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EXTREMES OF THE LONG-TERM MODULATION OF COSMIC RAYS IN FIVE LAST SOLAR CYCLES

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Abstract

The extreme values of long-term variations of cosmic rays (CR), obtained by continuous on-earth and near-earth observation, have been analyzed. The results are compared with observation data of the Sun's magnetic fields and of the sunspot numbers during the last five cycles of solar activity (SA). The aim of the research was to compare the cycles and to determine the similarities and differences of CR modulations during these cycles.

Introduction

The main feature of long homogeneous series of CR data is clear: SA cycles can be clearly seen during CR time changes and, even if there were no solar observations, the solar cycles and their most important periods would be revealed by observations of CR variations. At the present time this data covers 5 complete 11 year cycles of SA and three 22-year magnetic cycles, which are the main features of long-term CR variations. This work is based on the empirical description of CR using various solar-heliospherical indexes. The changes in the extreme values of CR and in the extreme values of the modulation characteristics, determined using observation data of various SA phenomena.

CR data

The extreme values of the monthly and yearly averages of CR variations (% to 1976) with a rigidity of 10 GV (A10) obtained on neutron monitors (about 40 NM, with a tentative estimation of long-term stability NM) and stratospheric observations (3 points) were used for the analysis. Here we study amplitude variations of CR with 10 GV rigidity, excluding variations associated with ground level enhancements of solar CR.

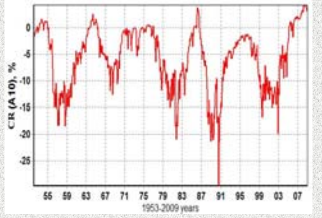

Fig1. Long-term 10 GV CR variations (monthly average, % to 1976) calculated from the neutron monitor network data for 1953 – 2009. The rigidity spectrum is received by means of approximation:

$$\delta(R) = a/(1 + bR^{\gamma})$$

Solar characteristics :

The characteristics of the SA global processes :

Bss - the average solar magnetic field intensity – the integral energy index of solar activity, such as the squared radial component of the magnetic field averaged over a sphere of fixed radius, gives the information on all magnetic stream which is passing through the source solar wind surface,

α -the heliospheric current sheet tilt,

Hpol – the solar polar magnetic field.

We found that using combined data (direct and indirect observations of solar large scale fields) we were able to describe CR modulation over a long period 1953-2009.

Method: [7]

The characteristic of the SA local processes :

W- the sunspot numbers

The changes in all the solar indexes and the CR are far greater between cycles than the changes in the of sunspot numbers. The differences are specific for each index. Thus in the changes α the peculiarities of the 23rd cycle are clearly visible. In the changes of Hpol – it becomes less from cycle to cycle, and in the Bss variations we see short periods of increased values during periods of the enhanced SA. It may be true that the sunspot numbers is not a sufficient characteristic of SA and it should be complemented by other solar indexes when describing CR modulation.

Cycles in CR and W

The changes of **the average values of the CR variations for each cycle A10m**, the value of which can be considered to be the characteristic for the power of a CR cycle show that each cycle is unique. The deepest modulation is to be seen in the 22nd cycle (-8.2%), the intensity of CR was least subject to modulation in the 20th cycle (-3%), and the remaining 3 cycles show practically identical modulation (19th - -6.9%, 21st - -6.7%, and 23rd 5.5%). If we compare these data with the corresponding cycles of sunspot numbers we find a completely different situation. The most powerful cycle, using classic definition, is the 19th. We should note that the extreme values of these characteristics also do not coincide. They differ radically in maximum values. For example A10 was maximum in 1982, W in 1979, A10 in 1991, W in 1989, A10 in 2003, W in 2000.

Which solar phenomena in the last 5 SA cycles are connected with similar behavior of the average intensity of CR and its extreme values, and is there any regularity? In order to answer this question we need to further analyze both the evolution of global cyclical processes in the Sun's magnetic fields and also the peculiarities of the outflow and distribution of solar wind in the heliosphere. In other words the factors that influences the integral characteristic of the interplanetary environment – the average intensity of cosmic radiation and its extreme values.

The cyclic changes of the CR extremal values and SA characteristics

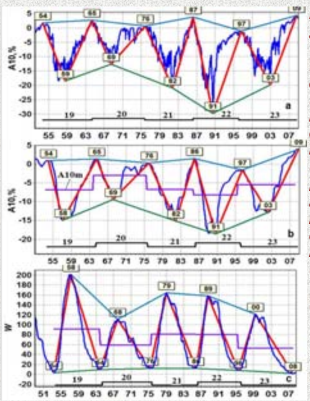

Fig.2 a) the average monthly CR variations A10 (dark blue), extremes of minimum A10 value (light blue) and maximum (green), red curves A10 passage between extremes (plan); b) A10 smooth averages over 12 months. Average for cycles A10m (violet), below - length of cycles (black); c) analogous curves (and colours) for W.

The extremal values of CR variations in SA minimum

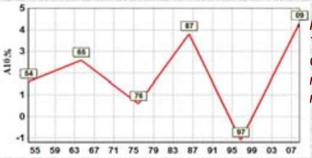

Fig.3 The extremal values of CR variations in SA minimum (the average monthly A10)

A 22-year wave is shown in changes of A10 extremes in the SA minimums. The amplitude of the 22-year wave of CR (the residual modulation) increases from year to year, from ~ - 1% in 1954-1976 to ~ – 5% in the first half of the cycle which began in 1997. The last period (SA decrease in the 23rd cycle) is especially remarkable. The value of the restored density of cosmic radiation exceeds all previous values observed in SA minimums

Extremum of CR variations and W

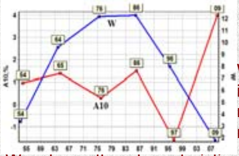

Fig.4 Extremum of CR variations (A10) and sunspot numbers W

We can say with certainty that in 22-year periodicity CR does not correspond to the sunspot numbers in SA minimums.

