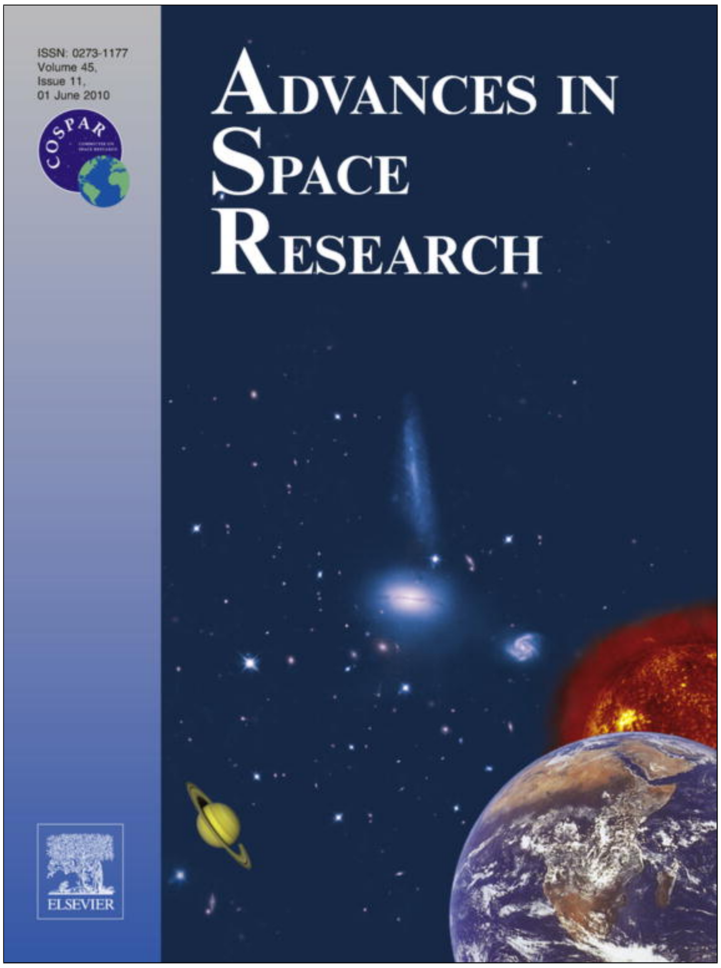
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Investigation of diurnal variations of cosmic ray fluxes measured with using ASEC and NMDB monitors

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Abstract

A study of daily variations of secondary Cosmic Rays (CR) is performed using data on charged and neutral CR fluxes. Particle detectors of Aragats Space-Environmental Center (ASEC), Space Environmental Viewing and Analysis Network (SEVAN) and neutron monitors of the Neutron Monitor Database (NMDB) are used. ASEC detectors continuously register various species of secondary CR with different threshold energies and incident angles. NMDB joins data of 12 Eurasian neutron monitors. Data at the beginning of the 24th solar activity cycle are used to avoid biases due to solar transient events and to establish a benchmark for the monitoring of solar activity in the new started solar cycle.

After eliminating changes associated with atmospheric pressure variations, solar diurnal variations are clearly seen in muon and neutron fluxes. Neutrons daily variations magnitudes, corresponding to the lowest energy primary protons, are comparable with the magnitudes of variations of charged secondary CR. Diurnal variations of neutron flux are higher for the high latitudes comparing with middle latitudes. For low energy muons, the variations are bigger comparing higher energy muons.

Keywords: Variations of cosmic rays; Secondary cosmic rays; Particle detector networks

1. Introduction

After discovery of Cosmic Rays (CR) and after starting particle flux monitoring at different locations worldwide, various types of periodic variations of CR intensity were found. Some of them were connected with galactic rotation (Compton and Getting, 1935), other ones with co-rotation of the CR with Interplanetary Magnetic Field (IMF), attached to the Sun (Parker, 1964). The first effect becomes apparent as periodicity in sidereal time, the second – as periodicity in local (solar) time, i.e., as diurnal variations. This paper presents the calculations of daily variations of secondary particle fluxes measured with particle detectors of Aragats Space-Environmental Center (ASEC). Monitors of particle detector networks Space Environmental Viewing and Analysis Network (SEVAN) (Chilingarian et al., 2009) and Neutron Monitor Database (NMDB) are also used. NMDB is a European project to develop a database of minute count rates of several Eurasian neutron monitors (NM).

