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The galactic cosmic ray intensity during the minima of solar cycles 21-24: the radial profiles and time behavior in the inner heliosphere and in the heliosheath

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Abstract: Using the spacecraft cosmic ray data for 1973-2007 we construct the equatorial radial profiles of the proton GCR intensity for the extreme phases of the solar cycles. Using these radial profiles we normalize the intensity to the same heliocentric position and solar magnetic phase and try to predict the main feature of the GCR behavior in the nearest future, taking into account the development and prognosis of the current (23^{rd}) solar cycle in the solar and heliospheric characteristics. The interpretation of the equatorial radial profiles of the intensity in the subsequent solar minima is briefly discussed.

Introduction

The network of the spacecraft existing for the last 35 years allows one to make some inference on the time and space behavior of the GCR intensity in the minimum phase of the last three solar cycles (SC 21-23). There are many works devoted to these questions but for our study the paper [1] was the initial point, where it was shown that the significant difference in the radial profiles of the GCR intensity during the solar minima of different polarity of heliospheric magnetic field persisted up to the solar wind termination shock and so it should be explained by the processes in the heliosheath. In [2, 3] we constructed the radial profiles of the GCR intensity during the extreme phases of solar cycles and in [4, 5] tried to interpret them with account for the external electric fields. To check the above picture the behavior of the GCR intensity during the forthcoming minimum of SC 24, especially in the vicinity of the termination shock, is very important. So in [6-8] we kept track of it using suggested in [3, 6, 8] method of the GCR intensity normalization, bringing the intensity to the same heliospheric position and magnetic phase. Here we shall briefly outline the construction and interpretation of the radial profiles of the GCR intensity and its normalization and then try to predict the behavior of the intensity in the nearest 2-3 years taking into account the characteristic features of the current SC 23.

The radial profiles of GCR intensity

The solid lines of different color and thickness in Fig. 1 show the behavior in 1975-2007 of the half-year smoothed 26-day average proton (≈ 120-250 MeV) GCR intensity measured aboard different spacecraft. The IMP8 data were kindly put at our disposal by the IMP8/GME team (PI Dr. McGuire), while the Voyager and Pioneer data are from [9, 10], respectively. The triangle shows the last smoothed intensity measured at V1. The dotted lines and other symbols will be discussed later.

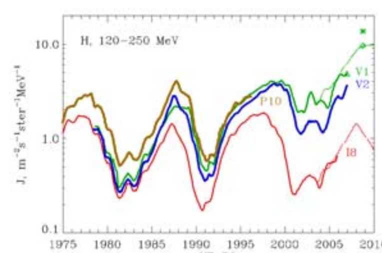

Figure 1:

As one can see from Figure 1, the GCR intensity measured aboard each spacecraft manifests the solar cycle variation, although, as the spacecraft move progressively out from the Sun, this variation sometimes looks strange. To understand it we first constructed the radial profiles of the GCR intensity in the extreme phases of solar cycles taking, as in [1], the extreme values of the intensity measured at different near-equatorial spacecraft and the corresponding heliocentric distances. In Fig. 2 the radial profiles of the same GCR intensity are shown for A > 0- and A < 0-minima (A is the polarity of the heliospheric magnetic field), the first of them being composed of the (J-r)-pairs for minima of SC 21 and 23. The radial profile for the maximum of SC 23 is also shown. Note that the solid parts of the profiles show the interpolation between the actually measured points, while those shown by the dashed lines are the extrapolation up to 110 AU (suggesting the constant relative radial gradient). The vertical dashed line marks the position of the termination shock, intersected by V1 in the end of 2004. Like in Fig. 1 the triangle shows the last {J-r} pair for V1. Two other symbols at r > 100 AU will be discussed later.

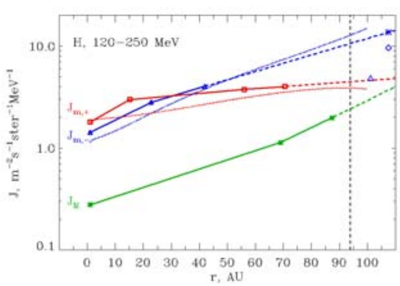

Figure 2:

It is easily seen that the current 0.5y-smoothed GCR intensity at r = 102 AU lies well bellow the equatorial radial profile $J_{m,-}(r)$ constructed using only IMP8, V2, P10 measurements in 1987 and extrapolated over 60 AU. One evident cause of this deviation is that V1 is even farther from the equator now (at latitude $\lambda \approx 34°$) than it was in 1987 ($\lambda \approx 28°$). Another possible cause is that, as we shall see, there are still about 1.5-2 years before the GCR intensity attains its maximum at V1 position.

