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ON THE BEHAVIOR OF THE MEDIUM ENERGY GALACTIC COSMIC RAY INTENSITY IN THE OUTER HELIOSPHERE

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Abstract

The development of the current solar cycle is considered in the solar characteristics important for the propagation of the galactic cosmic ray (GCR) intensity in the heliosphere and in the GCR intensity itself both near the Earth and in the outer heliosphere, using the IMP8, Pioneer 10, Voyager 1, 2 spacecraft cosmic ray detectors and also stratospheric data. The strong influence on the GCR intensity during the forthcoming solar minimum is predicted of the unusually weak solar high-latitude magnetic fields and, as a cosequence, of the large tilt to the equator of the heliospheric global current sheet. The position of both outer heliospheric spacecraft outside the latitude range occupied by the heliospheric current sheet is also important.

1. Introduction

Recently the investigation of the heliomagnetosphere entered a new stage: according to some features in the behavior of the magnetic field and energized solar wind particles the spacecraft Voyager-1 (V1) intersected the solar wind termination shock (TS) and entered the heliosheath (the last layer of the heliosphere in the strict sence, separating it from its boundary, the heliopause), [1-2]. As there are no plasma data from V1, some doubts exist if it was a real TS's crossing. The decisive word will be said in about two years from V2, where the plasma probe is in normal operation. As to the anomalous and galactic cosmic rays, the recent data do not fully correspond to the expectations. The majority of the researchers consider the TS as the very important region determining the characteristics of the anomalous cosmic rays and significantly influencing the galactic cosmic ray behavior in its vicinity. However, the observations at V1 show that both populations do not demonstrate in full measure the effects expected [3].

In this paper we continue our study of the current solar cycle (SC) in the GCR intensity (see [4] and references therein). First, we briefly consider the development and the strange features of the current (23rd) solar cycle in the solar and heliospheric characteristics important for galactic cosmic rays. Then some time features in the GCR intensity modulation in the outer heliosphere during and after the end of the maximum phase of SC 23 are considered and compared with those near the Earth. At the end we discuss what could be expected in the next two or three years during the minimum phase of the solar cycle 24.

2. The development of the solar cycle 23 on the Sun

In Figure 1 the time history of some solar activity characteristics important for the GCR modulation is shown for 1975-2006 (solar cycles 21-23) for N- and S-hemispheres: the sunspot area *S* (the first (upper) panel); the absolute values of the mean latitude of sunspots (the second panel), the line-of-sight component of the polar photospheric magnetic field as seen from the Earth, $B_{ls}^{N,S}$, (the third panel), and the latitude boundary of the IMF sector-structure zone, $\lambda_t^{N,S}$, (the lowest panel). The sunspot data are from science.nasa.gov/ssl/PAD/SOLAR/greenwch.html, while those for solar magnetic fields are from sun.stanford.edu/~wso/wso.html. All the initial data were smoothed with a 0.5-year period.

As one can see from Figure 1 up to the end of 2005 the mean latitude of the sunspots smoothly decreases, there are no high-latitude spots of the new cycle in any hemisphere, so we are still in the descending phase of solar cycle 23. However, one can already notice that the current solar cycle is rather unusual. The ascending phase is too long, so that its time profile *S(t)* looks almost symmetric with respect to the moment of maximum; the sunspot area (connected with the photospheric toroidal magnetic fields) during maximum phase was significantly lower than in previous even-numbered cycle, violating the Gnevyshev-Ohl rule; the polar field behavior is also very strange, [5].

Similar to the previous cycles the sunspot area demonsrates a decrease in the middle of maximum phase (a so called Gnevyshev Gap; see [6]). Note that in the last two cycles (22 and 23) it occurred approximately simultaneously in the N- and S-hemispheres, while in solar cycle 21 there was a notable shift, [7]. However, for the current solar cycle there is one more solar characteristic strongly influencing the GCR behavior. As we already mentioned in [4], the 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 1 that the polar magnetic fields in both hemispheres changed sign around 2000.0, but soon stopped increasing in strength and were rather small (less than a half of their maximum value) during next 5 years. As the poloidal branch of solar activity strongly influences the IMF polarity, the weak polar magnetic field is also reflected in rather large (≈ ±40°) and constant for 3 years latitude boundaries of the IMF sector-structure zone (or the tilt to the equator of the heliospheric global current sheet). This behavior of the heliospheric current tilt probably determined the very long maximum phase in the GCR intensity (2000.7-2003.7). During the next two years (2004-2005) the current sheet tilt slowly decreased, although it is still significantly greater than for the corresponding phase in the previous cycles.