The diurnal variations are the result of complex phenomena involving IMF, magnetosphere and, in addition, dependent on the latitude, longitude and altitude of detector location on the Earth. The diurnal CR variations comprise an important tool for understanding basic physics of the heliosphere and the Earth's magnetosphere.

Low-energy galactic CR (GCR, with energies below few tens of GeV) are moving mostly along lines of IMF and their intensity should have a peak at the time of the best connections of solar magnetic field (brought to 1 AU by solar wind) with magnetosphere (flux transfer events, see, for example Daly et al., 1984).

Diurnal variations can be characterized by the amplitude (maximal value) and phase (time of the maximal amplitude). Different species of the secondary CR undergo different diurnal variations. It is obvious that more the

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most probable primary energy of the monitored CR species (neutron, electron, muon, etc.) – less should be the amplitude of diurnal variation. Therefore, the third parameter, characterizing the diurnal variations at definite location and time, is so called upper limiting rigidity, i.e., the threshold rigidity not influenced by the solar, interplanetary and geomagnetic disturbances.

CR flux can be decomposed into radial and tangential components. Solar wind convective outflow in the radial direction compensates galactic CR flux. CR flux in the tangential direction generates variations with a maximum expected to happen at 18:00 local time (Krymsky, 1964; Mourzin, 1970; Forman and Gleeson, 1975; Bieber et al., 1983). However, as the Earth's magnetic field bends the flux in the tangential direction we expect that the maximum of intensity occurs few hours earlier (Dorman, 1970). Amplitude of daily variations detected by a ground-based detector reported to be less than 0.5% (Thompson, 1938) at latitudes ranging from 54.7N to 40S degrees.

The atmospheric effects also influence the daily variations of the count rate of particle detectors. However, the effects of temperature, humidity, electric field, and gravity are negligible in comparison to the effect of pressure; and the correction for the pressure is necessary (Pomerantz and Duggal, 1971; Lopez and Valdes-Galicia, 2000). Long term daily variations of the atmospheric pressure also are periodic and can introduce bias in the obtained results if not treated properly. Hadronic component of CR believed not to be influenced strongly by the temperature gradient in the atmosphere. On the other hand, variations of temperature gradient cause changes in count rates of secondary muons. According to Dorman (1975) atmospheric temperature effects of muons are in order of 0.1–0.2%.

There are various papers concerning dependence of the daily variations amplitude on geomagnetic activity. Agrawal et al. (1995) have shown that during the periods with low Ap geomagnetic index, amplitudes of diurnal variation are significantly smaller in comparison to the periods before and after. Kumar et al. (1993) found that distributions of amplitudes and phases for geomagnetically quiet days are very narrow in comparison to other days. Thus, they concluded that quiet days are better suited for the CR daily variation studies. Both groups have used data of middle latitude Deep River neutron monitor, located at latitude of 46°06′ North and longitude 77°30′ West.

Several papers investigate the dependence of daily changes on the phase of the solar activity cycle. It was found that the upper limiting rigidity varies with solar cycle. Begum (1974) has studied the variation of the upper limiting rigidity from 1965 to 1971. Neutron data of five mid-latitude stations and muon data of two stations have been used. They show that the limiting rigidity varies from minimum value of about 35 GV in 1965 to a maximum of about 125 GV in 1970. At the solar minimum in 1965, the annual mean diurnal variations were very small. Agarwal and Mishra (2008) showed that diurnal amplitude significantly decreases and phase shifts to the earlier hours during solar activity minimum years for high and middle latitude NMs.

Another group of papers presented dependence of daily changes on solar transient events.

El-Borie et al. (1996) observed large solar diurnal amplitudes associated with high values of solar wind speed, plasma temperature, and value of the IMF Bz component.

Duldig and Humble (1990) have analyzed enhanced cosmic ray diurnal variations of Mawson and Hobart neutron monitor and underground muon data. At the near solar activity minimum year 1987 the mean amplitude of the diurnal variation for underground muon detectors with median energy of response of about 170 GV was 0.03% and 0.05% for Mawson and Hobart detectors, respectively. For neutron data, the amplitude was 0.2% for Mt. Wellington and 0.21% for Mawson neutron monitor. They also claim that it is necessary to derive free space amplitudes outside the geomagnetic field. Then it will be possible to connect obtained parameters with IMF, solar wind and plasma data.

