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 predict the main feature of the GCR behavior in the nearest future, taking into account the development and prognosis of the current (23rd) solar cycle in the solar and heliospheric characteristics.

1. 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 papers [1, 2] were 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 (suggested earlier, see references in [1]) persisted up to the solar wind termination shock and so it should be explained by the processes in the heliosheath. In [3, 4] we constructed the radial profiles of the GCR intensity during the extreme phases of solar cycles and in [5, 6] 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 [7-9] we kept track of it using suggested in [4, 7, 9] 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 its behavior in the nearest 2-3 years.

2. The radial profiles of GCR intensity

The solid lines in Fig. 1 show the behavior in 1975-2007 of the half-year smoothed 26-day average proton (121-229.5 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 1,2 and Pioneer 10 data are from [10, 11], respectively. The dot lines and symbols will be discussed later.

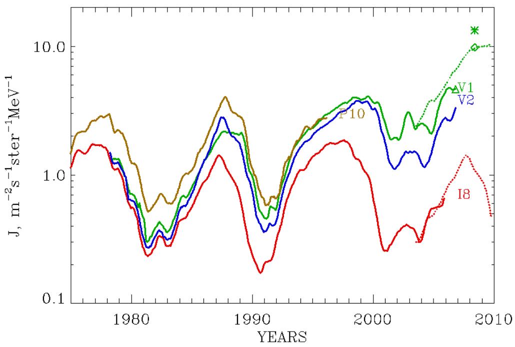

Figure 1

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, 2], the extreme values of the intensity measured at different spacecraft and the corresponding heliocentric distances (see also [3, 4]). It was suggested in [1] that the main parameter that determines the form of the GCR intensity radial profile during the solar minimum is the polarity A of the heliospheric magnetic field. So in Fig. 2 the radial profiles of the same GCR intensity are shown for A > 0- and A < 0-minima, 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. Both interpolation and extrapolation are made suggesting the constant relative radial gradient. The vertical dashed line shows the position of the termination shock, intersected by V1 in the end of 2004. Three symbols at r > 100 AU will be discussed later.

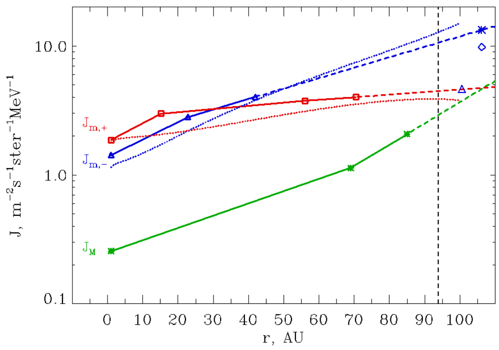

Figure 2

Before we start to normalize the GCR intensity time profiles using its radial profiles in the extreme phases of solar cycle, a few words should be said on the interpretation of the very pronounced difference between radial profiles during the successive solar minima. In [5, 6] 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 electric fields located in the heliosheath or beyond. The dashed lines around these profiles in Fig. 2 are the equatorial radial profiles calculated in [5, 6] 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 [12] needed substantially different (by a factor of 5) diffusion coefficients for A > 0- and A < 0- solar minima.

3. The normalized GCR intensity

To understand the difference in the manifestations of the solar cycle at different heliospheric positions we suggested in [4, 7, 9] 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 and J_M 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 11-year synchronous cycle in the GCR intensity is easily seen for all heliocentric distances. The pronounced deviation from the synchronous behavior in 1985-1987 for V1 is due to its latitude ($\approx$28°N) and the negative latitudinal intensity gradient during that period (see below). The distinct shift of the time of maximum of the GCR intensity in the outer heliosphere with respect to that near the Earth is seen in 1997-1999 (see [7]).

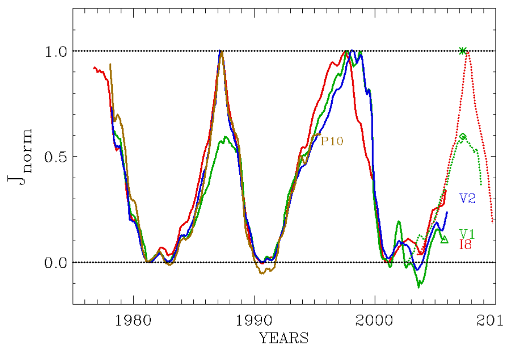

Figure 3

We propose that if the main processes forming the GCR behavior are the same in different parts of the heliosphere and/or in different periods of time the similar behavior of the normalized GCR intensity can be expected. 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). The dotted lines in Fig. 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. The pair (J, r) of the V1 expected equatorial intensity in the minimum of SC 24 fits the extrapolated radial profile for A < 0 - solar minimum shown in Fig. 2 surprisingly well.