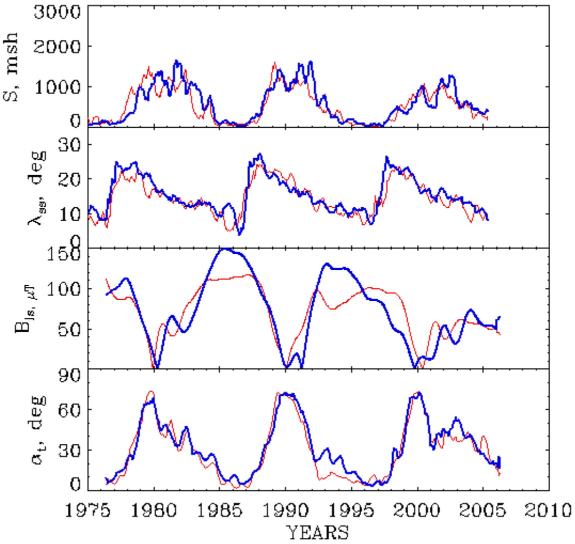

Figure 1. The solar cycles 21-23 in different solar and heliospheric characteristics (see text). The data are shown by the light (red) and darker (blue) curves, respectively, for the N- and S-hemispheres.

As to the causes of the very unusual behavior of the solar polar magnetic fields (the slowdown in the polar reversal and the slow buildup of the field after the reversal), it is connected in [5] with the weakness of the sources of the poloidal field (mainly the remnants of the toroidal field) and the systematic decrease in meridional flow amplitude. This conclusion resulted from the simulations with numerical flux transport dynamo-based model, using the data on meridional flow since 1996. However, to study the causes of the unusually low sunspot level during SC 23 the authors of [5] need the data on the meridional flow before 1996 be extracted from the helioseismic data for the previous 20 years.

3. The current solar cycle in the medium energy GCR intensity

One can suppose that in the part of the heliosphere where the solar wind structure does not change with distance, the GCR intensity variations at different heliocentric distances also should be similar. In this connection it is interesting to compare the development of the solar cycle variation in the GCR intensity of the same species and energy near the Earth and in the distant heliosphere. In Fig. 2 the time profiles of the 0.5-year smoothed GCR intensity are shown measured onboard the Earth's sattelite IMP8 and the Pioneer-10, Voyager-1, 2 spacecraft. As the data from the near-the-Earth IMP8 became less direct and detailed since October 2001, after this moment we used the intensity determined from the regular balloon monitoring of cosmic rays in the stratosphere (see [8]). The Voyager data are from http://voycrs.gsfc.nasa.gov/heliopause/heliopause.hml.

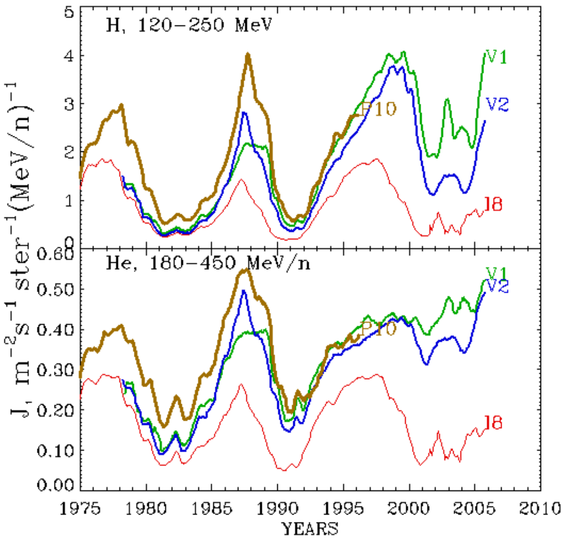

Figure 2. The solar cycles 21-23 in the medium energy GCR intensity. The data from the different spacecraft are shown by the lines of different darkness and color.