Using the data of neutron monitor network from 1965 to 2003, Belov et al. (2006) have derived diurnal variations for disturbed and quiet days by the Global Survey Method. They found that anisotropy in disturbed days has bigger amplitude and differs by the phase from the anisotropy in quiet days, but these differences are much less than those in solar wind parameters or in geomagnetic activity indices. Their main conclusion is that properties and long term behavior of CR anisotropy are mainly determined by the long term periodical changes on the Sun and in the heliosphere and not by particular disturbances in the solar wind.

Munakata et al. (1995), based on the data of surface and underground muon monitors, claim that during periods when the magnetic polarity of the Sun is positive the maximums of daily variations significantly shifted toward earlier hours. In recent paper by Kudela et al. (2008), daily variations were studied with using Climax, Oulu and Lominsky Ŝtit NMs. For these three monitors, no clear difference in the dependence of daily variations on the daily average IMF value, solar wind velocity and geomagnetic indices was observed. Badruddin (2006) found that enhanced diurnal anisotropy is a precursor to smaller (<5%) amplitude Forbush decrease.

Thus, we see that the detailed investigation of the diurnal variations can comprise a basis of scientific data to be used in a wide context of solar-terrestrial connections.

The goal of the presented paper is to calculate the phase, amplitude for the ASEC monitors at the minimum of the solar activity year. This data will be used for physical analysis of ASEC particle detectors data as 24th solar activity cycle proceed. Comparison with some NMDB neutron monitors and hybrid detectors of SEVAN network is made.

The paper is organized as follows: in Section 2 brief description of the ASEC monitors is given; in Section 3 used data and methods of analyzing the diurnal variation are described; in Section 4 daily variations detected by ASEC, NMDB and SEVAN monitors are presented and discussed.

2. ASEC particle detectors

Particle detectors of the ASEC (Chilingarian et al., 2003, 2005) are located at slopes of the mountain Aragats and in Yerevan, Armenia; geographic coordinates are 40°30′N, 44°10′E, altitudes – 3200 m, 2000 m and 1000 m. Various ASEC detectors, measuring fluxes of various secondary cosmic rays, are sensitive to different energetic populations of primary cosmic rays. Two neutron monitors (18NM-64), operating at Nor Amberd and at Aragats research stations, detect secondary neutrons. The Nor Amberd muon multidirectional monitor (NAMMM) detects low energy charged particles and muons. The threshold energy of the detected muons is estimated to be 250 MeV. The Aragats Multidirectional Muon Monitor (AMMM) registers high energy muon flux (threshold energy – 5 GeV). The Aragats Solar Neutron Telescope (ASNT) measures neutrons and charged particles. ASNT is a part of a world-wide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University. Another monitoring system, based on the scintillation detectors of the Extensive Air Shower (EAS) surface arrays, MAKET-ANI and GAMMA (3200 m a.s.l.), detect low energy charged particles. New worldwide particle detector network, named SEVAN, is under construction now in Armenia, Bulgaria, Croatia and India (Chilingarian and Reymers, 2008; Chilingarian et al., 2009). Three SEVAN detectors are already operating in Armenia at altitudes 3200, 2000 and 1000 meter and two other monitors are working in Bulgaria and Croatia. SEVAN detectors also are measuring low energy charged particles, neutral particles (gammas and neutrons) and high energy muons. NAMMM and ASNT measuring channels are equipped with Analog-to-Digital (ADC) convertors and microcontroller based advanced electronics. Data Acquisition (DAQ) electronics and flexible software triggers allow to register not only the count rates of the detector channels, but also to get histograms of energy releases, correlations of the charged and neutral fluxes and many other physical phenomena. Details of detector operation can be found in Chilingarian et al. (2007) and Arakelyan et al. (2009). A new type particle detector, which registers horizontal muons, was recently installed in Yerevan (Chilingarian and Hovsepyan, 2009).

3. Data and methodology

For daily variation studies, we use 1-month time series taken from May 2008 until January 2009. Data of the SEVAN Aragats (located at 3200 m) are available from October 2008. We took January and February 2009 data of SEVAN Yerevan. Data of SEVAN Bulgaria and SEVAN Croatia are from December 2008. December 2006 data on muons >5 GeV of AMMM are taken. Raw data were corrected by median filtering algorithm (Chilingarian and Hovhanissyan, 2009) to eliminate spikes and abrupt changes of mean, i.e., changes caused by errors of the data acquisition electronics.

