Relation of muon flux local anisotropy with primary spectrum index

A N Dmitrieva, N V Ampilogov, I I Astapov, N S Barbashina, A A Kovylyaeva, V V Shutenko, E I Yakovleva
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, Moscow, 115409, Russia
E-mail: ANDmitriyeva@mephi.ru

Abstract. Muon hodoscope URAGAN allows to obtain the angular distribution of the muon flux. This distribution may be characterized by a vector of local anisotropy (the sum of the vectors of the particle arrival directions, normalized to the total number of muons). It was shown that annual variations in the vertical projection of the anisotropy vector $A_Z$ are not related with changes in atmospheric conditions. The dependence of $A_Z$ on the index of the primary particles spectrum $\gamma$ was calculated for several zenith angle intervals with the help of simulation of generation and propagation of secondary cosmic ray particles through the atmosphere using the CORSIKA package. Experimental temporal series of the vertical projection of the local anisotropy $A_Z$ for several intervals of zenith angles were obtained for 2007-2015. According to the obtained $A_Z$ time series, annual and diurnal changes of $\Delta\gamma$ were estimated.

1. Muon hodoscope URAGAN

Muon hodoscope URAGAN [1] is a wide-aperture precision muon hodoscope (Moscow, Russia, 55.7° N, 37.7° E, 173 m a.s.l.) which is used to study atmospheric and heliospheric processes responsible for variations in the muon flux at the Earth surface [2]. The hodoscope consists of separate horizontal assemblies (supermodules) with the area of 11.5 m$^2$ each. Three supermodules (SM) of the hodoscope are now under operation in the exposure mode. The supermodule detects muons with high spatial and angular accuracies (1 cm and 1º, respectively) over a wide range of zenith angles (0°-80°). One-minute matrix of each SM contains about 70-80 thousand events. For the analysis of muon flux variations caused by extra-atmospheric processes it is necessary to introduce corrections for meteorological effects.

2. Corrections for basic atmospheric effects

Barometric effect is the anticorrelation of cosmic ray intensity with the pressure at the observation level. Temperature effect is caused by changes of the temperature at all altitudes of the atmosphere. Corrections for barometric and temperature effects are introduced as follows:

$$M^{\text{corr}}(\theta, \varphi, t, \Delta t) = M(\theta, \varphi, t, \Delta t) - \Delta M_T(\theta, t, \Delta t) - \Delta M_P(\theta, t, \Delta t),$$

(1)

where $\theta$ and $\varphi$ are zenith and azimuth angles for matrix cell centers; $M(\theta, \varphi)$ is the number of reconstructed events in a cell $(\theta, \varphi)$ of the matrix $M$; $\Delta M_T$ and $\Delta M_P$ are corrections for temperature and pressure effects:

$$\Delta M_P(\theta, t, \Delta t) = B(\theta) \cdot (P(t, \Delta t) - P_0),$$

(2)
$P$ is the current pressure at registration level, $P_0 = 993$ mbar is the averaged over a long period pressure at the registration level, $B(\theta)$ are barometric coefficients;

$$\Delta M_\tau(\theta) = M_\tau(\theta) - \sum W_\tau(h, \theta) \Delta T(h) \Delta h / 100\%,$$

where $W_\tau(h, \theta)$ are differential in atmospheric depth temperature coefficients [3], $\Delta T(h) = T_{SMA}(h) - T(h)$ is the change of the temperature, $h$ is the atmospheric depth, $\Delta h = 0.05$ atm, $T(h)$ is the current temperature profile of the atmosphere, $T_{SMA}(h)$ is the temperature profile for standard model of the atmosphere [4]. Information about temperature profile of the atmosphere is obtained from meteorological balloon flights and numerical forecasting model of the atmosphere GDAS (The Global Data Assimilation System) [5].

In this work, four intervals of zenith angle are considered: $26^\circ\text{-}34^\circ$, $34^\circ\text{-}44^\circ$, $44^\circ\text{-}70^\circ$ and $25^\circ\text{-}70^\circ$. These intervals correspond to the following values of the mean energy of primary protons: 74, 82, 109 and 86 GeV. As an example, counting rates (without and with corrections for atmospheric effects) for zenith angle interval $25^\circ\text{-}70^\circ$ are shown in figure 1. After correction, annual variations disappear.

