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Variations of the vertical cut off rigidities for the world wide neutron monitor network over the period of continues monitoring of cosmic rays

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Vertical cut off rigidities for the world wide neutron monitor network are obtained with one year resolution during the period of 1950-2020 by the method of trajectory calculations and using the models of International Geomagnetic Reference Field. In addition, the cut off rigidities for the whole period were obtained using model by Tsyganenko Ts89 with involving yearly mean values of *Kp* index. In each case an estimation of penumbra contribution was made in approximation of flat and power spectra (0 and -1) of cosmic ray variations. The results testify total decrease of cut off rigidities practically in the all locations.

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1. Introduction

Magnetospheric effects of cosmic rays (CR), i.e. response of a CR flux to the changes of a condition of a magnetosphere, opened when carrying out the latitudinal measurements (J.Clay in 1927), are rather well studied now. But modern development of experiment, both in duration of observations and in accuracy of the obtained experimental data, demands more careful researches of magnetospheric effects. It is connected with that for the sixty-year observation period of cosmic rays the dipole part of a geomagnetic field decreased approximately by 4%, but in different regions reduction goes with a different speed that is revealed in movement of poles as well. At once, the contribution of high harmonicas of a geomagnetic field for this period, on the contrary, increased to 30%.

To estimate consequences of such big reorganization of a magnetic field from the point of view of magnetospheric effects at CR, it is necessary to receive planetary distribution of geomagnetic cut off rigidities (R_c) for the entire period of measurements, taking into account only internal current systems. According to preliminary estimates in certain regions change of this main power characteristic of the coming particles (R_c) reaches ~ 2 GV, (> 10% for the equatorial detectors) that is very important at research of long-term variations of the CR.

Two key concepts: cut off rigidity (sufficient for the description of variations of isotropic part of CR) and an asymptotic cone of reception of particles (for the description of variations of anisotropy), - allow to describe all magnetospheric effects of CR. At the description of long-term variations it is enough to be limited to isotropic approach. The problem of exact definition of one of the most important characteristics of space radiation - geomagnetic cut off rigidity- has exclusive value for definition of spectra of primary CR.

The theory of magnetospheric effects very intensively developed in the fifties within Stormer's theory [1]. But divergences between theoretical and experimental data (the equator, the latitudinal course, the east- western anisotropy of CR) showed that dipolar approximation of a geomagnetic field is too rough. For receiving more exact results it is necessary to consider the higher harmonicas of a geomagnetic field at calculation of cut off rigidities of CR. But even the modified Stormer's theory allowing to consider the higher harmonicas in some approach didn't remove all contradictions of the theory and experiment. All analytical methods of calculation of cut off rigidities are confidants. Other essential lack of analytical methods is difficulty of the accounting of external sources in that case when fields of these sources aren't axial - symmetric (for example, for taking note of a loop of a magnetosphere). The best consent with experiment was received at calculations of cut off rigidity by numerical integration of CR trajectories in a real geomagnetic field. Moreover, in the approximation of the geomagnetic field may be taken into account both internal and external sources of the geomagnetic field.Such approach allowed to consider also external sources of a magnetic field that has paramount value in the analysis of solar cosmic rays.

The review of magnetospheric effects at an early stage was made in works [2, 3], the review of modern works can be found in [4].

The fullest and systematic researches of magnetospheric effects of CR are conducted by Shea M. and Smart D. So on the basis of models of a geomagnetic field for the corresponding eras and trajectory calculations they calculated global distributions of vertical rigidity of geomagnetic cut off with a step 5°×15° on the latitude and longitude for eras 1955, 1960, 1965, 1975, 1980, 1990, 1995. Vertical rigidities of geomagnetic cut off are received for all stations of the World network for 9 five-year eras 1955-1995 [5].

Shea and Smart [6] also paid attention to unevenness of changes of planetary distribution of rigidity of geomagnetic cut off in 20 years from 1955 to 1975, especially in the northern and southern area of the Atlantic Ocean. In the southern part of the Atlantic Ocean reduction, while in northern – approximately same increase in vertical cut off rigidity was observed.

For the last four eras such calculations for the operating network of CR detectors weren't carried out. Besides, for the last 20 years some new neutron monitors and multidirectional muon telescopes for which such characteristics are required to be defined, are put into operation.