So the expected equatorial GCR intensity in the minimum of SC 24 fits neatly into the radial profile of the GCR intensity for A < 0 solar minimum constructed using the data for SC 22. 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 will be less poignant due to the negative latitude gradient.

4. SC 23: development and prognosis

If the development of the SC 23-24 were the same as that of SC 21-22 the proton GCR intensity near the Earth would attain its maximum in 2007, while at V1 the intensity would be maximal in 2008.

However, the last assumption does not hold in details. In Figure 4 the time history of some solar and heliospheric activity characteristics important for the GCR modulation is shown for 1960-2007 (solar cycles 19-23), [13]. All indices are averaged between both hemispheres and smoothed with a 0.5-year period (except those of the polar activity, 1-year smoothed): a - the sunspot area; b – the strength of the line-of-sight projection of the high-latitude photospheric magnetic field (thick blue line) and the number of solar faculae (thin green line); c – the strength of the heliospheric magnetic field B_{HMF} near the Earth's orbit; d – the tilt α_{CS} of the global heliospheric current sheet. As one can see from Fig. 4 the sunspot area during SC 23 maximum phase was lower than in the previous two cycles and the strength B_{HMF} mimics it. Till the present time the stable spots of the new cycle have not emerged, so we are still in the descending phase of SC 23. Some of the prognostic studies predict rather long SC 23. For example, the dotted line in the upper panel shows the approximation of five last cycles and prediction of the sunspot area in 2004-2009 according to dominated harmonics method by V.I. Kaftan, [14].

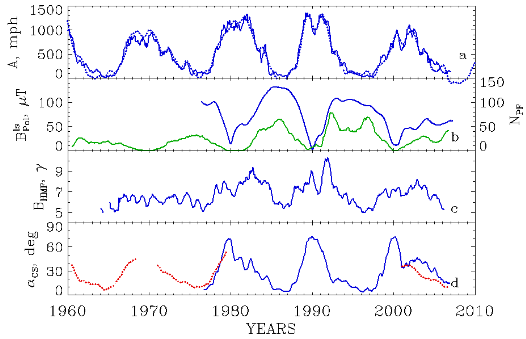

Figure 4

So we expect the minimum of SC 23 to occur in the second half of 2007 or even in the beginning of 2008. The second special feature of the current solar cycle is a strange behavior of the high-latitude (poloidal) photospheric magnetic field. It is easily seen in Figure 4 that the polar magnetic field changed sign around 2000.0, but soon stopped increasing in strength and was rather small (about half of its maximum value) during next 6 years. Note that the number of solar faculae, the independent index of high-latitude solar activity, is also rather low in SC 23. As the poloidal branch of solar activity strongly influences the HMF polarity, [15], the weak polar magnetic field is also reflected in large and about constant for 3 years tilt of the heliospheric current sheet. The dotted lines in Fig. 4, d, show the predicted behavior of the tilt from the simple regression model connecting α_{SC} with A and polar fields, [15]. During the next three years (2004-2006) the current sheet tilt slowly decreased, although it is still significantly greater than for the corresponding time in the previous cycles. Probably this feature also means that there is some time before the sunspot area will attain its minimum level in SC24 and the residual tilt will be greater than in the previous cycles.

So as we expect that the length and residual current sheet tilt will be greater for SC 23 than for SC 21, the proton GCR intensity near the Earth and at V1 could attain its maximum later than shown in Figs. 1, 3 and their maximum values would be somewhat smaller and the peak-like form would be less pronounced.

5. Conclusions

1. The equatorial radial profiles of the GCR proton intensity in the successive minima of solar activity are significantly different. In the main these profiles can be described with account for the external electric fields.

2. The normalization of the GCR intensity to the same heliospheric position and magnetic phase allows both the comparison of the GCR behavior in different parts of heliosphere and the prediction of the main features in the GCR intensity.

3. The minimum of the forthcoming (24^{th}) solar cycle is expected in 2007 or in the beginning of 2008. It can be characterized by the low level of the high-latitude solar magnetic fields and, probably, greater residual tilt of the heliospheric current sheet.

4. Near the Earth the proton GCR intensity will attain its maximum in 2008-2009 and its time profile will be peak-like in general. In the middle-latitude outer helosphere the GCR intensity time profile will be less poignant due to the negative latitude gradient with its maximum attained in 2009-2010.

Acknowledgements

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