INDICES OF THE COSMIC RAY ACTIVITY AS REFLECTION OF SITUATION IN INTERPLANETARY MEDIUM

A. V. Belov, E. A. Eroshenko, V. G. Yanke

Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 142092, Troitsk, Moscow region, Russia
e-mail:abelov@izmiran.troitsk.ru

ABSTRACT

Till now there were not quantitative estimations of the cosmic ray (CR) disturbance, as, for example, it is made for the geomagnetic activity. In present work we try to give the special indices on the level of CR activity, which can characterise some peculiarities of the space weather. These indices are calculated for every hour and every day within the period 1990-1995 on the base of CR density and anisotropy, obtained from the world neutron monitor network. As examples of these indices behavior several events during this period are considered. The possibility to obtain indices from a single station data is discussed.

INTRODUCTION

Various indices, as a simplified quantitative characteristic of complicated versatile phenomena, are extensively used in solar-terrestrial physics. The indices of the solar activity (Wolf numbers, for example) and geomagnetic disturbances (Kp, Ap, Dst, AA and others) (Bartels 1957, Mayaud 1972) allow to select and compare the different phenomena, to distinguish the quiet and disturbed periods.

Cosmic rays (CR), being a component of the interplanetary medium, naturally respond to its changing, and not less sensitively, than the Earth magnetosphere. The analogue of the magnetic storms in cosmic rays are Forbush-effects (FEs), associated with the solar ejecta (CME) and with propagating solar wind disturbances. In fact, these are the storms in cosmic rays, when a density and anisotropy of CR are changing significantly and sometimes catastrophically (for examples, Belov et al. 1997b). All the more strong disturbances may occur with the solar CR incoming at Earth, when CR flux may grow more than in order, and an anisotropy increases practically to 100% (Shea and Smart 1993). Surely, such events are rare enough to occur, but the variations of CR are evident forever, and the level of their disturbance changes permanently, reflecting the conditions of the interplanetary medium. However, no quantitative characteristic of such a disturbance exists till now. The aim of the present work is to propose a method for calculation the indices of CR activity (CRA-indices), to study the behaviour of these indices and their relation with solar activity, with interplanetary and geomagnetic disturbances.

METHODS AND DATA

Data from the world wide neutron monitor (NM) network have been used as the basis to obtain of CRA indices. This multichannel detector has a long (>40 years) homogenous set of data, containing an information about variations as density, so anisotropy of cosmic rays. These variations reflect all great disturbances of the interplanetary space and most important (in terms of the radiation danger) solar cosmic ray enhancements. Hourly data of density and first harmonic of CR anisotropy (for CR 10 GV rigidity) through 1990-1995, found by the global survey method (Belov at al. 1997a), have been used for calculations of the indices.

Intuition suggests, what a distinct is between quiet and disturbed state of the cosmic rays. In the quiet conditions the density and anisotropy of CR are almost constant and amplitude and direction of the anisotropy are close to the normal for a given period. In contrast to this, the big changes of density and anisotropy and significant deflections from normal anisotropy are inherent for disturbed period.

Let we know the density variation A_o and three component of the anisotropy vector A_x, A_y, A_z in the ecliptic reference system for two consecutive hours t-1 and t. To compare observed and normal anisotropy it is better to use the Earth's reference system and only two components of the anisotropy a_x and a_y because of the difficulties on definition of the absolute value of the north-south anisotropy (Belov et al. 1990) and of its strong IMF polarity dependence. We can present a disturbance of CR as following:

$$D = \sqrt{\left(\frac{\Delta_0}{s_0}\right)^2 + \left(\frac{\Delta_1}{s_1}\right)^2 + \left(\frac{\Delta_{xy}}{s_{xy}}\right)^2}\,, \qquad (1)$$

where $\Delta_0^2 = \left(A_0(t) - A_0(t-1)\right)^2$,

$$\Delta_1^2 = \left(A_x(t) - A_x(t-1)\right)^2 + \left(A_y(t) - A_y(t-1)\right)^2 + \left(A_z(t) - A_z(t-1)\right)^2,$$

$$\Delta_{xy}^2 = \left(a_x(t) - a_{x0}\right)^2 + \left(a_y(t) - a_{y0}\right)^2,$$

and s_0, s_1, s_{xy} – are the normalizing coefficients.