2. Method of calculations of geomagnetic cut off rigidities and model of geomagnetic field

Now the standard and the most exact way of determination of rigidity of geomagnetic rigidity is the method of trajectory calculations based on the solution of the equation of moving of charged particles in a geomagnetic field.

The problem of the movement of charged particles in a real geomagnetic field has no exact analytical decision, and is solved in number, for example, by the Runge-Kutta method of the 4th order of accuracy with an adaptive step [7]. As basic data geographical coordinates of station and components of an initial vector of speed serve. Particles start with height of 20 km.

Integration comes to the end in three cases: 1) after the set time (the particle is considered taken), 2) the particle crossed a magnetopause surface (went beyond a magnetosphere) 3) its radius vector appeared less, than (R_E+20) km (R_E - Earth radius) (the particle returned to the atmosphere). In case of the second outcome this trajectory is marked as resolved, otherwise — forbidden. As a result of calculation the discrete G(R) function accepting "0" and "1" values for all values of rigidity with a step 0.001 GV is formed. Rigidities of geomagnetic cut off are calculated for model of the main magnetic field of IGRF. Such models are created since 1950, with a five-year interval up to 2015, and taking into account a century variation of a magnetic field the model is continued till 2020 [8]. The field is presented by 13 spherical harmonicas, but the predictive model is limited to 8 harmonicas for the atmosphere of two types of variations: flat ($\gamma = 0$) and power ($\gamma = -1$) spectra.

3. Taking into account the penumbra of cosmic rays

Lemartre and Vallarta [9] at calculation of trajectories of particles in a dipolar field found area of a penumbra. Developing Stormer's theory and the concept of the forbidden cone, they entered concept of the resolved cone when all trajectories are resolved, and concept of the main cone which includes the resolved cone and area of a penumbra.

This transitional area represents difficult alternation of the forbidden and resolved directions of arrival of particles and leads to emergence of two important consequences. First, rigidity of geomagnetic cut off of CR for the same point on Earth is a several various for devices with various coupling functions .

Secondly, even at constancy of a geomagnetic field and, therefore, constancy of area of a penumbra, at temporary variations of a power spectra of primary space radiation outside a terrestrial magnetosphere there will be corresponding temporary variations of geomagnetic cut off rigidities of space radiation, which are various for devices with different coupling coefficients. This circumstance leads to that it is impossible to characterize any point on Earth by some universal rigidity of geomagnetic cut off. It is various for different devices and changes in time [3, 10]. Effective rigidity geomagnetic cut off can be defined variously. In the simplest case it is possible to carry out simple summation of the resolved and forbidden areas which are defined by penumbra area. More correctly such summation can be carried out, using the expected CR spectrum as weight function. It is fair outside the atmosphere. For accounting an influence of atmosphere it is necessary to include in the weight function also an influence of atmosphere using coupling coefficients.

Generally with the accounting of a spectrum of variations $\delta J/J$and influences of the atmosphere, considered by means of coupling function $W(R, h)$, effective rigidity of geomagnetic cut off $R_{\text{eff}}$is defined from the equation given in [3]:

$$\int_{R_{\text{eff}}}^{R_H} W(R,h)\cdot \delta J\, J(R)\cdot \mathrm{dR}=\int_{R_S}^{R_H} g(R)\cdot W(R,h)\cdot \delta J\, J(R)\cdot \mathrm{dR}, \qquad (1)$$

where R_H and R_S is magnetic rigidity of the main cones and Stermer cones, and g(R) is delta function which is equal 0 or 1 for forbidden and resolved directions accordingly.

To solve an equation respectively R_{eff}spectrum of CR variation is approximated as a power function $\delta J/J = \text{aR}^{-\gamma}$, and influence of the atmosphere is accounted via coupling function which in relatively small area of penumbra is also approximated as power function $W(R)=cR^{\eta}$. Then, after integration, we obtain:

$$R_{\text{eff}}^{\gamma+\eta+1}=R_H^{\gamma+\eta+1}-(\gamma+\eta+1)\int_{R_S}^{R_H} g(R)\cdot R^{\eta+\gamma}\,\text{dR} \qquad (2)$$

In particular case of primary spectrum which isn't depending on the CR energy (a white or flat spectrum, i.e. $\gamma = 0$) and neglecting influence of the atmosphere (i.e. $\eta = 0$) we will receive expression for effective rigidity of geomagnetic cut off:

$$R_{\text{eff}}=R_H-\int_{R_S}^{R_H} g(R)\,\text{dR} \qquad (3)$$

The case of a white spectrum of CR variations physically isn't realized, but, when there is no strict requirements to accuracy, such calculations of effective rigidity of cut off are convenient and are often used.

