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Planetary long term changes of the cosmic ray geomagnetic cut off rigidities

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Abstract. The geomagnetic cutoff rigidities for vertical and inclined detectors of the World Network neutron monitors and muon telescopes were obtained with an annual resolution for the period 1950-2015 and for the forecast time up to 2050 by the method of trajectory calculations on the basis of the IGRF model. The results of the calculations indicate the manifestation of two World anomalies of the time dependence of the rigidity of geomagnetic cutoff and an irregular course for the north-western and south-eastern directions for detectors in the northern and southern hemispheres.

1. Introduction

The modern development of the experiment, both in the duration of observations, and in the accuracy of the experimental data obtained, requires more thorough studies of magnetospheric effects. This is due, for example, to the fact that during the sixty-year period of observations of cosmic rays the geomagnetic field has decreased by ~ 4%, and in different regions of the Earth the decrease is at a different rate. It was noted in [1] that while the dipole moment decreased significantly by 6.5% since 1900, the contribution of high field harmonics during the same period increased by ~ 30%. The center of the dipole has shifted by 200 km in the direction of the Pacific Ocean.

To assess the consequences of such a large adjustment of the magnetic field from the point of view of the magnetospheric effects in cosmic rays, it is necessary to obtain a planetary distribution of the rigidity of geomagnetic cutoff for the entire observation period. In some regions the change in the main energy characteristic of incoming particles, the rigidity of geomagnetic cutoff, reaches ~ 2 GV, which is very important for the study of long-period cosmic ray variations.

An overview of the magnetospheric effects can be found in [2-7]. The most complete and systematic studies of the magnetospheric effects of cosmic rays, including their long-term changes, were carried out by M. Shea and D. Smart. Based on the geomagnetic field models for the respective epochs and trajectory calculations, global distributions of vertical geomagnetic cutoff rigidities were calculated in increments of 5°×15° in latitude and longitude for the epochs 1955, 1965, 1975, and 1980, [8-11] and 1990, 1995, 2000 [12-14]. Vertical rigidity of geomagnetic cutoff was obtained for all neutron monitors of the world network for the nine five-year epochs of 1955-1995 [15].

Shea M. and Smart D. [10], Storini M. [16], drew attention to the unevenness of changes in the planetary distribution of the geomagnetic cutoff rigidity in 20 years from 1955 to 1975, especially in the northern and southern waters of the Atlantic Ocean. In the southern part of the Atlantic Ocean, a decrease in rigidity was observed, while in the northern part a comparable increase was observed.
For the last four epochs, such calculations for the operating network of detectors have not been carried out. In addition, over the last 20 years, about a third of new neutron monitors have been included into operation and a network of multidirectional muon telescopes has been created for which the rigidities of the geomagnetic cutoff.

2. Method of calculation

It is known, there is no analytical solution of the equation of charge particle moving even in the field of a magnetic dipole (except of the trajectories in the equatorial plane).

The solution of the problem of the charged particle motion in the earth's magnetosphere was carried out by the method described in [17]. Integration is completed in three cases:

0 - the particle has moved beyond the magnetosphere - the trajectory is allowed;

1 - the particle penetrated to a depth less \((R_{\text{Earth}} + 20)\) km (the particle returned to the atmosphere, the trajectory is forbidden): there are two options here - the rigidity of the particle is less than Stormer's rigidity or rigidity higher, but particle collided with the surface of the Earth);

2 - the integration is completed after a predetermined time (the particle is considered to be captured by the radiation belt)

As a result of the calculation, a discrete function of the penumbra \(g(R)\) is formed with the values 0, 1 or 2 for all rigidity values with the step 0.001 GV selected by us.

![Figure 1. Changes with respect to the 1950 period of vertical rigidities of geomagnetic cutoff of the World Neutron Monitor Network. The insertion shows the changes in the planetary distribution of the vertical rigidities of the geomagnetic cutoff [20].](image-url)