Using variations of CR we can't forget of their statistical nature. A typical statistical error of the density of 10 GV CR obtained by global survey method is about 0.05%, and for the components of the anisotropy it is a little more – about 0.1%. These statistical errors may be taken to obtain the normalizing coefficients. Another possible approach is to investigate the behavior and distribution of the CR disturbance components (the items in (1)) during the selected quiet period. For our data it was 1995 year, when rms deviations for Δ_0, Δ_1, Δ_{xy} are 0.07%, 0.14% and 0.21% respectively. These values have been used as the normalizing coefficients S_0, S_1, S_{xy}. All three items in (1) give an approximately equal contribution under this approach.

Vector of CR anisotropy has a significant longterm variation, especially within the solar magnetic cycle Thus, it turned in 1990-1995 from~85º to ~59º, that associated with the solar polarity reverse (Belov at al., 1997a). To avoid such long-term effect, as the components of the normal anisotropy a_{x0} и a_{y0} we used running averaged a_x and a_y for one solar rotation, directly preceded to the current hour. Therewith, if only one difference a_x-a_{x0} or a_y-a_{y0} exceeded by absolute value $2s_{xy}$, this hour was excluded from the averaging.

To go from D to CRA- indices the following has been done: 1) since the anisotropy appears in two items of (1), but density is only in one, the first item was doubled; 2) to reduce the contribution of stochastic fluctuations, D was exchanged on D-1, and when (D-1)<0, it was replaced on 0; 3) obtained values were rounded off to an integer for convenient using.

On the basis of hourly means CRA it is easy to obtain indices averaged by more long intervals, for example, for the last 3 or 24 hours: CRA_3, CRA_{24}. Respectively, daily mean CRA_d is an averaged CRA for one day.

GLOBAL INDICES

Indices CRA,_CRA_3, CRA_{24} and CRA_d were calculated through the period of 1990-1995. These 52484 hours contain as the extremely disturbed periods (in 1991), so the quiet ones (especially in 1995). So, our data set includes practically all possible levels of solar and cosmic ray activity. The mean value of CRA indices over this whole period was 3.56±0.01, median and mode were 3. Zero values were only in 1.2% of all hours. The most frequently CRA indices were in 1-5 interval. Although the range of values extends to 205, only in 5% of all cases CRA exceeded 7, and only in one case from 1000 - exceeded 30. CRA>8 appeared once per day, >15- once a week, and >27 - once per month. The distribution of CRA indices in different periods could strongly differ from the average. Thus, in the quiet 1995 CRA indices exceeded 7 only once per week and never was >13.

The most disturbed hours were recorded during the increasing of solar cosmic rays (GLE) 24.05.90 and 15.06.91. We have to point here, that used global survey method is not dedicated for GLE analysis, so, found for GLE hours characteristics density and anisotropy are not precise and not associated with 10 GV particles, sooner, with 3 GV. However, they reflect adequately enough the level of CR disturbance, and we can expend on these hours the common method of CRA-indices calculation. The periods with significant contribution of solar cosmic rays are very seldom. Practically all along the changing of CRA-indices is conditioned by the galactic cosmic ray variations and disturbances of the interplanetary space.