Planetary change of the width of penumbra region calculated for era 2015 by the model IGRF is shown in Fig. 1 (right scale in GV).

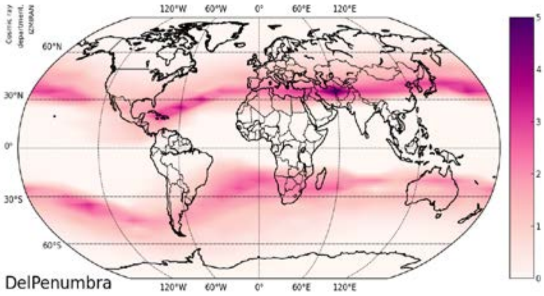

Fig. 1. Planetary change of the width of penumbra region calculated for era 2015 by the model IGRF (right scale in GV).

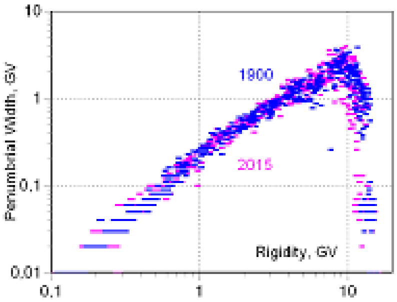

Fig. 2. Dependence of penumbra width on geomagnetic cut off rigidity. Blue-for epoch 1900.0, violet – for 2015.0

From fig. 1 it is visible that in a real magnetic field the structure of area of a penumbra and planetary change of its width has very difficult character. In east part of the northern hemisphere width of a penumbra area reaches 4 GV while in east part of the southern hemisphere width is much less, but the penumbra is observed up to polar latitudes. Dependence of width of a penumbra on rigidity of geomagnetic cut off is given in fig. 2. It is interesting that between width of a penumbra and geomagnetic cut off rigidity almost determined communication is observed. Besides, rigidity dependence of width of a penumbra for two eras practically didn't change in spite of the fact that in hundred years there were, in general, changes in a geomagnetic field, grandiose for this time scale.

4. Discussion of the results

Firstly, the calculations of planetary distributions of geomagnetic cut off rigidities were performed by the net 5° on the latitude and 15° on the longitude for the epoch from 1950 to 2020 with the steps of 5 years for the field IGRF. Digital and graphs results can be found on the server [11]. Such distributions allow make visualization a dynamic of cut-off rigidities. Planetary distributions obtained by interpolation, for example, on the basis of Bessel formula allow get geomagnetic cut off rigidity for any point if it is possible to have a limit accuracy of some tenth of GV. Changes of planetary distribution of the vertical cut off rigidities for epoch 2015 relatively to epoch 1950 (i.e. over the whole period of NM observations) are shown in Fig. 3.

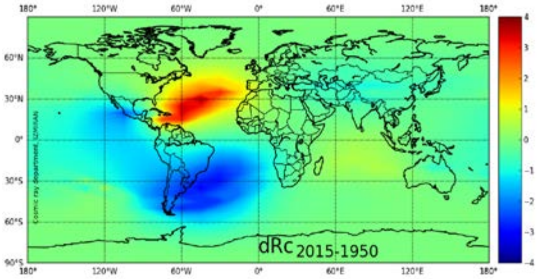

Fig. 3. Variation of planetary distribution of vertical cut off rigidity for the epoch 2015 relatively to epoch 1950.

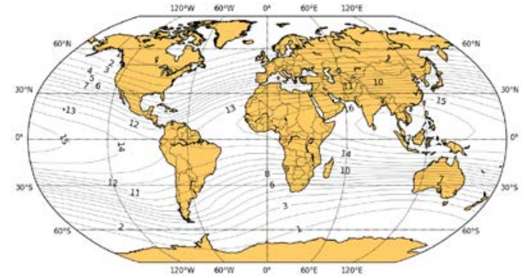

Fig. 4. Example of planetary distribution of vertical geomagnetic cut off rigidity for the epoch 2015.