![Figure 1. Counting rate of muon hodoscope URAGAN ($\theta = 25^\circ\text{-}70^\circ$).](image1)

![Figure 2. Vertical projection of the vector of local anisotropy ($\theta = 25^\circ\text{-}70^\circ$).](image2)

### 3. Vector of local anisotropy

URAGAN allows to obtain the vectors of the particle arrival directions and we can use their vector sum. The summed vector normalized to the total number of muons (the vector of local anisotropy) will characterize the angular distribution of the detected particles. The projections of this vector ($A_S$, $A_E$ and $A_Z$) can be generally defined from the original matrix data $M$ as follows [6]:

$$A_S(t, \Delta t) = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi, t, \Delta t) \cos \varphi \sin \theta, \quad A_E(t, \Delta t) = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi, t, \Delta t) \sin \varphi \sin \theta,$$

$$A_Z(t, \Delta t) = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi, t, \Delta t) \cos \theta, \quad N = \sum_{\theta} \sum_{\varphi} M(\theta, \varphi, t, \Delta t).$$

Experimental temporal series of the vertical projection of the local anisotropy $A_Z$ for aforementioned intervals of zenith angles were obtained for 2007-2015. For $A_Z$ estimations, 1 h averaged muon matrices with corrections for barometric and temperature effects were used. As seen from figure 2, the annual variations in the vertical projection of the anisotropy vector $A_Z$ are observed, and they are not related with changes in atmospheric conditions. It was supposed that the annual variations are caused by changes in the shape of the energy spectrum of primary particles. This dependence can be estimated with a help of simulation of generation and propagation of secondary particles through the atmosphere.

### 4. Scheme of muon spectrum calculations with CORSIKA and experimental results

The direct simulation of propagation and interaction of protons of primary cosmic rays (CR) takes a long time. The method of relatively fast simulation of cosmic rays flux at the Earth's surface (with similar statistics) with a help of the CORSIKA package [7] in a wide range of zenith angles and
energies was developed earlier [8]. For simulation of the flux of CR components, version 6.980 of the CORSIKA code was used. A combination of models of hadronic interactions SIBYLL + FLUKA was chosen. The differential energy spectrum of muons at the Earth surface $\frac{dN_{\mu}}{dE_{\mu}}$ can be estimated by the following formulas:

$$\frac{dN_{\mu}}{dE_{\mu}} = \frac{1}{\ln(10) \cdot E_{\mu}} \cdot \frac{dN_{\mu}}{d(lg E_{\mu})} = \int \frac{dG_{\mu}(E_{\mu}, E)}{d(lg E_{\mu})} \cdot \frac{dN_{\mu}}{d(lg E)}.$$  

(5)

Here $dG_{\mu}(E_{\mu}, E)/d(lg E_{\mu})$ is the distribution in the logarithm of the energy of muons for a fixed energy $E$ of primary particle. The shape of the primary spectrum: $dN_{\mu}/dE \sim E^{\gamma}$. The integration over the energy of the primary protons is replaced by summation:

$$\frac{dN_{\mu}}{dE_{\mu}} \approx N_{\mu} \cdot \sum_{i} \left[ \frac{E_{i}}{E_{i} - \Delta E_{i}} \right]^{-1} \frac{\Delta G(E_{i}, E_{i})}{\Delta \lg(E_{i})} \cdot \Delta \lg(E_{i}).$$  

(6)

Here $N_{\mu i} = E_{i} \cdot \ln 10 \cdot dN_{\mu}(E_{i})/dE_{\mu} = 8.28 \cdot 10^{-2}$ (cm$^{-2}$·s·sr)$^{-1}$ is the normalization coefficient; $E_{i} = 10$ GeV is the reference energy for primary cosmic ray particles; $\Delta \lg(E_{i})$ is the step in the logarithm of the energy of primary protons; $\gamma$ is the index of the primary particles spectrum.

Counting rate for the cell of zenith angle $\theta$ for a current value of $\gamma$ can be estimated by the next formula:

$$M_{Z, \text{SM}}(\theta, \gamma) = I(\theta, \gamma) \Delta \Omega(\theta),$$  

(7)

where $\Delta \Omega(\theta)$ is differential in zenith angle acceptance of setup, $I(\theta, \gamma) = \int E_{\text{min}}^{\infty} \left( \frac{dN_{\mu}(0, E, \gamma)}{dE_{\mu}} \right) dE_{\mu}$ is the integral intensity for zenith angle $\theta$ and threshold energy $E_{\text{min}}$; $dN_{\mu}(0, E, \gamma)/dE_{\mu}$ is the calculated differential spectrum. The value of the vertical projection of the vector of local anisotropy $A_{Z, \text{SM}}^{\text{SM}}(\gamma)$ for different zenith angle intervals can be calculated using the following formula:

$$A_{Z, \text{SM}}^{\text{SM}}(\theta_{\text{min}} \leq \theta < \theta_{\text{max}}, \gamma) = \sum_{0 = 0, \theta_{\text{max}}}^{0 = \theta_{\text{max}}} M_{Z, \text{SM}}^{\text{SM}}(\theta, \gamma) \cos \theta / \sum_{0 = 0, \theta_{\text{max}}}^{0 = \theta_{\text{max}}} M_{Z, \text{SM}}^{\text{SM}}(\theta, \gamma).$$  