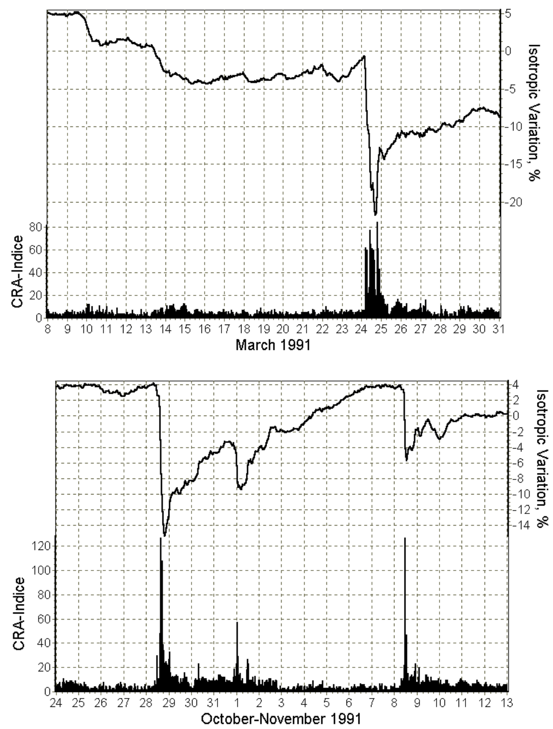

Figure 1. Variations of CR density and CR activity indices in disturbed periods of 1991.

The behavior of CRA indices in two disturbed periods of 1991 is presented in Fig. 1 a, b. The biggest increasing of the activity we see during the great FEs 24.03 , 28.10 and 8.11.1991. In the first of these events CRA indices reached the value 84, and in two last-127. It is the greatest modulation effects over the whole 6 years. FEs of 24.03 and 28.10 are in the list of the biggest FEs for the history of observations, and FE of 08.11 despite of the lower amplitude of decrease, was followed by the extremely large magnetic storm, when

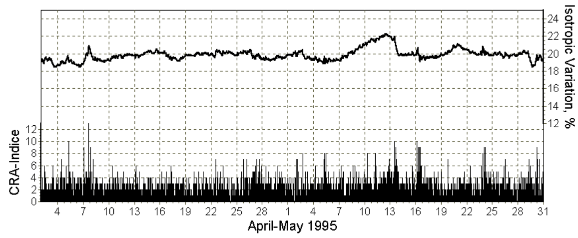

Figure 2 Variations of CR density and CR activity indices in quiet period of 1991.

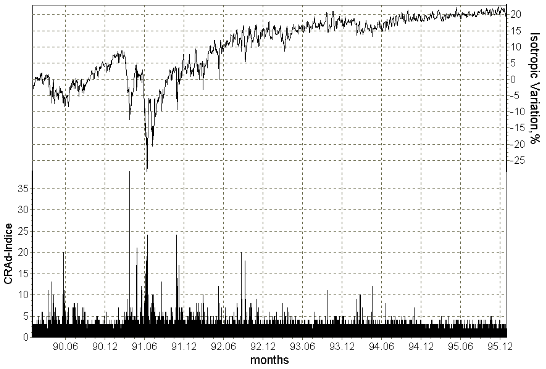

Figure 3. CR density variations and CRAd indices through 1990-1995.

Dst-variation fall down to -345. The disturbance increased also during another FEs in this periods (9-10.03,13-14.03, 1.11 and other). As a rule, the big CRA-indices correspond to the large FEs, but not always. For example, on 01.11.98 CRA-index increased to 48, that not strongly differs from the maximal indices in the giant FE on 24.03. On the period under consideration CRA-indices very often exceeded 10, and small indices (0-4) appeared rarely. For a comparison the quiet period (practically any time of 1995) was considered. The variations of CR density and CRA- indices in April-May 1995 are presented in Fig.2. Of course, CR variations don't disappear completely near the solar activity minimum (Belov et al. 1997a), but the big effects are absent at this time. Indeed, no one FE during two considered months exceeded 2%, and total change of CR density was less 4%. CRA-index reaches 10 only once for this period. From other side, there were several long intervals, when CRA indices was <=4. On this quiet background the increase of CRA indices to 8 looks outstanding. It seems, the increasing CRA to 6-10 is typical enough for the small FEs.

The behavior of daily CRA_d indices over the whole 6 years is presented in Fig.3. The range scale for CRA_d is, naturally, less than for CRA indices, it varied from 1 to 38, but mainly (in 85% cases) was 2-4. CRA_d reached the maximal value on 24.03.91, and this day seems to be mostly disturbed over the whole studied period. From this picture the relation of CR disturbance with solar activity is seen well: near the maximum, on 1991, annual CRA-indices was 4.9, whereas close to minimum on 1995 it decreased to 2.6.