It is possible to note substantial increase of geomagnetic cut off rigidity from east coast of North America up to Gibraltar and considerable decrease geomagnetic cut off rigidity near South America. It is necessary to pay attention to emergence of two big areas concentrated mainly in the northern and southern water area of the Atlantic Ocean. In epicenter of these areas, where the change of geomagnetic cut off rigidity reaches almost 3 GV, there are no CR detectors, but even on the periphery of change the cut off rigidities are considerable. So, the periphery of area in northern Atlantic includes many American and Canadian stations and part of the European stations. In general for all these points increase of rigidity to 1 GV is observed. In the southern part of the Atlantic Ocean decrease of rigidity is even more and reaches 2 GV.

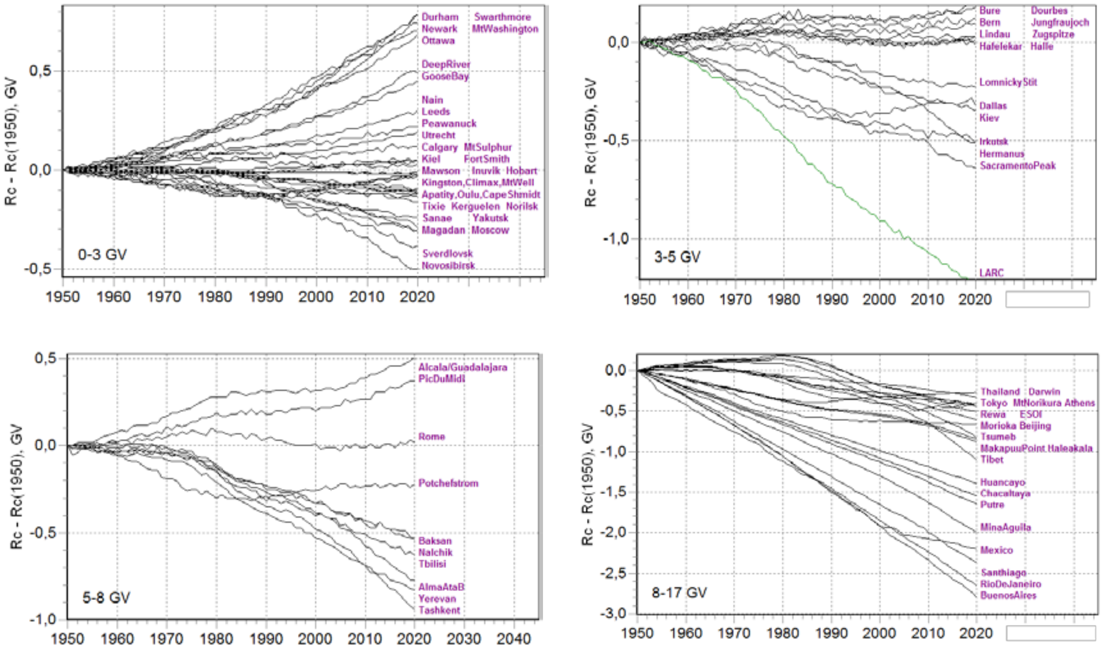

Fig. 5. Changes of vertical geomagnetic cut off rigidity for 4 groups of the CR stations relatively to the epoch 1950 (in the approach IGRF and flat spectra of CR variations)

The example of planetary distribution of vertical geomagnetic cut off rigidity for an era 2015 is present in fig. 4, and common presentation about changes of geomagnetic cut off rigidities on the CR stations of worldwide network gives fig. 5, the results for which were obtained for the field IGRF. Here in figure changes of vertical geomagnetic cut off rigidity relatively to the epoch 1950 are plotted for 4 groups of the CR stations over the whole period of cosmic ray monitoring. Time variations of the geomagnetic cut off rigidity at high latitude detectors (<3 GV) reach 0.5 GV, herewith of different sign. For American, Canadian and some of European stations the systematic increase of cut off rigidities is observed. It caused by influence of periphery region in the northern part of Atlantic. For other CR detectors insignificant decrease of cut off rigidities is recorded. For intermediate values in the range of 3 - 8 GV the rigidity generally decreases, except of several detectors in the western coast of Europe, area which is the periphery of Mid-Atlantic anomaly. For low-latitude detectors, up to equatorial, essential decrease of geomagnetic rigidity for all detectors is also observed. Thus, the global decrease of the geomagnetic cut off rigidities is seen except of mid-Atlantic anomaly, where, unfortunately, there are no operating CR detectors.