The normalized GCR intensity

To understand the difference in the manifestations of the solar cycle at different heliospheric positions we suggested in [3, 6, 8] to consider the variation of the normalized intensity

$$J_{norm}(t) = \frac{J(r,t) - J_M(r)}{J_m(r) - J_M(r)}, \qquad (1)$$

using the radial intensity profiles $J_m(r)$ and $J_M(r)$ for solar minimum and maximum, respectively, as boundaries within which the solar cycle was developing. As the time passes the change of the current boundary radial intensity profiles should be taken into account. In Fig. 3 the solid lines show the time profiles of the GCR intensity normalized according to (1) with the time shift $\Delta t = (r-1)/V_{sw}$, V_{SW} = 450 km/c, accounting for the propagation of the intensity details with the solar wind velocity. The clear synchronous 11-year cycle in the GCR intensity is easily seen for all heliocentric distances with a few notable exceptions (see [6]). Here we are mostly interested in the pronounced deviation from the synchronous behavior in 1985-1987 for V1 due to its latitude ($\lambda \approx 28°$N) and the negative latitudinal intensity gradient during that period.

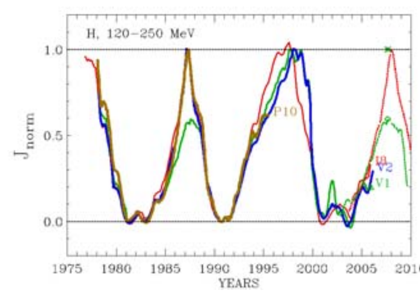

Figure 3:

In order to predict the time behavior of the GCR intensity during the descending phase of the current solar cycle and in the minimum of the solar cycle 24, we propose that the similar behavior of the normalized GCR intensity can be expected if the main processes forming the GCR behavior are the same in different parts of the heliosphere and/or in different periods of time. So if we assume that (1) the main processes in the GCR propagation in the heliosphere in 2004-2009 are the same as in 1983-1988 and (2) there is nothing drastically different in the GCR modulation in the radial and latitudinal range {r=90-106 AU; λ=34-35} where Voyager-1 will be in 2004-2009, and in the range {r=15-33; λ=17-29} where it was in 1983-1988, we can suggest that the time profiles of the normalized GCR intensity for both IMP8 and V1 in 2004-2009 will be similar to those in 1983-1988 (with due account for different radial distances in the time shift). But before we shift the normalized intensity for the 1980s by two solar cycles for its prediction in 2004-2010 the difference between the current solar cycle and SC 21 should be considered.

SC 23 versus SC 21

In the upper panel of Fig. 4 the time history of the smoothed with 0.5-year period sunspot area (according to [11]) in SC 23 is shown by the solid line, while the dashed line shows the same characteristic for SC 21 but shifted in time to make the minima of both cycles (shown by the squares) coincide. The left asterisk shows the shifted end of the SC 21 while the right one indicates the moment when we expect the current cycle to end, [12].

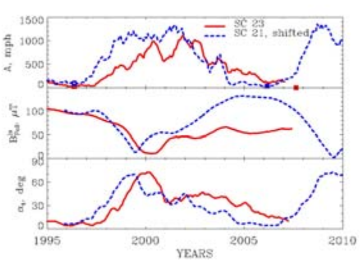

Figure 4:

It can be seen that besides the different levels of sunspot activity the important difference of the current cycle as compared with SC 21 is its longer duration. In the middle panel of Fig. 4 the strength of the line-of-sight projection of the high-latitude photospheric magnetic field is shown for the current solar cycle by the solid line and that for the SC 21 shifted by the same amount of time as for sunspot area by the dashed line. We can see that another very important difference between the two cycles is much lower polar activity in the current cycle. The lower panel shows in the same format the behavior of the tilt of the heliospheric current sheet, α_{cs}, for SC 21 and 23 and it can be seen that at present time the tilt for the current solar cycle is significantly greater than for the end of SC 21. In fact the large tilt of the heliospheric current sheet is just the consequence of the weak polar magnetic field, see [13]. As the normalization (1) brings the GCR intensity to the same radial position, comparing it for the equatorial and out-of-equator spacecraft one can also study the behavior of the latitudinal gradient of the intensity in the 1980s to compare it with that in the 2000s.