As one can see from Figure 2, near the Earth after the maximum phase (2000.7-2003.7) with a pronounced Gnevyshev Peak the GCR intensity grew rather fast for half a year, but then the growth stoped and in 2004.3-2005.7 the intensity-time profiles looked flat. Note that there were no periods of such pronounced GCR intensity modulation during the descending phases of the previous solar cycles (except an anomalous "mini-cycle", 1974-1975). The solar source of the enhanced GCR modulation is not clearly seen in Figure 1. Since October 2005 the intensity increases steadily.

During the period under discussion the spacecraft moved progressively out from the Sun and by the end of 2005 the Voyager 1 and 2 were at 97 AU and 78 AU, respectively. In the maximum phase of the current solar cycle the pronounced Gnevyshev Peaks are also seen at both V1 and V2, although with the structure somewhat different from that near the Earth ([3]; see also [4]). However, the 11-year cycle, i .e., the modulation of the intensity from 1998-1999 level to that in 2001-2004, looked rather unusual: for helium nuclei (the lower panel) the intensity-time profile even does not demonstrates the cycle, the intensity during the maximum phase being higher than that in the solar cycle minimum. In the descending phase the growth of the intensity at V1 and V2 started in the end and in the beginning of 2004, respectively, being steady without any period of the enhanced modulation like that near the Earth. Note that there is no any indication in the intensity-time profiles of the TS crossing by V1 in the end of 2004.

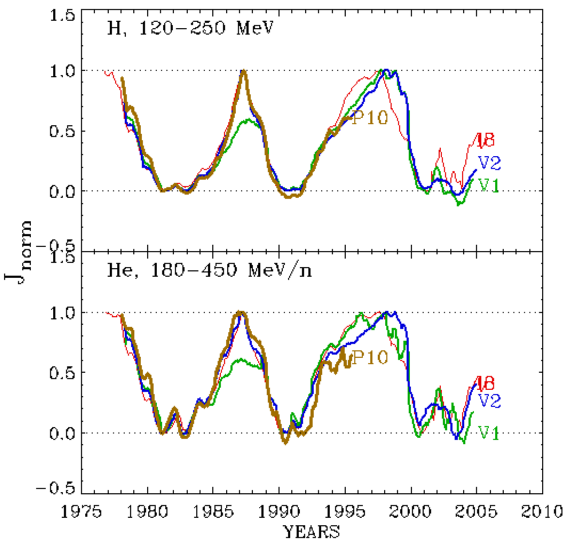

Figure 3. The same as in Figure 2 for the GCR intensity normalized using (1).

To understand the difference in the manifestations of the solar cycle at different heliospheric positions we suggested in [9, 10] 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 is developing. When the time passes the change of the boundary radial intensity profiles should be taken into account (see [10]). The only difference in the normalization procedure that we use in this paper from that used in [10] is that here we consider the maximum phase as the prolonged period of the reversal of the regular magnetic fields in the heliosphere (see [11]), so that for this period the radial profile for the minimum phase should correspond to the virtual one without the preferred IMF polarity (see [9] for the discussion of these questions). In Fig. 3 the time profiles of the normalized according to (1) GCR intensity are shown with the time shift $\Delta r/V_{sw}$, with V_{SW}=450 km/c, accounting for the propagation of the intensity detailes 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 (≈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 [10]).

In the descending phase of the current cycle (after 2003.7) the normalized intensity corrected for the solar wind propagation increases steadily in the outer heliosphere, although being significantly lower than that near the Earth. This is due to the fact, that in (1) we used the radial intensity profile for the A<0-minimum obtained by the linear extrapolation (in semi-log scale) of the radial dependence observed during SC 22 (at r=23-42 AU). If one makes $J_{m,-}$ somewhat lower (e. g., using G_r ~ *1/r*), the normalized intensity at V1, 2 would coinside with that near the Earth. Note that the time profiles of the normalized intensity do not demonstrate the enhanced modulation observed in 2004-2005 near the Earth. However, because of the correction for the solar wind propagation we can expect this feature in the GCR intensity behavior in the near future.