More detailed, on the basis of model IGF for 1950-2015, and using prognostic model – for 2020with one year resolution, vertical geomagnetic cut off rigidities are calculated by trajectory method for NM of world wide network (121 NMs) worked long enough period. As an example the results for some detectors are presented below. In Fig.6 time variations of cut off rigidity are shown for two points: Hermanus и Tsumeb. Couple of curves are the results of calculation by model IMRF with account penumbra in approach of flat (γ=0, point line) and power (γ=-1, solid line) spectra of the CR variations. These curves are almost similar for Hermanus, but significantly differ for station Tsumeb. It is caused by the big width of a penumbra of Tsumeb station (fig. 6) that results in bigger sensitivity to a spectrum of variations. The assessment of the accuracy 0.08 GV, such mistake is shown for an era 2002. The working period of station is marked in the gray color on one of the top curves. In Fig. 6 there is also comparison with the results of the first trajectory calculations [12], obtained by the expansion of magnetic field in terms of the first six harmonics for the epoch 1955 (red square). The estimation of accuracy is 0.1 GV. Circles mark the result obtained also by the method of trajectory calculations but for a field IGRF [5]. Step of integration of the equation is 0.01 GV, account of penumbra was followed an approximation of the flat spectrum of CR variation. Difference in the obtained results we connect with more accurate step of integrating of the equation of moving. As an example another couple of detectors may be considered (Tibet and Beijing), which also strongly differ in a penumbra width.

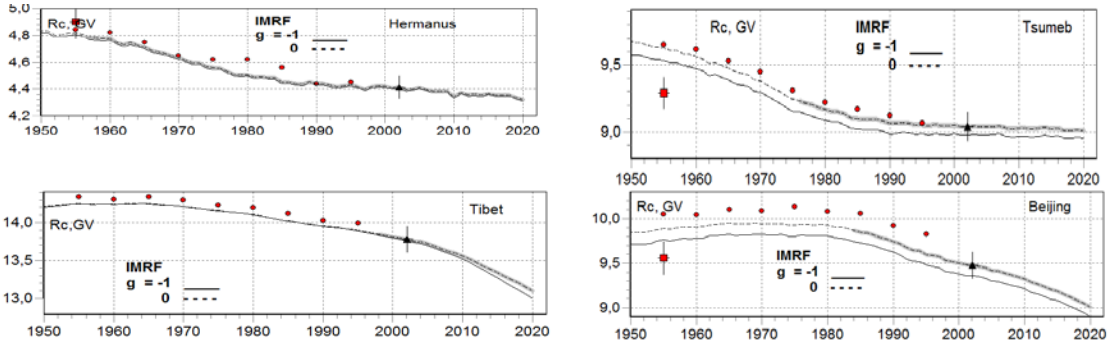

Fig. 6. Changes of the cut off rigidities for a couple of stations Hermanus and Tsumeb and couple of Tibet and Beijing. Model of magnetosphere IMRF with accounting of a penumbra in the approximation of flat (γ=0) and power (γ=-1) spectra of the CR variations. Triangle-score calculation error.

Accuracy of calculation of geomagnetic cut off rigidities depends on three factors: accuracy of representation of a geomagnetic field, an error of a method of integration of the equation of the movement of particles in such field and accuracy of the accounting of area of a penumbra. The main contribution to an error is made by an error of the accounting of area of a penumbra, then rather well controlled error of integration of the equation of the movement of particles and, at last, accuracy of representation of a geomagnetic field. The total error of calculations in the range of rigidities 5÷12 GV makes 0.15 GV and is slightly less out of this interval.

5. Contribution of an external field in the long term variations of the cut off rigidity

Long term changes of the Earth magnetosphere are caused by solar activity. To estimate of such changes, for example, the model of a magnetic field of Tsyganenko of Ts89 may be involved. The input parameter of this model characterizing a condition of an external magnetic field is *Kp*-index. Average annual values of *Kp*-index were defined from Ap indexes by the corresponding recalculations. For example in Fig.7 the results on the mid-latitude station Lomnicky Stit is presented by the same designations as in Fig.6.

The result of calculations for the IGRF model and comparison with results of other authors is also given in the top part of fig. 7 [5,12]. Geomagnetic cutoff rigidities for Tsyganenko model Ts89 are given in the middle part of Fig. 7 for each *Kp*-index from 0 - 4 as curves number 0-4.