(8)

Comparison of experimental values of $A_{Z}$ averaged over 2007-2015 period and $A_{Z, \text{SM}}^{\text{SM}}$ calculated with help of CORSIKA for $\gamma = 2.7$ shows good agreement (figure 3, statistical errors are less than the points). The simulations showed that between $A_{Z}$ and $\gamma$ there is almost a linear dependence, which is well fitted by the formula $A_{Z, \text{SM}}^{\text{SM}}(\gamma) = a + b \gamma$. Values of coefficients $a$ and $b$ are presented in table 1. Consequently, from the relative changes of $A_{Z}$ we can estimate the changes of $\Delta \gamma$.

**Table 1. Coefficients of linear dependence $A_{Z, \text{SM}}^{\text{SM}}(\gamma) = a + b \gamma$.**

| Interval on zenith angle | $a$     | $b$     |
|-------------------------|---------|---------|
| 26°-34°                 | 0.864090| 5.7·10^{-4} |
|                         | ± 8·10^{-6} | ± 3·10^{-6} |
| 34°-44°                 | 0.774952| 0.001418 |
|                         | ± 8·10^{-6} | ± 3·10^{-6} |
| 44°-70°                 | 0.557446| 0.016378 |
|                         | ± 10·10^{-6} | ± 4·10^{-6} |
| 25°-70°                 | 0.678386| 0.026527 |
|                         | ± 20·10^{-6} | ± 7·10^{-6} |

**Figure 3. Comparison of experimental and calculated values of $A_{Z}$.**
Figure 4. Estimations of monthly averaged changes of $\Delta \gamma$ (lines connecting points are to guide eyes only) obtained from the data in different zenith angle intervals.

Figure 5. Estimations of year averaged diurnal changes of $\Delta \gamma$ from the data for zenith angles $34^\circ$-$44^\circ$ for several years.
According to the obtained $A_Z$ time series, the monthly averaged changes of $\Delta \gamma$ for 2007-2015 were estimated (figure 4). Annual changes in the slope are well observed. Estimations of year averaged diurnal changes of $\Delta \gamma$ (figure 5) shows a maximum at 10-12 h UT, and a minimum at 00-02 h UT. Year averaged amplitudes of diurnal changes of $\Delta \gamma$ are presented in figure 6.

5. Conclusion
Annual and diurnal changes in the slope of the energy distribution of primary protons are observed. In the range of the mean energy of primary protons 70-110 GeV, the annual changes of $\gamma$ are 0.02-0.04, and the diurnal changes are 0.0025-0.004.

In year averaged diurnal changes of $\gamma$, the maximum is observed at 10-12 h UT, and the minimum at 00-02 h UT.

In the interval $\theta = 34^\circ-44^\circ$, minimum of diurnal changes was observed in 2011. In the intervals $\theta = 26^\circ-34^\circ$, 44º-70º and 25º-70º, minimum of $\Delta \gamma$ was during the year of the solar activity minimum, and value of $\Delta \gamma$ was 0.0025. Then changes increased to 0.004 with increasing of solar activity until 2012, and slightly decreased until 2014.

This work was performed at the Unique Scientific Facility “Experimental complex NEVOD” with the support of the Ministry of Education and Science of the Russian Federation (contract RFMEFI59114X0002) and MEPhI Academic Excellence Project.

References
[1] Barbashina N S et al. 2008 Instrum. Exp. Tech. 51 180
[2] Yashin I I et al. 2013 J. Phys.: Conf. Ser. 409 012192
[3] Dmitrieva A N et al. 2011 Astroparticle Physics 34 401
[4] Glagolev Yu A 1970 (in Russian) Reference Book on Physical Parameters of the Atmosphere, (Leningrad: Gidrometeoizdat) (Original Russian title: Spravochnik po fizicheskim parametram atmosfery)
[5] http://ready.arl.noaa.gov/gdas1.php 2004 NOAA Air Resources Laboratory (ARL)
[6] Shutenko V V et al. 2013 Geomagnetism and Aeronomy 53 571
[7] Heck D and Pierog T 2012 http://www-ik.fzk.de/corsika/ Extensive Air Shower Simulation with CORSIKA. A User’s Guide (Germany: Karlsruhe Institute of Technology)

[8] Kovylyaeva A A et al. 2013 J. Phys.: Conf. Ser. 409 012128