Study of cosmic ray semidiurnal variations

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Abstract.
On the basis of long-term registration of cosmic rays with the muon spectrograph at Yakutsk (62°01′N, 129°43′E) and multidirectional muon telescope at Nagoya (35°10′N, 136°58′E) the cosmic ray semidiurnal variation seasonal change and the change of cosmic ray semidurnarl variation with the solar activity level has been found. The modeling of the seasonal change has been made.

1. Data analysis
It is known that long-term variations of an angular distribution of cosmic rays reflects a variability of large-scale processes in the interplanetary medium. In this work a data of long-term registration of semidiurnal anisotropy with a high accuracy of the order of 0.002% – 0.005% of its annual average amplitude are used. We have used the hourly data of muon telescopes at Yakutsk (http://ysn.ru/ipm/) for the 1972 to 2011 period at sea level and underground at depths of 7, 20, 60 m w. e. of following directions: vertically and under the 30° relatively to a zenith to the south and the north. The accuracy of hourly registration of muons at these levels in a vertical direction is 0.1%, 0.14%, 0.20% and 0.37%, respectively.

The most stable device since 1971 is the muon spectrograph based on scintillators at the Nagoya station (35°10′N, 136°58′E) (http://www.stelab.nagoya-u.ac.jp/stelwww/div3/muon/muon3.html). From the data of 17 directions of this device we have used the data of three directions: a vertical, the north 30° and the south 30°.

2. Results
Figure 1 present the temporal change of the semidiurnal variation amplitude by telescope measurements of the st. Yakutsk and st. Nagoya, the numbers of solar activity for the last three solar cycles, and also values of a radial magnetic field flux [1]. Note that the calculation of influence of the geomagnetic field on the galactic cosmic ray anisotropy was made by using the methods stated in [2]. It is clear that during the periods of a solar activity minimum and sign-changes of general solar magnetic field the amplitudes of $A_2$ of the semidiurnal variation decreases. However, the decrease of $A_2$ during the solar activity minima is much more than during the moments of solar activity sign-change. Such a dependence of the semidiurnal variations with the specified parameters is spread up to the depth 60 m w.e., i.e. $E_m = 263GeV$. The best correlation between the amplitude fluctuations of the semidiurnal variation is observed at the energy levels 66 GeV (Nagoya) and 78 GeV (Yakutsk, 20 m w.e.). The number of
coronal emissions grows during phases of increase and decrease of solar activity in the solar activity minima, and during the sign-change periods of general solar magnetic field it falls. A disappearance or decrease of the number of coronal emissions are accompanied by the decrease of an open magnetic flux from the Sun. The open magnetic loops are formed as a result of...
reconnection of the magnetic field in the corona and related to the outer heliosphere. The reduction of the number of such loops leads to the decrease of the cosmic ray anisotropy amplitude.

During more than 30 years the average amplitude $|A_2| \pm 0.01$ at the mentioned stations is equal and does not almost depend on energy (table 1). The time of semidiurnal variation maximum in the median energy range of 50-263 GeV has remained constant and equals to $T_{2,\text{max}} = 3.12 \pm 0.19h$.

### Table 1. Median energy, average amplitude and average phase of cosmic ray semidiurnal variation at st. Yakutsk and st. Nagoya.

| Station            | Median energy, GeV | Average amplitude, % | Average phase, h |
|--------------------|--------------------|----------------------|-----------------|
| MT Yakutsk 0 m w.e. | 50                 | 0.112±0.010          | 3.233±0.329     |
| MT Nagoya 0 m w.e.  | 66                 | 0.118±0.004          | 3.108±0.088     |
| MT Yakutsk 7 m w.e. | 78                 | 0.110±0.015          | 3.034±0.478     |
| MT Yakutsk 20 m w.e.| 123                | 0.107±0.021          | 3.323±1.017     |
| MT Yakutsk 60 m w.e.| 263                | 0.117±0.056          | 3.932±1.745     |

Except the long-term variability, we have studied an annual change of semidiurnal variation. For this purpose we have used the data of the south $30^\circ$ (fig. 2) of st. Yakutsk and the data of the vertical of st. Nagoya. Taking into account the difference in geographical latitudes, this telescopes have approximately the same directional sensitivity. The data have been smoothed: only first and second harmonics of annual change were saved. In the right part of figure 2 are shown the annual average vector of semidiurnal variation with the semianannual harmonic and the annual harmonic of vector.
3. Discussions

The semidiurnal variation of cosmic rays reflects a tensoral part of its distribution function. The seasonal change could be caused by the changes of direction of the Earth’s rotation axis in the solar coordinate system and also it could be while the change of the Earth’s heliolatitude, if the cosmic ray distribution changes with the heliolatitude. Here we will try to separate this two effects.

As was shown in [2], the main mechanism, which creates the cosmic ray tensoral angular distribution, is magnetic screening. The particles that moves at low angles to regular interplanetary magnetic field penetrates into magnetic sectors on lower depths than the particles that moves perpendicularly to the force tubes. That is why in average in the magnetic tubes the deficiency of particles at the magnetic field directions has to appear.

The other reason of this tensoral distribution could be a shift flow of medium that scatters cosmic rays in this case - the shift flow of solar wind.

This mechanisms creates in the solar coordinate system the distribution that is described by harmonics $a_0^2$, $a_1^2$, $b_1^2$, $a_2^2$, $b_2^2$. Thus the antisymmetrical harmonics $a_1^2$, $b_1^2$, if they exist, have to be caused by the heliolatitudeal shift of solar wind’s speed, i.e. the north-south asymmetry of speed. The modeling of Earth’s behavior in this distribution shows that the semiannual harmonic of semidiurnal variation is caused by the component $a_0^2$, the annual - by the components $a_1^2$, $b_1^2$ and the annual average vector - by the components $a_2^2$, $b_2^2$. Thus the end of monthly vectors in the model would describe the circle as with the period of a year so with the period of a half of year. The observed ellipses could appear if the components $a_2^2$, $b_2^2$ depend on heliolatitude. Thus for the semannual changes this dependence has to be symmetric (square), and for the annual - antisymmetric (linear).

The combination of all this pointed factors gives the picture that is shown in figure 2. It corresponds to the average inclination of interplanetary magnetic field from the radial direction on $47^\circ$.

If to combine the symmetric and the antisymmetric dependences and to present as $b_2^2(\theta) = b_2^2(\theta_0)\cos^2(\theta - \theta_0)$ then we will be able to calculate $\theta_0$ - the magnitude of inclination of symmetry center of heliolatitudeal distribution of semidiurnal variations. Using our data that are presented in (fig. 2) we obtained $\theta_0 = -6^\circ$. The point of symmetry is shifted from helioequator on $6^\circ$ to the south. This is in agreement with the works [3, 4].

4. Conclusions

1. The semianual and the annual changes of semidiurnal variation of cosmic rays are in agreement with the magnetic screening mechanism and with the shift flow mechanism of solar wind.

2. In order to achieve the agreement between the model and the result of observations it is necessary to assume that the screening effect depends on heliolatitude and reaches the maximum at $6^\circ$ S.

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