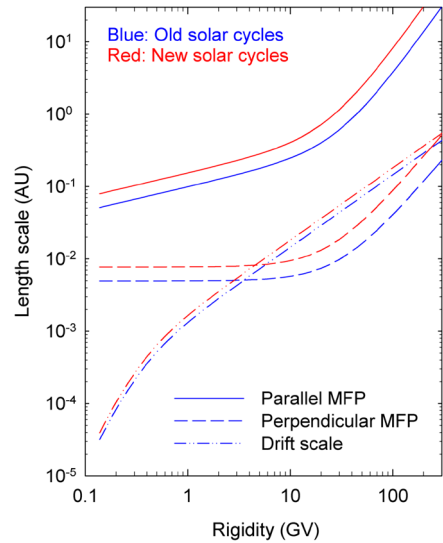
diffusion coefficients, the corresponding mean free paths (MFPs) are shown. For the pur-
poses of this study, where the weak-scattering drift coefficient was adopted, the drift scale
reduces to be at most the Larmor radius of a CR (see also the discussion by Minnie *et al.*,
2007). This drift scale is shown to illustrate the "magnitude" of the drift processes. Follow-
ing what was shown in Figure 3, the MFPs for the 2009 solar-minimum epoch have to be
significantly larger than in previous cycles, while the drift scale also shows this tendency
because of the unusually low HMF magnitude in 2009.

What caused these larger MFPs (and exceptionally low modulation levels) in 2009? An
obvious explanation is a less turbulent heliosphere (see also Zhao *et al.*, 2013), but this is
not conclusively supported by the HMF variance values shown in Figure 1. Although these
values are slightly lower than previously, this might not be enough to account for the strong
increase in the MFPs. A more detailed study of the underlying HMF turbulence in 2009 is
needed, in particular, a study of the level and spectral shape of the corresponding turbulence
power spectra, before reliable conclusions can be made in this context. From a global point
of view, the lower HMF magnitude may also explain this behaviour because it is generally
assumed that the MFPs and drift scale are proportional to $1/B$, with B the heliospheric
magnetic-field strength. Time-dependent CR-modulation models, using MFPs derived from
fundamental turbulence quantities may give some insight here (*e.g.* Manuel *et al.*, 2011;
Ndiitwani *et al.*, 2013), but the levels of turbulence are still generally unknown for most of
the heliosphere. Another explanation may lie in the duration of the 2009 minimum epoch.
It was at least twice as long as previous cycles, with the result that a larger volume of the
heliosphere had these almost-perfect solar-minimum modulation conditions. We recall that
a 100 MeV Galactic proton, observed at Earth, typically needs at least 400 days to traverse
the heliosphere to Earth (Strauss *et al.*, 2011b). In addition, multiple solar-polarity cycles
may be stored in the heliosheath regions (Ferreira, Potgieter, and Scherer, 2007), so that
when the solar-minimum modulation period is significantly extended, some of them may
fade away, together with the absence of global merged interaction regions (Potgieter, 2013).
This means that the effective MFPs (averaged throughout the heliosphere) became higher in
2009 globally because the heliosphere was in the *most relaxed state* ever observed. However,
because of the non-linearity of the modulation processes in the given transport equation, we

Figure 5 Computed global polar gradient (averaged between $\theta = 90°$ and $\theta = 45°$) as a function of kinetic energy for HMF cycles and solar-minimum modulation conditions classified new for 2009 and old for all previous solar minima periods. The HMF polarity dependence of the polar gradient is a characteristic feature of drift effects. Note that the difference between the $A > 0$ and $A < 0$ gradients is less for the new solar cycles than for the old cycles although the drift scale was larger for the new cycles, as shown in Figure 4.
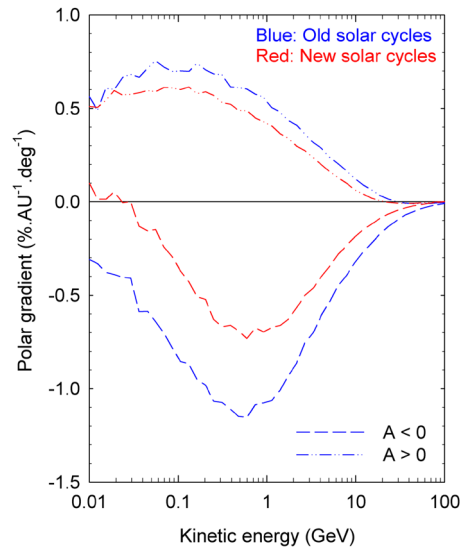
may not be able to pin-point the exact cause of the unusual CR increase in 2009. Most likely, it is a combination of the macro- and micro-processes described above.