We chose the characteristics of the large-scale and polar magnetic fields as indices of global processes on the Sun. The yearly and monthly averages of these fields were calculated on the surface of the source of solar wind. Our choice of SA parameters is explained and confirmed in our works [3-5] where we propose the structural characteristic of the global field and quantity characteristics for the empirical description of CR cycles. These include the tilt of the heliospheric current sheet α and quantity characteristics – the integral energy index Bss together with the size and direction of the polar fields on the Sun – Hpol.

Extremum of CR variations, Bss, Hpol and α

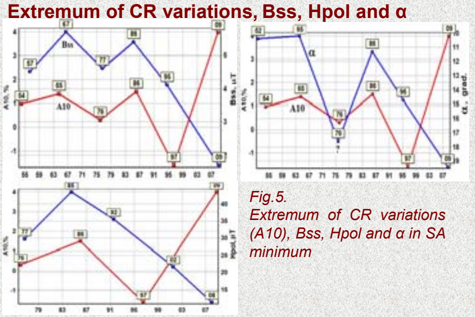

Fig.5. Extremum of CR variations (A10), Bss, Hpol and α in SA minimum

In the changes of the extremes of index Bss (fig.5a) in the periods near to minimum SA of five last cycles we can see a 22-year periodicity which coincides with the phase of a similar CR wave. A peculiarity of the Bss time change is a sharp fall in the value of the index at the end of the 23rd cycle and minimum of the 24th cycle. During this period the Bss changes contribute less to CR modulation than at the same periods in previous cycles. Maybe the decrease in the residual modulation of the CR minimum in the 23rd cycle can be partially explained by this fact.

It can be concluded that up until the last cycle, in the minimum extremes α changes with a 22-year periodicity in antiphase with CR. Calculating the value of the contribution to the observable modulation of CR from cyclical changes of SA indexes we obtained [9], that the contribution to modulation in CR from changes in α in the minimums of the last cycles has a 22-year wave.

The solar characteristic Hpol can participate in creation of the 22-year wave of CR extremes in SA minimums. Babcock discovered the cyclical changes (period of ~ 22 years) of the magnetic field of the solar polar latitudes. When we examine the link between CR extremes and the extreme values of the module of the solar polar field Hpol we discover that it clearly decreases from cycle to cycle. This is especially noticeable in the 23rd cycle.

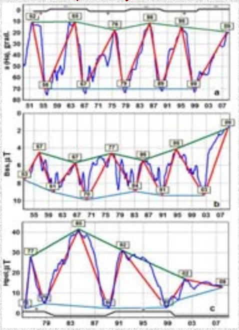

Fig.6 - temporal changes: a) tilt α, determined for period 1.1953-4.1976, using optical observations of filaments and calculated using method [7], for 5.1976-12.2009 using direct observations of the magnetic field, the obs.Wilcox http://quake.stanford.edu/-wso); b) Bss - intensity of field (using data from Wilcox and Kit-Peak observatories; c) Hpol - of the polar filed. The colours of the curves are analogous to the colours of the curves in fig.1. In fig 2 black shows the positive periods (+1), and negative periods (-1) of the global field on the sun and periods of its inversion (0).

In reply to the question as to which characteristics of SA show anomalous behavior in the 23rd cycle, resulting in the unusually high density of CR, we can say that these are the characteristics linked to the average size of the field on the Sun, its structure and the size and polarity of the polar field. The combined influence of these factors brought about this result - high intensity of CR.

CR extremum in SA maxima

The most difficult periods for the description of the behavior of long-term CR variations using SA indexes are the periods of SA maximum. In all our models of modulation, the largest divergences between the observed long-term CR variations and the expected variations were in 2003, 1991, 1982, 1969 and 1959. This result was achieved for all the versions of the multi-parameter description of the CR variations. The years mentioned were periods of extreme A10 values and at the same time periods of significant sporadic phenomena on the Sun (the flares and the coronal mass ejections).

Conclusion

The research of the long-term CR variations of with the rigidity of 10 GV during the last 5 SA cycles (19-23) using A10m averages and extreme A10 values of CR intensity have shown that:

1) the value of A10m, which indicates the power of the CR cycle, is significantly inconstant in the examined cycles of SA. They do not coincide with the changes of the average values of such characteristic of local solar fields, like the sunspot numbers in cycles and A10m can be a useful SA index;

2) in SA minimums we observed a 22-year wave in CR intensity. The amplitude of this wave increases from cycle to cycle and achieves a peak in the 23rd cycle;

3) on the basis of analysis of the extreme values behavior of the modulation parameters in cycles and their link with the corresponding CR variations extreme values it was received that: a) changes in the structural characteristic of the large scale solar field (the structural characteristic is determined by the current sheet tilt α) make a contribution towards the creation of a 22-year periodicity in CR minimums, and b) variations in quantity (determined by the magnitude of the average intensity of the field – the integral index Bss, and also by changes in size and value of the magnetic field of the polar regions Hpol);

4) in the behavior of the extreme values of CR intensity A10 in the maximums there exists a complex link between the changes in these periods corresponding to the characteristics of SA cycles examined in this work.

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