In case of neutron data, we have performed the following operations. Filtered and pressure corrected (Chilingarian and Karapetyan, 2009) daily data were fitted by the harmonic approximation function for each day of the selected period. In this way, distributions of amplitudes and phases of daily variation were got. The following approximation was used (Kudela et al., 2008):

$$f(t_i) = A + B \cdot \cos(\omega t_i + \psi) \tag{1}$$

Here A is the daily average value of cosmic ray intensity, B is the amplitude of daily variations, ω is the angular frequency and ψ is the phase of daily variations. Phase is directly connected to local (solar) time. The quality of fit d, the difference between experimental data and the fit is calculated according to Kudela et al. (2008):

$$d^2 = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} [Y_i - f(t_i)]^2 \tag{2}$$

Amplitudes and phases obtained from Eq. (1), and fit quality calculated with using Eq. (2) for ASEC and some other NMs are presented in Table 1 in Section 4.

In case of SEVAN monitors, we decided to present the fitting of the monthly averaged curves of daily variations, which were found to be more illustrative. Daily data were summed and presented in percents. Thereafter averaged daily curves were fitted by cosine function of Eq. (1), the amplitude and phase of a curve were estimated and quality of the fit by Eq. (2) also was calculated.

Table 1
Daily variations of NMDB neutron data.

May 1–31, 2008	Median amplitude (%)	Median phase (local time)	Median quality of the fit	Most probable primary energies (GeV)
NANM	0.24	14:34	0.67	7.1
ARNM	0.24	14:07	0.62	7.1
Alma-Ata NM	0.24	14:38	0.61	6.7
Lominsky Štit NM	0.34	14:37	0.79	4
Moscow NM	0.38	14:49	0.91	2.46
Kiel NM	0.33	15:01	1.14	2.29
Apatity NM	0.37	15:47	0.83	0.65

4. Daily variations detected by ASEC and NMDB monitors

4.1. Daily variations of neutron data

Recently, a new electronics was installed on all ASEC particle detectors (Arakelyan et al., 2009) and barometric coefficients were recalculated (Chilingarian and Karapetyan, 2009). After appropriate filtering (Chilingarian and Hovhanissyan, 2009) the 1-min daily data were summed for all 18 channels of the ASEC and NMDB NMs. Then 1-min time series were summed into hourly time series. Daily, 1-h time series of May 2008 were pressure corrected and fitted by Eq. (1). Days with abnormal values (for example, negative amplitudes) were eliminated. Totally, three days were excluded from Moscow data and two days of Nor Amberd Neutron Monitor (NANM) data.

In Fig. 1, we present daily data typical for NANM. Data are pressure corrected and presented in percents. Mean values of count rates are calculated for each day. As it is seen from Fig. 1 the amplitude of variation is about 0.24% and phase is 3.307 radians, which corresponds to 11:22 in UT or 15:22 in local time.

Several Eurasian neutron monitor groups join efforts to create an on-line database of their data. The NMDB project (funded by European FP7 programme) contains time series of 12 NMs located on high, middle and low latitudes. We compare daily changes of several monitors to investigate the latitude effects. In Fig. 2, Moscow, Alma-Ata and Nor Amberd neutron monitors' daily data of 11 May 2008 are compared. Variations of Moscow monitor are much bigger than two others'. Phases are almost the same if to take into account that Alma-Ata local time (LT) is UT+7, Nor Amberd LT is UT+4 and Moscow LT is UT+3.

After fitting the data of Moscow, Alma-Ata and Nor Amberd NMs, taken from 11 May 2008, the values of amplitudes – 0.47%, 0.20% and 0.24% were obtained, respectively. Phases in local time for these monitors are 14:53, 15:25 and 15:21 accordingly.