The frequency histogram of hourly mean (CRA) and daily mean (CRA_d) indices is given in Fig.4.

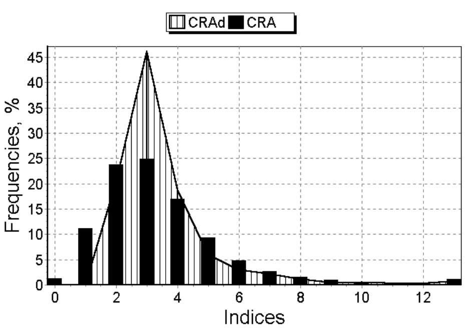

Figure 4 Histogram of CRA and CRAd indices

INDICES OF A SINGLE STATION

To analyze of CR disturbance we not accidentally used as a basis the CR density and anisotropy, obtained from the whole NM network. In comparison with these data the measurements from a single detector have some evident and essential drawbacks. The main deficiency of indices, obtained from such a data, will be caused by the limited space cone of each detector for coming CR. It responds to the CR disturbance only into his own cone and will not «notice» a disturbance in other directions. So, the sensitivity of the single detector to CR disturbance will depend on the direction of CR anisotropy and on the time of day, and will vary with time. Such a data doesn't allow to distinguish the variations density and anisotropy. These variations and station moving because of the Earth rotation may superimpose on one another by such a way, that counting rate from detector will remain unchanged even on the very strong disturbance. However, data from a single NM has an advantage, which force us to put up with all these demerits: these data allow to estimate of CR disturbance in the real time.

To apply the approach, already used for CRA calculation, to the single detector data, we have to study the daily run of the counting rate variations. During the quiet days we have in the NM data sinuslike daily variation. It is defined by the characteristics of the normal for the current period anisotropy and location of the station. Thus, on the Moscow station counting rate mainly increases on the first half of the day and decreases on the second one. The changing of the density and anomalous behavior of the anisotropy should lead to distortion of the daily run, and the greater is of CR disturbance, the more is distortion. Let in hour t the variation of the counting rate relatively to daily mean is $\delta(t)$, and its change in an hour is $d(t)= \delta(t)- \delta(t-1)$. Comparing this value with the same for the quiet period $d_0(t)$, we can find hourly indices of CR disturbance for the single station as:

$$CRAmosc = b\frac{|d(t) - d_0(t)|}{s} - a \qquad (2)$$

Four-letter station name, added to the sign of indices (here is Moscow station) is taken from the standard list using in GLE Database (Shea et al., 1987). Parameter S is a standard statistical error of the hourly mean counting rate. For Moscow station this value was obtained as 0.17% from a distribution of 1-minute data in the quiet periods. Constant a=1 is inserted to reduce the influence of the small random variations. The normalizing coefficient b was found as 3 to match CRAmosc and CRA indices over the 1995. Indices

CRAmosc3, CRAmosc6, CRAmosc24 may be obtained by averaging hourly mean indices for 3, 6, 24 hours.

CRA indices for Moscow station were calculated through 1995-1998 years. As a whole, CRAmosc index

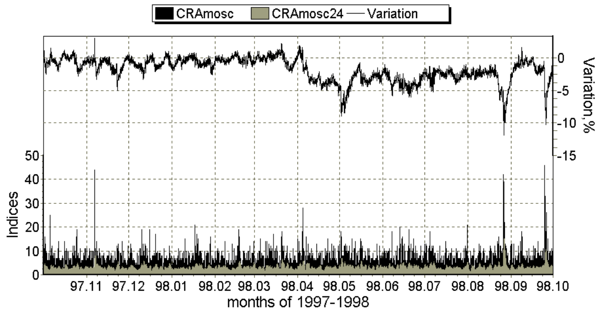

Figure 5 The Moscow NM count rate variation and CR activity indices for Oct. 1997 - Sept. 1998