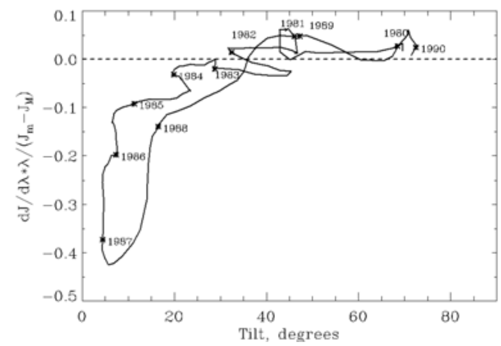

Figure 5:

In Fig. 5 the difference between the normalized intensity at the latitude λ of V1, J^{λ}_{norm}, and that near the equator (IMP8), J^{0}_{norm},

$$J^{\lambda}_{norm} - J^{0}_{norm} \cong \frac{dJ}{d\lambda} \cdot \lambda / (J_m - J_M) \ ,$$

is shown as a function of α_{cs} for the 1980s. It can be seen that the latitude gradient was very small for the large values of the tilt and it got large and negative only when $\alpha_{cs} < 10°$ (1985-1987.5). Note that the nonlinear dependence of J on α_{cs} is well known and its different dependence before and after the onset of modulation can be brought together by constructing the average tilt for the whole heliosphere (see, e. g., [14]). As according to Fig. 4 up to now $\alpha_{cs} \geq 10°$, the period of the significant negative latitude gradient in the current cycle is still in the future (if at all).

Prediction and interpretation

For the time being we do not know for sure how the greater tilt of the current sheet would affect the normalized intensity. So to estimate its behavior for IMP8 and V1 after the beginning of the descending phase of SC 23 we shift to this moment the normalized intensity-time profiles for both spacecraft stretched by the amount which makes the duration of both cycles coincide. The dotted lines in Figs. 3 and 1 show the expected time behavior of the normalized and absolute GCR intensity for IMP8 and V1. The triangle and rhomb symbols in Figs. 1-3 show, respectively, the last observed and maximum expected intensities at V1, while the asterisk indicates the maximum expected intensity near the equator, i. e., corrected for the negative latitudinal gradient. In general we expect that in the near few years time profile of the GCR proton intensity near the Earth will be peak-like in general, while that at V1 (and V2) will be less poignant due to the negative latitude gradient. However, the details would depend on the behavior of the latitude gradient in the latitude range $\lambda < 35°$ which in turn depends on the $\alpha_{cs}(t)$. A few words should be said on the interpretation of the very pronounced difference between radial profiles during the successive solar minima. In [4, 5] we tried to describe the radial profiles during solar minima and came to the conclusion that it could be done easier with account for the external radial electric fields located in the heliosheath nearer to the heliopause or beyond it. The dotted lines around these profiles in Fig. 2 are the equatorial radial profiles calculated in [4, 5] with account for these fields using the same set of diffusion parameters for both profiles. Note that to describe these radial profiles with approximately the same accuracy without the external electric fields the author of [15] needed substantially different (by a factor of 5) diffusion coefficients for A > 0- and A < 0- solar minima.

Conclusions

1. The suggested earlier normalization of the GCR intensity helps in formulating the expected time behavior of the intensity in the magnetic phase similar to that in the past.
2. In the analysis of the expected behavior of the intensity one should take into account the features that make SC 23 different from SC 21:
- the lower level of sunspot activity
- the lower polar activity (and hence greater tilt of heliospheric current sheet)
- the longer duration.
3. If the forthcoming minimum of SC24 confirms the strong dependence of the equatorial radial profile on the magnetic polarity even beyond the termination shock, it will be difficult to explain this dependence only by the drift in the near heliosheath. Some additional source (possibly, the radial electric field nearer to the heliopause) may be needed.

Acknowledgements

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