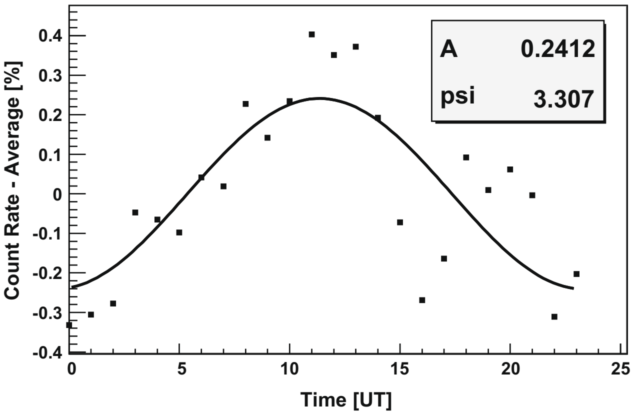

Fig. 1. Daily variations of the NANM pressure corrected hourly data fitted by cosine function.

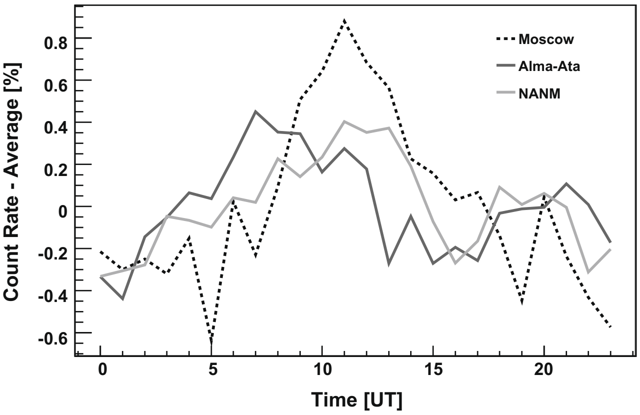

Fig. 2. Comparison of the Moscow, Alma-Ata and Nor Amberd neutron monitors daily data.

In Fig. 3, we present the distributions of amplitudes and phases of diurnal variation of Moscow and Nor Amberd NMs, obtained by fitting with cosine function. Data of May 2008 are taken. The diurnal amplitude is significantly larger in Moscow neutron monitor (median value is 0.38%). Moscow neutron monitor is more sensitive to low energy particles due to lower cutoff rigidity of the site.

In Table 1, we present the parameters of the pressure corrected diurnal variations for seven NMs of NMDB (data were taken from http://www.nmdb.eu.website). Standard deviations for all amplitudes were calculated to be about 0.1%. Most probable energies of primary particles were obtained from computer simulation using CORSIKA code (Zazyan and Chilingarian, 2009). It was expected that a primary particle (mostly proton) trajectory bend is weaker at higher latitudes. Consequently, phases of diurnal

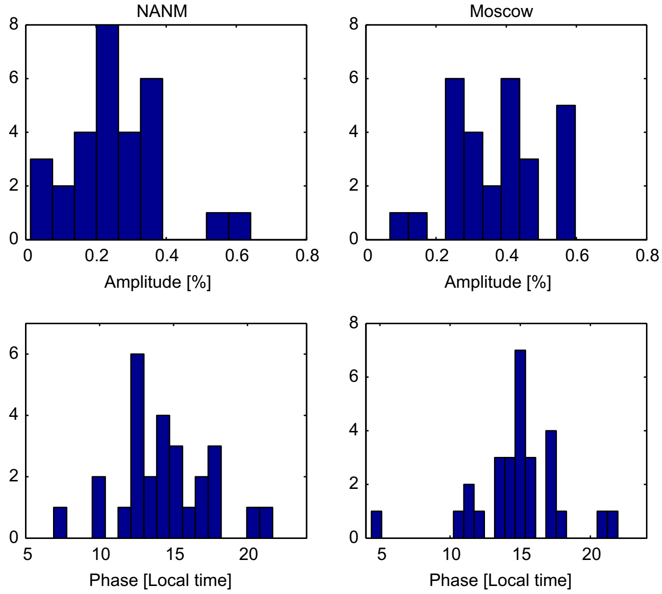

Fig. 3. Comparison of the Moscow and Nor Amberd neutron monitors data: distribution of amplitudes and phases of daily variations of May 2008 data.

variation were expected to be larger, i.e., local time of maximum is later for lower cutoff rigidity stations. At the same time, amplitudes of variations should be bigger at high latitude stations, because of high sensitiveness to lower energy primary CR.

Actually, there is a tendency that high latitude monitors show bigger amplitudes. However, the amplitude of the Apatity monitor, being greater than calculated for Aragats monitors, is comparable with Moscow monitor. Moreover, the amplitude of Kiel monitor is comparable with the amplitude calculated for Lominsky Ŝtit, whereas the latter one is located at much lower latitude. These discrepancies can give a hint to find some instrumental effects to check the quality of data.