3. Discussion of the results. Neutron monitors

In work [18] for vertical directions of arrival of particles for every five epochs since 1900 by method of trajectory calculations the calculations of planetary distributions of geomagnetic cutoff rigidity \((R_c)\) for grid 5° in latitude and 15° in longitude were performed. Geomagnetic cutoff rigidities were obtained using the International Geomagnetic Reference Field (IGRF) model [19]. Digital results for all epochs can be found on the server [20]. For the same period with an annual resolution, the geomagnetic cutoff rigidities were obtained for the World wide neutron monitor network (NMN). The results on the changes of the planetary distributions of the geomagnetic cutoff rigidity indicate the manifestation of two World anomalies (figure 1, insertion): in the zone of one, the rigidity decreases with time, while in the zone of the other, it increases with respect to the 1950 period, but globally rigidity of the geomagnetic cutoff decreases by approximately 3.4% for 50 years.
The time variations in the $R_c$ for each station are determined by the influence of the anomaly in the zone of action of which the station is located. Figure 1 (left panel) shows the changes (increase) in the $R_c$ of a group of stations that are in the zone of influence of the North Atlantic anomaly, and in figure 1 (right panel) the changes (decrease) of the $R_c$ of a group of stations that are in the zone of influence South Atlantic anomaly. At peripheral stations, insignificant changes (~ 0.1 Gv) in the rigidity of the geomagnetic cutoff are observed. The accuracy of the obtained rigidity values is better than 0.05 GV.

4. Discussion of the results. Muon telescopes

To date, the world network of muon detectors has about 20 devices: super-telescopes, medium telescopes (~ 10m$^2$) and small telescopes (several m$^2$), as well as several hodoscopes. These are Nagoya, Hobart, Sao Martinho, hodoscope Kuwait, the short description of which can be found in [21], a giant hodoscope GRAPES-3 [22], hodoscope Moscow Nevod [23], spectrographYakutsk [24], Novosibirsk [25], Moscow-OPTO [26], Mustang [27-28], hodoscope Sierra Negra [29]. All detectors, with the exception of small, except vertical, detect particles from a large number of inclined directions. So, for the Nagoya telescope this is a vertical and 16 inclined directions.

Calculations of temporal changes in the rigidity of geomagnetic cutoff were carried out for all muon detectors of the World Network. The result for the Nagoya telescope is shown in figure 2. For 1971 (square), the value of $R_c$ obtained by the authors of a multichannel super-telescope Nagoya [30] using the model [31].

Attention is drawn to the irregular behavior of time dependences for some directions of arrival of particles, which is especially clearly seen when considering the relative changes in $R_c$ (figure 2, right panel). First of all, in order to eliminate the code error, independent test calculations were performed [32], which are shown in figure 2 (circles). In addition, figure 2 (left panel, insert) shows the temporal stiffness for Nagoya.n1 for the lower $R_c$, upper $R_{ch}$ and effective $R_{eff}$ of the geomagnetic cutoff stiffness. This detailed comparison of our and independent calculations shows that code errors can be eliminated.

Let us consider the behaviour of the rigidity of geomagnetic cutoff for the inclined directions of arrival of particles. Analyzing the time course of the cutoff rigidities for the inclined directions of the World Network muon detectors, two groups of detectors can be distinguished. Detectors of the first group, have an irregular course in time dependence only for inclined north-west directions for
detectors of the northern hemisphere (in particular, Nagoya, in the sum of 17 detectors, figure 3, left). Detectors of the second group have an irregular course only for inclined directions south east (in particular, Hobart, in the sum of 6 detectors, figure 3, right) for detectors of the southern hemisphere.

The reasons for this behavior of the geomagnetic cutoff rigidity for inclined directions can be understood by considering the penumbra, its variations, and the particle trajectories themselves.

Figure 3. Relative changes in vertical rigidities of geomagnetic cutoff for 2 groups of cosmic ray stations relative to the 1950 period. The first group is the telescopes of the northern hemisphere (left side), the second is the telescopes of the southern hemisphere (right side).

The region of $R_c$, according to the modern Stormer theory, taking into account the results of Lemaitre and Wallart [33], can be represented as follows:

- **Störmer region of rigidities**, within which all trajectories are forbidden;
- **The main area of rigidity**, within which all trajectories are allowed;
- **The area of semi-shadow “penumbra”** between the Stormer and the main areas, but within this zone there are intermittent permitted and forbidden areas; it is important for us that the penumbra zone is formed by two regions or two types of trajectories:
  - **The shadow rigidity region** immediately following the Störmer boundary rigidity and actually adjacent to it is filled with particles crossing the Earth’s surface; the latter region is characteristic of obliquely incident particles facing the north or south pole, and is of greatest importance at large zenith angles;
  - **The region of rigidities of trapped particles** to the left of and to the right of the Störmer boundary rigidity is the region formed by particles of small rigidities captured by radiation belts; The latter area is typical only for medium latitudes and in the case of low latitudes is not visible;

Figure 4. Penumbra for two types of trajectories (Nagoya.se2 - left panel and Nagoya.nw2 - right panel) and two epochs – 1990 and 2010.

