On diurnal variation of cosmic rays: statistical study of neutron monitor data including Lomnický Štít.

K. Kudela , K.A. Firoz , R. Langer, V. Kollár

Abstract. **Results of statistical study of diurnal wave amplitude and phase on day-to-day basis using Lomnický Štít neutron monitor (NM) data, in addition to the longer time series of Oulu and Climax NM data, are reported. The data set constructed is useful for checking the time profiles of the diurnal wave characteristics and their relations to solar, interplanetary and geomagnetic parameters. On the extended data set we indicate that the narrower phase distribution with non-significantly changed position of maxima is obtained at all three stations when the amplitude to dispersion ratio is increasing; the different long term behavior of the amplitude and phase; and the significance of B_{tot} of interplanetary magnetic field for the amplitude of the diurnal wave.**

1. INTRODUCTION

There are many studies of diurnal variation of cosmic rays (CR) observed by neutron monitors and by muon telescopes. Only few of the studies are mentioned here. Parker [23] published the theory of streaming of cosmic rays and its relation to diurnal variation. Ahluwalia and Singh [1] described the diurnal, semi-diurnal and tri-diurnal variation of cosmic rays as observed by neutron monitors with different cutoff rigidities. Ahluwalia and Riker [2] reviewed the long-term changes of solar diurnal variation over period 1965-1976 and obtained the rigidity dependence of parallel diffusion coefficient. Swinson et al. [28] explored the diurnal anisotropies with Interplanetary magnetic field (IMF) over 21 years. Results of other studies relevant to diurnal variability of cosmic rays are e.g. in papers [3-5, 7, 9, 12-15, 17, 18, 24, 26, 30 among others]. Assuming that at 1 AU the solar wind average speed is 400 km/s and the Earth orbital motion is about 30 km/s, cosmic rays will overtake the Earth from local time direction of ~ 18 h [8]. Analysis by El-Borie and Al-Thoyaib [10] have shown the difference in diurnal variations measured in toward and away polarity days of IMF. In the study by Kumar et al. [16] the time/spatial variations in the amplitude and phase of the diurnal anisotropy become more pronounced for 60 geomagnetically quiet days. Paper [19] indicated the shift of the diurnal and semi-diurnal anisotropy vectors on geomagnetically quiet days to earlier hours when the solar poloidal magnetic field (SPMF) was positive during the periods 1971-79 and 1992-95 as compared to that during the periods 1964-70 and 1981-90 when the the field was negative, showing a periodic nature of daily variation in CR intensity with poloidal magnetic field of the Sun. Tiwari et al. [29] indicated the anomalies in diurnal anisotropy during descending phase of solar cycle 22, namely that in 1992, in comparison with earlier years, the diurnal phase shifted to later hours, but anomalously recovered in 1993 and 1994, and then again shifted to earlier hours continuously since 1994 to 1997. Moraal et al. [22] have shown that during the solar minimum period of 1954 the cosmic-ray diurnal variation as observed by neutron monitors and muon telescopes underwent a dramatic swing in its direction of maximum intensity, from the normal value between 16 and 18 h local time to as early as 08 h. This can be explained as being due to a negative radial density gradient of cosmic rays in the inner heliosphere. Singh and Badruddin [27] found that the amplitude of the diurnal anisotropy varies with a period of one solar cycle (similar to 11 years), while the phase varies with a period of two solar cycles (similar to 22 years). The authors also indicated the difference in time of maximum of diurnal anisotropy (shift to earlier hours) is observed during A < 0 (1970s, 1990s) polarity states as compared to anisotropy observed during A > 0 (1960s, 1980s). A>0 is assigned for the time intervals when IMF is directed away from the Sun above the current sheet (in north), while A<0 for the intervals with IMF directed to the Sun above the current sheet. Enhanced and low amplitude wave trains of diurnal variation were examined e.g. in papers [20,21]. Recently, Sabbah and Duldig [25] pointed out that the amplitude of the diurnal variation observed by underground muon telescopes is lower for even cycles (20 and 22) than for the odd cycle. Badruddin [6] reported that enhanced diurnal anisotropy and intensity deficit of CR have been identified as precursors to Forbush decreases (Fds) in CR.

Here we use data from the middle latitude high mountain neutron monitor at Lomnický Štít over the period of 1982 – 2006 for checking the characteristics of amplitude and phase of the diurnal variation on day-to-day basis. For comparison the hourly data from Oulu and Climax neutron monitors are used too. After description of the data and method used we review the long term behaviour of amplitude and dispersion of the fit, the distribution of the amplitude and phases for the complete data set and its selections. Selections with better quality of the fits provide narrower phase distributions and

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better correlation with total interpalnetary magnetic field which is the parameter for which we see the clear dependence. Although assuming the large data set, the correleation of amplitude with solar wind speed and geomagnetic activity indices is different from zero, their values are relatively low. There is no clear dependence between diurnal wave characteristics and north-south component of IMF (B_z). The dependences look similarly at all three monitors for the periods when all data are available. The data set constructed with extension to longer time interval and additions of more neutron monitor and muon telescope data can be used in detailed studies of diurnal variation and its relation to solar, interplanetary, and geomagnetic activity parameters.