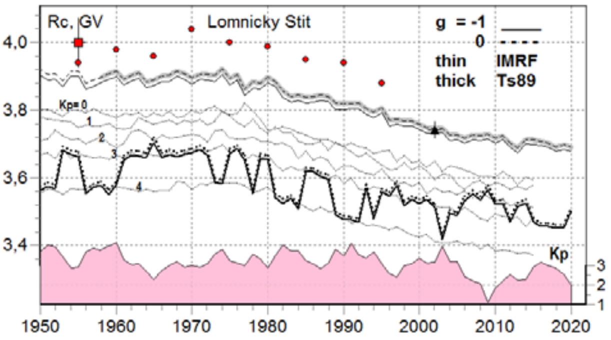

Fig. 7. Time variations of geomagnetic cut off rigidities at station Lomnicky Stit for two models (IMRF and Ts89) of magnetosphere with accounting of penumbra in the approximation of flat and power spectra.

The possible corridor of cut off rigidity variations within change real values of the size of *Kp*-index is shown by points and solid line. Also average annual *Kp*-index are given in the lower part of fig. 7. Calculation shows that accounting of impact an external magnetosphere on long-term variations of cut off rigidities leads to reduction of rigidity by some tenths of GV and reaches 0.4 GV for high-latitude detectors, for example at the stations: Kerguelen, Deep River, Durham, Apatity. Observed 11-year' variations of geomagnetic cut off rigidity are in an antiphase with the changes of *Kp*-index; they are insignificant and don't exceed 0.1 GV.

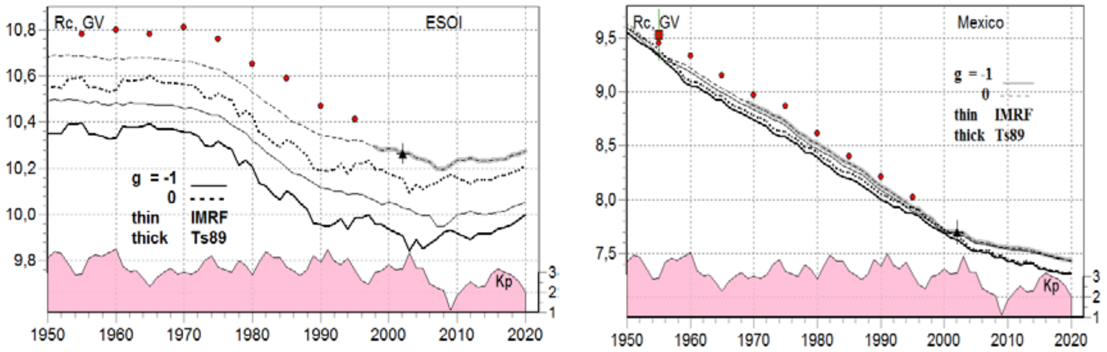

Fig. 8. Change of the cutoff rigidity for Mt.Hermon and Mexico. Indications are the same as in Fig. 7.

6. Conclusion

Essential reduction of a magnetic field of Earth against which its peculiar "contrast" increases, with existence of areas with sharp change of a field near poles and magnetic anomalies, and also change of a vector of movement of poles and anomalies, is the reason of essential change of geomagnetic cutoff rigidities.

In general geomagnetic cutoff rigidity decreases, especially on low latitudes. Long-term changes of effective geomagnetic cutoff rigidities for a world network of neutron monitors for various eras of a geomagnetic field with account penumbra are determined by method of trajectory calculation with involve of field model IGRF for each time-point.

The changes of effective geomagnetic cutoff rigidity caused by influence of a penumbra can reach several tenths GV, for example, for the detector Mt Hermon it is 0.1GV.

Additional comment

All obtained the results in digital and graph forms are published in the Internet [11]. Results include calculations of planetary distribution of geomagnetic cutoff rigidities for field of IGRF model for a grid 5°×15° for eras from 1955 to 2015 with a step of 5 years and the forecast on 2020. The area of a penumbra was considered for a flat spectrum of the CR variations.

Besides, are published geomagnetic cutoff rigidities for 118 detectors of the World network of neutron monitors for the entire period of observation with a step one year. Geomagnetic cutoff rigidities are received for model of a magnetic field of IGRF and the Ts89 model. The area of a penumbra was considered for a flat and power spectra taking into account influence of the atmosphere.

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