was in the range 0-46 from January, 1995 to September, 1998 and CRAmosc24 varied from 0.48 to 15.08. The mostly disturbed day within this period was 28.08.1998. The behavior of CRAmosc and CRAmosc24 from October, 1997 to September 1998 together with counting rate variations are presented in Fig.5. This time falls on the phase of the solar activity growth, and CR disturbance here is rather higher than in preceding two-three years. The increasing CRAmosc was especially evident on November 6, 1997, when it reached of 44, and also at the end of August and September 1998 (42 and 46 respectively). On November 6 the first and until the largest solar CR enhancement in 23-rd solar cycle was recorded (GLE55), and in August-September the biggest in the current solar cycle FEs were observed. So, the behavior of CRAmosc indices reveals really the greatest CR disturbances.

The problem of the random variations on using the indices from a single station become more pressing than on working with global CRA-induces. To analyze this problem the special calculations of CRAmosc indices have been made, with the random haussian distributed numbers (with rms error 0.17%) instead of the real CR variations. A standard error of such a random indices was found as 2.7, so, it is reasonable enough to use integer rounded indices from one station, although, for CRAmosc24 it is undesirable. The random indices exceeded 8, 12 and 15 with probability 0.036, 0.0025, 0.0003 respectively. So in the case of a single increase of CRAmosc indices we may be sure in the real disturbance only if CRAmosc>15, or, better, >18. If we want to obtain a reliable information about smaller disturbances, we have to analyse hourly mean indices for several last hours and use the averaged indices (CRAmosc24 and so on). Moscow neutron monitor is a large-square detector with 24 counters, but it is suited close to sea level and is exceeded in a number of recorded particles by some high mountain stations. Using data from such stations (for example, Alma-Ata, 3340m) for calculation of CRA- indices can reduce a statistical error of indices more than once. But the most prospectively is to combine in real time data from several NMs. So far we realized and presented here the only possibility to obtain CRA indices in real time. We may look online the behavior of such induces via INTERNET on the experimental page: http://helios.izmiran.rssi.ru/cosray/main.htm, where CRAmosc and CRAmosc24 plot is updated every hour.

CONCLUSION

The variations of CR density and anisotropy, calculated by the global survey method, give the reliable base for the retrospective analysis of CR disturbance and calculation of the global CRA-indices. Data from a single NM allow to follow of CR disturbance in real time. However, the prompt (in an hour) and reliable information about disturbance onset from such data one can pick up until only for a great disturbance. The involving on INTERNET the complementary data from other stations (especially from high mountain) in real time, is bound to take off this problem.

ACKNOWLEDGEMENTS

This work is supported by the Russian Federal Program "Astronomy" and RFFR grant 980217315.

REFERENCES

Bartels J. (1957), The technique of scaling indices K and Q of geomagnetic activity., *Ann. Intern. Geophys. Year* v. 4, part I, pp. 215-236

Belov A.V., Dorman L.I., Eroshenko E.A., Oleneva V.A. (1990) Determination of the absolute value of north-south cosmic ray anisotropy from ground-based data. *Proc. 21-th ICRC. Adelaide,* v.6, pp. 357-381

Belov A.V., Eroshenko E.A., Yanke V.G. (1997a) Modulation effects in 1991-1992 years. *Proc. 25 ICRC,* v.1, pp.437-440

Belov A.V., Eroshenko E.A., Yanke V.G. (1997b) Modulation effects in 1991-1994 years. *Correlated phenomena at the Sun, in the Heliosphere and in Geospace,* SP-415, ESA, ESTEC, pp. 463-469

Mayaud P.N., (1972) The aa-indices: a 100-year series characterizing the magnetic activity. *Journal of Geophysical Research* , v.77, No.34, pp. 6870-6874

Shea M.A. and Smart D.F. (1993) History of solar proton event observations. *Nucl. Phys. B (Proc. suppl.),* 39A, pp. 16-25

Shea M.A., Smart D.F., Humble J.E., Fluckiger E.O., Gentile L.C. and M.R. Nichol (1987). A revised Standard Format for Ground Level Event Data, *Proc.20th ICRC,* v.3, pp.171-174