The quality of the interpolation calculated with using Eq. (2) is rather low for all monitors, i.e., diurnal variations are close to the sinusoidal and discrepancy between fitting curve and experimental data is small.

4.2. Daily variations of muon data

We also have investigated daily variations of charged secondary particle fluxes corresponding to the primary GCR with different energies. Most probable energies of primary particles generating secondary charged particles reaching the Earth's surface are higher than energies of primaries corresponding to neutrons. For instance, most probable primary proton energies corresponding to muons with energies >5 GeV is 42 GeV. Consequently, charged secondary CR are not influenced by atmospheric pressure changes as much as neutrons. However, for muons, besides pressure corrections, the temperature corrections are essential; see, for example, Dorman (1975). Unfortunately, due to the absence of appropriate temperature data we do not apply corrections for changing gradient of temperature in the atmosphere above the detector.

In Fig. 4, one can see the daily changes of Aragats Multichannel Muon Monitor data. AMMM measures muons with energies higher than 5 GeV. The pattern of daily variations of 5 GeV muons is more complicated than for neutrons. A similar structure was also observed with using Tibet air shower array (Munakata et al., 1999). Existence of two minima and maxima between them needs additional analysis for relevant interpretation. Apparently, AMMM data cannot be fitted by Eq. (1), more complicated function is required, for taking into account both solar and sidereal (Compton and Getting, 1935) periodicities. To describe daily variations of muons with energies >5 GeV, data were fitted by two cosines with 24- and 12-h periods.

SEVAN monitor consists of three layers of plastic scintillating detectors and 5 cm thick lead filters up and below the middle detector (see Fig. 5). Upper and lower scintillators have a thickness of 5 cm, middle scintillator is 25 cm thick and sensitive to neutrons. Lead filters absorb low energy muons and lower detector is sensitive to muons with energies >250 MeV. SEVAN hybrid particle detectors allow us to register fluxes of neutral particles, fluxes of high (>250 MeV) and low (>7 MeV) energy charged particles. Various coincidences of the three layered detectors give a possibility to distinguish above mentioned components (Chilingarian and Reymers, 2008).

SEVAN monitors are already installed at Aragats (3200 m), Nor Amberd (2000 m), Yerevan (1000 m), Mt. Moussala (Bulgaria) and Zagreb (Croatia). Fig. 6 shows daily variations of upper, lower and middle detectors of SEVAN monitors located at Nor Amberd, Aragats, Moussala and Zagreb. On the pictures geographical coordinates and altitudes of the monitors are also presented.

In Fig. 6, we can see that detectors located at close geographic co-ordinates demonstrate similar patterns of the daily variations. When comparing Aragats and Balkanian monitors we can deduce that both latitude and longitude of site location influence the diurnal variations' pattern.

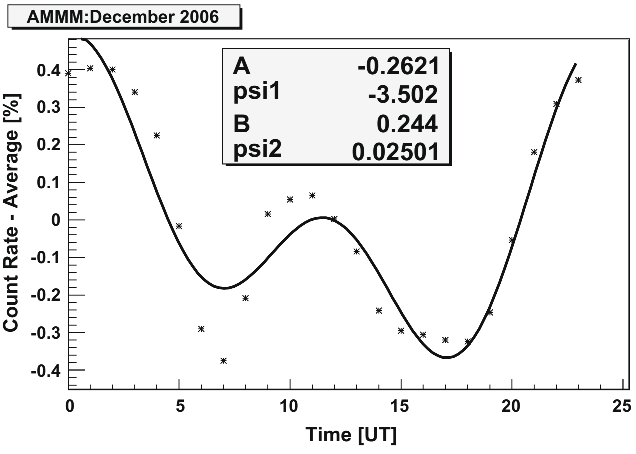

Fig. 4. Daily variations of the AMMM data fitted by sum of harmonic functions – $f(t_i) = A \cdot \cos(2\pi t_i/24 + \psi 1) + B \cdot \cos(2\pi t_i/12 + \psi 2)$.