Let us consider for 1990 and 2010 years the structure of the penumbra for the directions **Nagoya.se2** (figure 4, the left panel), the time course of the rigidity of the geomagnetic cutoff which behaves monotonically. For these directions there are neither captured ($trapping=0$) nor intersecting the Earth’s surface ($intersected=0$) trajectories. Consequently, the region of the penumbra is absent.

A completely different structure has a penumbra for the directions **Nagoya.nw2** (figure 4, right panel), for which the time course of the rigidity of the geomagnetic cutoff behaves "unexpectedly
strange”. For these directions there are also no trapped \((trapping=0)\) trajectories, but a large number of trajectories crossing the Earth's surface are observed, i.e. penumbra is formed only by trajectories that cross the Earth's surface. The width of the penumbra region for the 1990 period is 1.990 GV, and for the 2010 epoch 3.320 GV, i.e. for 20 years from 1990 to 2010, the rigidity of the geomagnetic cutoff for the direction \textit{Nagoya.nw2} increases by 1.3 GV, which follows and from figure 2 (right panel).

Consequently, for inclined directions the penumbra region is very wide, and its strong variability with sufficiently small changes in the geomagnetic field leads to changes in the rigidity of the geomagnetic cutoff, sometimes even sharp, for inclined incident particles. Lemaitre and Vallarta [33] concluded that the shadow region contains particles with trajectories near the horizon from the north or south directions and have the largest values at large zenith angles. But for real detectors located not only on the equator, the increased shadow region of rigidities is characteristic for particles coming from north-west or south-east directions.

5. Results of digital calculations

For the practical use of the results of numerical calculations, an archive of geomagnetic cutoff rigidities data was created for all detectors of the World Network of neutron monitors and muon telescopes, which can be found on the Internet resource [20]. The archive also contains some graphical results and animations:

1) Digital and graphical results for all neutron monitors of the World network during the period 1950 - 2015 and prognosis to 2050 in the directory “\(R_c\) for all neutron monitors (Table and Graph)”.

2) Digital and graphical results for all telescopes of the World network during the period 1950 - 2020 and prognosis to 2015 in the directory “\(R_c\) for all Telescopes (Table and Graph)” (see \textit{guide.pdf}).

3) Animations of the trajectories, in particular, for the directions \textit{Nagoya.se2} and \textit{Nagoya.nw2} for 2010 are found in the section “Traces for some Trajectories (Graph)”.

4) Penumbra and animations, in particular, for the directions \textit{Nagoya.se2} and \textit{Nagoya.nw2} for 1990 and 2010 – in the section “Penumbra for some Example (Graph)”.

5) Tables of the planetary distribution of vertical \(R_c\) with a resolution of 5º×15º in latitude and longitude for the epochs from 1900 to 2050 with a step of 5 years in the section “Tables of planetary distributions \(R_c\)”.

6) Calculator of the geomagnetic cutoff rigidity \url{http://crsv.izmiran.ru/cutoff}. It calculates the rigidity of the geomagnetic cutoff for a given date and a given geographic point. The program can calculate trajectories for one of the given model of the magnetosphere: dipole, IGRF, Tsyganenko IGRF+T89, IGRF+T96, IGRF+T02. The result of the program is the lower \(R_S\), upper \(R_H\) and the effective \(Reff\) values of the geomagnetic cutoff rigidity and the penumbra.

6. Conclusions

1) The reason for the significant change in the rigidity of geomagnetic cutoff is the general decrease in the Earth's magnetic field, against which background its peculiar "contrast" is growing with the appearance of two anomalous zones: the North and South Atlantic anomaly and its plume.

2) The temporal changes in the \(R_c\) for vertically arriving particles at stations of the World Network of neutron monitors are completely consistent with the behavior dictated by these two anomalous zones.

3) Over the observational period of cosmic rays, the mean planetary \(R_c\) for the vertical arrival of particles decreased by 0.2 GV or 3.4%, which leads to an increase in the measured particle flux by \(-1\%\) over 50 years. In the epicenter of anomalies, during the same period, the flux changes to 12%.

4) The temporal changes in the \(R_c\) for oblique incoming particles for the muon telescopes of the World Network are also completely consistent with the behavior dictated by the two anomalous zones. But the second factor also acts, since the change in the magnetic field leads to a significant variability of the penumbra and, ultimately, to the instability trajectories of the particles from inclined directions.