So the comparison of the time profiles, corrected for the change with the spacecraft's position of the intensity limits within which the intensity changes, demonstrates that they are rather similar which can be considered as an indication that there is no drastic changes in the solar wind and IMF structure important for GCRs in the heliocentric distance range r=1-97 considered. The absence of the observed manifestations in the GCR intensity of the crossing of the termination shock by the Voyager-1 spacecraft in the end of 2004 also fits in with this picture.

4. On the GCR intensity behavior in the minimum phase of solar cycle 24

As the forthcoming minimum phase of solar cycle 24 is characterized by the A<0 IMF polarity, one can expect in the next 2-3 years the pointed intensity-time profiles for the positively charged particles as in SC 20 and 22. However, two significant notes should be made. First, the strength of the high-latitude solar magnetic fields is much lower in the descending phase of SC 23 than it was in the preceeding cycles. As the source of these fields (the sunspots or the toroidal magnetic fields) is also weak, the significant buildup of the polar fields in the next 2-3 years is rather improbable. It means that the heliospheric current sheet during the forthcoming minimum phase would not be as flat as it was in this phase for the previous cycles, which in its turn could result in the different level of the negative latitude gradient and hence in different time profiles.

The second note is about the latitudes of the spacecraft. As one can see from Figure 4, in spite of rather large latitude range occupied by the current sheet in the descending phase of SC 23, it is decreasing and since 2005 V1, V2 and Ulyssis are outside the IMF sector zone. It means that when (and if) the current sheet is sufficiently flat to form the strong negative latitude gradient, the intensity-time profiles at both V1, V2 and Ulysses will be as different from those near the solar equator (IMP8) as the V1 intensity-time profiles in 1985-1988 were different from those for the low-latitude spacecraft (IMP8, P10, V2)

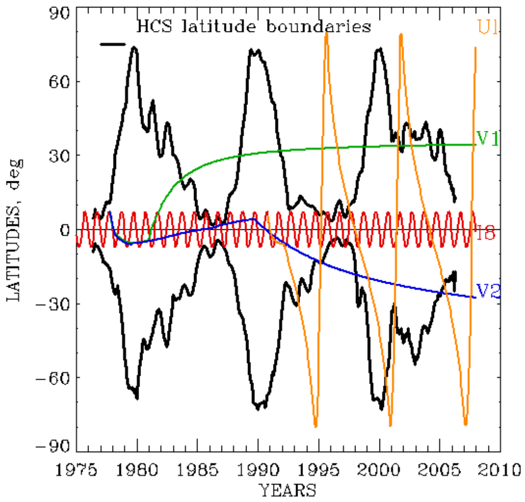

Figure 4. The latitudes of the spacecraft as compared with the latitude boundaries of the IMF sector zone.

5. Conclusions

1. The special feature of the maximum and descending phases of the current solar cycle is a weakness of the high-latitude photospheric magnetic field after its reversal in 2000. It is resulted in rather large tilt to the equator of the heliospheric global current sheet.
2. The similarity of the GCR intensity-time profiles, corrected for the change with the spacecraft's position of the intensity limits within which the intensity changes and the absence of the observed manifestations in the GCR intensity of the crossing of the termination shock by the Voyager-1 spacecraft in the end of 2004 can be considered as an indication that there is no drastic changes in the solar wind and IMF structure important for GCRs in the heliocentric distance range r=1-97.
3. As it is rather improbable to expect the significant buildup of the polar fields in the next 2-3 years, the heliospheric current sheet during the forthcoming minimum phase would not be as flat as it was in this phase for the previous cycles, which in its turn could result in the different level of the negative latitude gradient of the GCR intensity and in different intensity-time profiles. However, if the current sheet were sufficiently flat to form the strong negative latitude gradient, the intensity-time profiles at the V1, V2 and Ulysses would be quite different (flat) from those near the solar equator (pointed).

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