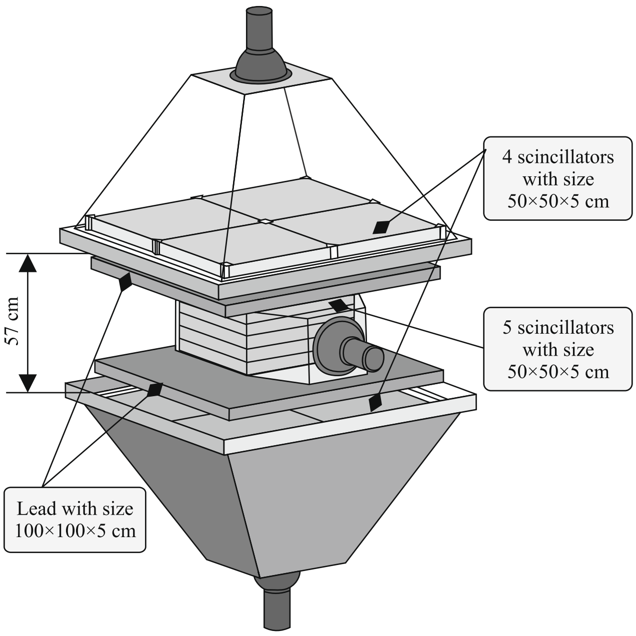

Fig. 5. The basic detecting unit of the SEVAN network.