5) The instability of particle trajectories from inclined directions leads to an irregular course of the time dependence of the \(R_c\) for certain directions, which are determined by the location of the detector relative to the geomagnetic equator. Thus, for detectors of northern hemisphere (\textit{Nagoya, Kuwait,}...
Yakutsk, GRAPES, YangBaJing, Yerevan2000, Norikura, SierraNegra, Mustang/Greifswald, Mustang/Kiel, Moscow, Moussala, Blagoevgrad, Guangzhou, Novosibirsk, Ottawa, Bure) irregularity of the temporal course of the rigidity of geomagnetic cutoff is observed for oblique north-west directions. For detectors of the southern hemisphere (Hobart, SaoMartinho, Putre, Leonsito, Adelaida & BucklandPark, ZhongShan) irregularity of the temporal course of the rigidity of geomagnetic cutoff is observed for oblique south-east directions.

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References
[1] Xu Wen-Yao, Wei Zigang, Ma Shizhuang 2000 Chin. Sci. Bull 45 21 2013
[2] Hofmann D J, Sauer H H 1968 Space Science Reviews 8 750
[3] Dorman L I, Smirnov V S, Tyasto M I 1971 Cosmic rays in the Earth's magnetic field (Moscow: Nauka) P400
[4] Smart D F, Shea M A, Flückiger E O 2000 Space Science Reviews 93 1 305
[5] Kudela K, Bobik P 2004 Solar Physics 224 № 1-2 423
[6] Bobik P, Boella G, Boschini M J et al. 2006 JGR 111 № A5 CiteID A05205
[7] Dorman L 2009 Cosmic Rays in Magnetospheres of the Earth 358 (Springer) 770
[8] Shea M A, Smart D F 1967 JGR V 72 № 7 P 2021-2028
[9] Shea M A, Smart D F 1975 AFCRL-TR-75-0381 № 524
[10] Shea M A, Smart D F 1975 Proc. 14th ICRC (Munich) 4 1298
[11] Shea M A, Smart D F. 1983 Proc. 18th ICRC (Bangalore) 3 514
[12] Smart D F, Shea M A 1997 Proc. 25th ICRC (Durban) 2 401
[13] Smart D F, Shea M A 2007 Proc. 30th ICRC (Mexico) 1 733
[14] Smart D F, Shea M A 2007 Proc. 30th ICRC (Mexico) 1 737
[15] Shea M A, Smart D F 2001 Proc. 27th ICRC (Hamburg) 4063
[16] Storini M, Shea M A, Smart D F, Cordaro E G 1999 Proc. 26th ICRC (Salk Lake City) 7 402
[17] Shea M A, Smart D F, McCracken K G 1965 J. Geophys. Res. 70 4117
[18] Gvozdevskii B B, Abunin A A, Kobelev P G et al. 2016 Geomagnetism and Aeronomy 56 4 381
[19] Thébault E., Finlay C.C., Toh H., Special issue “International Geomagnetic Reference Field— the twelfth generation” Earth, Planets and Space 2015 67:158/ doi 10.1186/s40623-015-0313-0; Model IGRF ePub 2015 http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
[20] Mag_Effect ePub 2016 ftp://crsb.izmiran.ru/MagEffect See guide.pdf
[21] Munakata K, Kozai M, Evenson P et al. 2018 ApJ 862 170 9
[22] Gupta S K, Antia H M, Dugad S R 2009 Nuclear Physics B 196 153
[23] Ampilogov N V, Astapov I I, Barbashina N S et al. 2016 Journal of Physics 675 3 id 032042
[24] Starodubtsev S A, Grigoriev V G, Gololobov P Y u 2017 Izvestiya RAS ser. fiz. 81 4 577
[25] Yanchukovsky V L, Grigoriev V G, Krymsky G F et al. 2016 Solnechno-Zemnaya Fizika 2 1 76
[26] Kartyshov V G, Abunin A A, Klepach E G et al. 2018 Proc. 26th ECRS (Barnaul, Russia) GEO36
[27] Hippler R, Mengel A, Jansen F et al. 2008 Proc. 30th ICRC (Mexico) 1 (idSH980) 347
[28] Banjac S, Galsdorf D, Heber B et al. 2015 Proc. 34th ICRC (Hague) id1026
[29] Ortiz E, Valdes-Galicia J F, Matsubara Y et al. 2015 Revista Mexicana de Fisica 61 6 466 doi:
[30] Nagoya Telescope 1970 http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon 464
[31] Finch H P, Leaton B R 1957 O. Monthly Roy. Astron. Soc. Geophys. Suppl. No 7 314
[32] Gvozdevsky B B, Belov A V, Gushchina R T et al. 2017 Nuclear Physics and Engineering 8 4 19
[33] Lemaitre G E, Vallarta M S 1936 Phys. Rev. 50 493