The 2009 solar-modulation minimum was different from the previous solar cycles also in the sense that drift effects seemed to be almost absent. De Simone *et al.* (2011), for instance, compared *Ulysses* and PAMELA observations and found a much smaller latitudinal intensity gradient than expected from a drift point of view. Some authors (*e.g.* Cliver, Richardson, and Ling, 2011) interpreted this as the absence of drifts in 2009. This interpretation is mistaken, however, because from Figure 4 it is clear that the drift scale (and therefore also the drift velocity) is larger for 2009 than in previous solar cycles. Furthermore, Vos *et al.* (2013) reported clear differences between the modulation of Galactic protons and electrons from 2006 to 2009 as observed by PAMELA.

When we examine drift effects, we see that the $\mathbf{v}_d \cdot \nabla f$ term appears in the transport equation. Even if $\mathbf{v}_d$ was higher in 2009, the gradient in f was lower (caused by the much larger diffusion coefficients), so that the net drift effects were indeed weaker. A similar conclusion was reached by Potgieter *et al.* (2014), who studied PAMELA proton spectra for 2006 to 2009. They showed that although the *effects* of drifts were weaker in 2009 than in previous cycles, significant particle drifts still had occurred and contributed to the higher CR flux in 2009. The authors also illustrated that the proton spectra had become gradually softer from 2006 to 2009 (see also Bazilevskaya *et al.*, 2012), which requires that the rigidity dependence of the diffusion coefficients in modelling must become weaker at lower rigidities, in addition to the global increase in these diffusion coefficients during this period. As an illustration of diminished drift effects (but not weaker particle drifts) in CR modulation as described above, the global polar gradient (averaged between $\theta = 90°$ and $\theta = 45°$; see Strauss and Potgieter, 2010 for details) was computed for both the old and new solar cycles and is shown in Figure 5 as a function of kinetic energy. This illustrates that the difference in the polar gradients, as a direct cause of particle drifts, when comparing the old and new solar cycles (with different solar-modulation conditions) can be smaller although the drift scales (and speeds) are actually higher, as required for 2009.

We showed here that drifts were not absent in 2009, but that global modulation seems to have been *diffusion dominated*, with drift *effects* essentially *diminished* by the very effective diffusion of CRs during this particular time.

5. Conclusions

Various solar-activity proxies, going back to ≈ 1960, were examined with the aim of finding any unusual behaviour during the 2009 solar minimum-modulation period. We emphasized that the MHF magnitude was significantly lower in 2009, and that this particular solar-minimum period lasted significantly longer than previous cycles.

Galactic proton spectra observed during the past five solar-minimum modulation cycles were shown, and we illustrated that the 2009 spectrum was the highest ever observed despite being an $A < 0$ spectrum. Importantly, this spectrum was higher than previously observed $A > 0$ spectra, which seems to contradict predictions made with drift-modulation models. By comparing modelled results with observed spectra, we showed that 2009 was indeed unusual from a Galactic CR-transport point of view: the modulation conditions during the four preceding minimum periods were similar so that the Galactic proton intensities could be reproduced by assuming the same levels of modulation and changing only the HMF polarity (drift) cycles. To reproduce the 2009 spectrum with our modulation model, the diffusion coefficients needed to be increased by a factor of almost two. From a fundamental-physics point of view, it is still unclear what led to this increase in the MFPs, although it is clearly related to the lower HMF magnitude and the longer duration of minimum modulation conditions.

We also showed that although drift *effects* were less pronounced in the recent solar minimum, the drift speeds (scale) were the highest in 2009 and that CR particle drifts were still present and contributing to the global modulation process. The unusually high MFPs in 2009 suppressed drift *effects* significantly in this period, but particle drifts were still present in 2009. Global modulation seem to have become *diffusion dominated* during this period.

We showed that if the same modulation conditions were present during the next $A > 0$ solar-minimum period (expected at about 2020), Galactic-proton intensities might be even higher because of drift effects. It can therefore be concluded that the highest CR flux is yet to be observed, and this could happen during the next solar-minimum period.

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