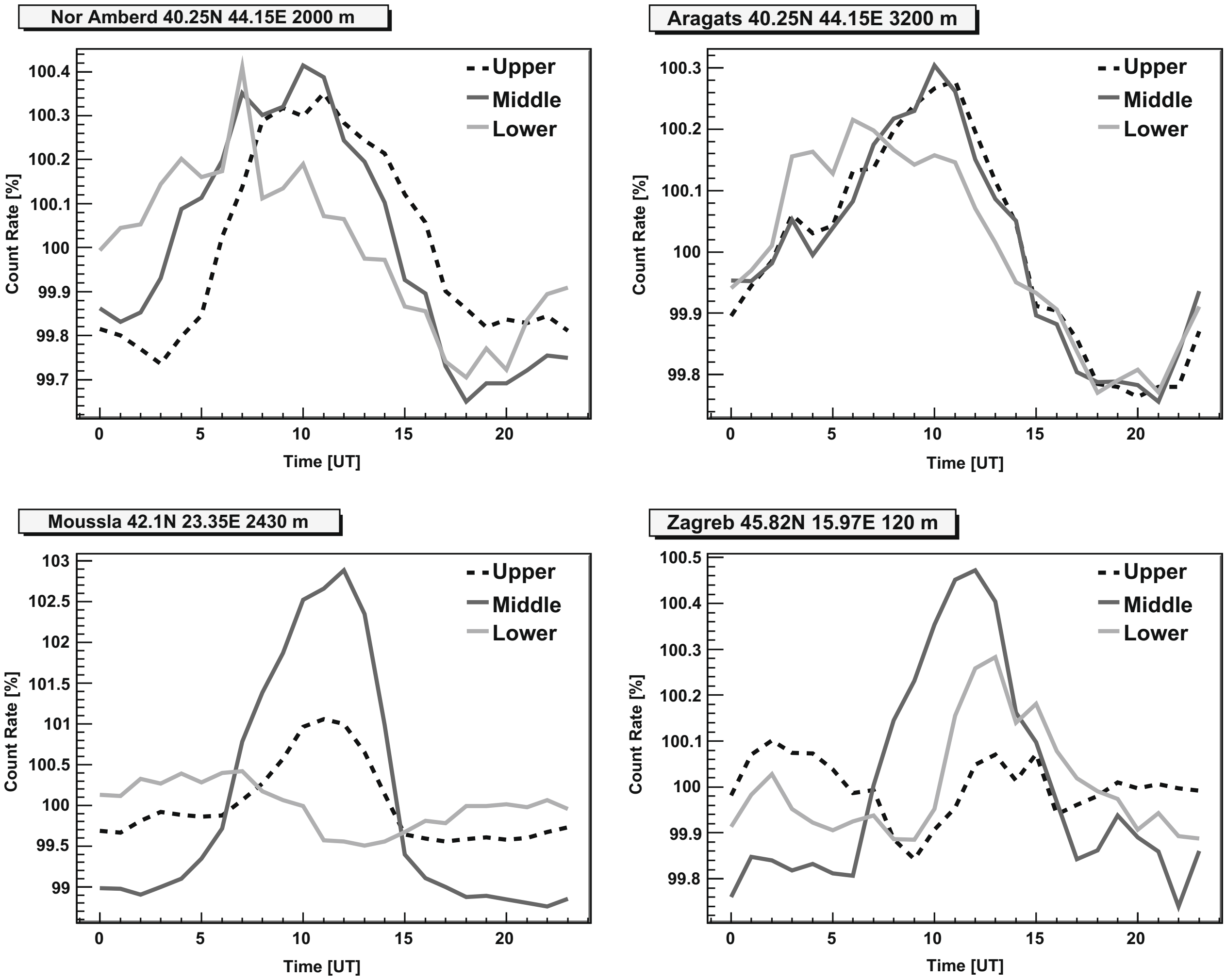

Fig. 6. Daily variations of high, low energy charged fluxes and neutral fluxes according to the SEVAN detectors located in Nor Amberd, Aragats, Moussala and Zagreb. Month-averaged daily count rates of Nor Amberd May 2008 data, Aragats – October 2008, Moussala and Zagreb December 2008–January 2009.

However, very large amplitude of Moussala monitor's middle scintillator point on possible defects in light proofing of the middle detector. It is worth mentioning that Balkanian SEVAN monitors are working in a test mode yet.

In Table 2, we present the parameters of the best fit curves by Eq. (1) for monitors presented in Fig. 6. We do not fit curves with two peaks and without apparent peak. For Nor Amberd's SEVAN, as it was expected daily changes of lower energy fluxes are bigger than for higher energy fluxes. The magnitude of variations for upper, middle and lower detectors are about 0.3%, 0.35% and 0.2%, respectively. In local times the maximums are at 15:00 for

Table 2
Daily variations of the SEVAN monitors data; Nor Amberd data of May 2008, Aragats data of October 2008, Moussala and Zagreb data of December 2008–January 2009 are taken.

	Median amplitude (%)	Median phase (local time)	Quality of the fit	Most probable primary energies (GV)
SEVAN NA upper detector	0.28	15:13	1.33	14.6
SEVAN NA middle detector	0.34	12:55	1.15	7.1
SEVAN NA lower detector	0.24	10:36	0.18	18.4
SEVAN Aragats upper detector	0.23	12:42	0.71	14.6
SEVAN Aragats middle detector	0.21	12:27	0.62	7.1
SEVAN Aragats lower detector	0.20	11:17	0.33	18.4
SEVAN Mousalla upper detector	0.55	11:58	2.31	
SEVAN Mousalla middle detector	1.80	12:33	8.16	
SEVAN Mousalla lower detector	No peaks			
SEVAN Zagreb upper detector	Two peaks			
SEVAN Zagreb middle detector	0.28	12:39	1.35	
SEVAN Zagreb lower detector	0.12	14:43	0.51	

upper and middle detectors, and few hours earlier for lower detector. Similar to SEVAN Nor Amberd, Aragats' upper and middle detectors also show maximum with magnitude about 0.3% at 15:00 LT, and lower detectors show variations approximately 0.2% at 11:00 LT. For these two monitors, secondary particles corresponding to higher energy primaries show smaller variations. Data of SEVAN Yerevan were unsuitable for daily variation studies.

5. Conclusion

ASEC NMs can register diurnal variations in large range of primary rigidities. It opens possibilities to follow the changes of parameters of daily wave (amplitude, phase, maximal limiting rigidity) during starting 24th solar activity cycle.

Magnitude of daily variations of neutrons corresponding to the lowest energy primary protons is comparable to the magnitude of variations of charged secondary CR.

Diurnal variations of neutron flux are bigger for the high latitudes comparing with middle ones. For low energy muons the variations are bigger in comparison to higher energy muons. Phases for high latitude NMs are comparable with those for middle latitude monitors. Amplitude of variation is 0.24% and phase is about 14:00 and 14:30 local time, for Aragats and Nor Amberd neutron monitors, respectively.

Amplitudes of muon data are comparable with those calculated for neutron data, except AMMM data (energy of primary protons higher than 42 GeV), which have a more complicated shape of variations and lower amplitude. The first data available from SEVAN network demonstrate that charged component variations are comparable with neutron variation and that diurnal variations are sensitive to longitude of site location.

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