2. DATA AND METHOD

The hourly pressure corrected data from neutron monitor Lomnický Štít for interval 1982-2006 are used. When maximum 5 hours data is missing, linear interpolation is used. Figure 1 displays a plot of the data and its power spectrum density in narrow interval about diurnal variation.

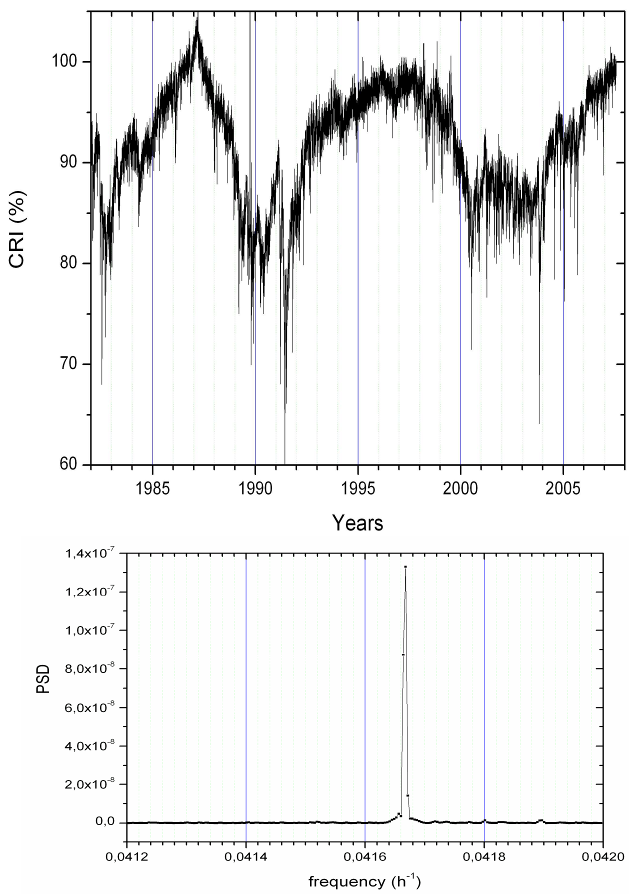

Fig.1. Hourly cosmic ray intensity measured by neutron monitor Lomnický Štít. The power spectrum density (in units $\%^2$/Hz) has the clear diurnal wave. The value 1,745.200 counts per hour corresponding to September 1986 average is taken as 100%.

On day-to-day basis the fit of hourly data was obtained to characterize the diurnal variation. Intensity of cosmic ray at hour t_i is considered by the equation as

$$f(t_i) = A + B.cos(\omega t_i + \psi) \qquad (1)$$

Here A is assumed as daily average intensity of cosmic rays, B is the amplitude and ψ is the phase of diurnal variation. $\omega = \frac{2\pi}{T}$ is the angular velocity where T = 24 hours, $i=1, ..., 24$. Using the diurnal variability only plus stationarity of the process from the least square method, we found out the values of A, B, ψ which are obtained by subŠtítuting the hourly data Y_i. The ideal form of the diurnal wave is determined by (1). The quality of the fit, i.e. the measure of deviation from the ideal one, is characterized by the dispersion d

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

where n=24.

The values A, B, ψ and d were obtained for each day starting from January 1, 1982 until July 24, 2007. Value ψ was recalculated to the local time of Lomnický Štít position. The data base was added by interplanetary magnetic filed and its components, solar wind velocity, density and temperature, sunspot number and geomagnetic activity indices on daily basis from NASA web site (http://omniweb.gsfc.nasa.gov/) for the period until year 2006, day 334.

For comparison the hourly data from two other neutron monitors, namely Oulu (1964, day 92 – 2006, day 334) and Climax (1963, day 331 – 2006, day 334) were examined in similar way and added to the data base constructed. These data were downloaded from sites (http://cosmicrays.oulu.fi/) and (http://ulysses.sr.unh.edu/NeutronMonitor/Misc/neutron2.html) respectively. Normalization to 100% for Oulu (OU) and Climax (CL) is done in the same way as it is for Lomnický Štít (LS). More details on the method are in [11].

3. AMPLITUDE, PHASE AND DISPERSION

Since the daily fits include various interplanetary situations as well as Fds, ground level events (GLEs) and responses to particles accelerated in interplanetary space, the distributions of the amplitudes and dispersions were examined to skip the irregular strong events from the following analysis.

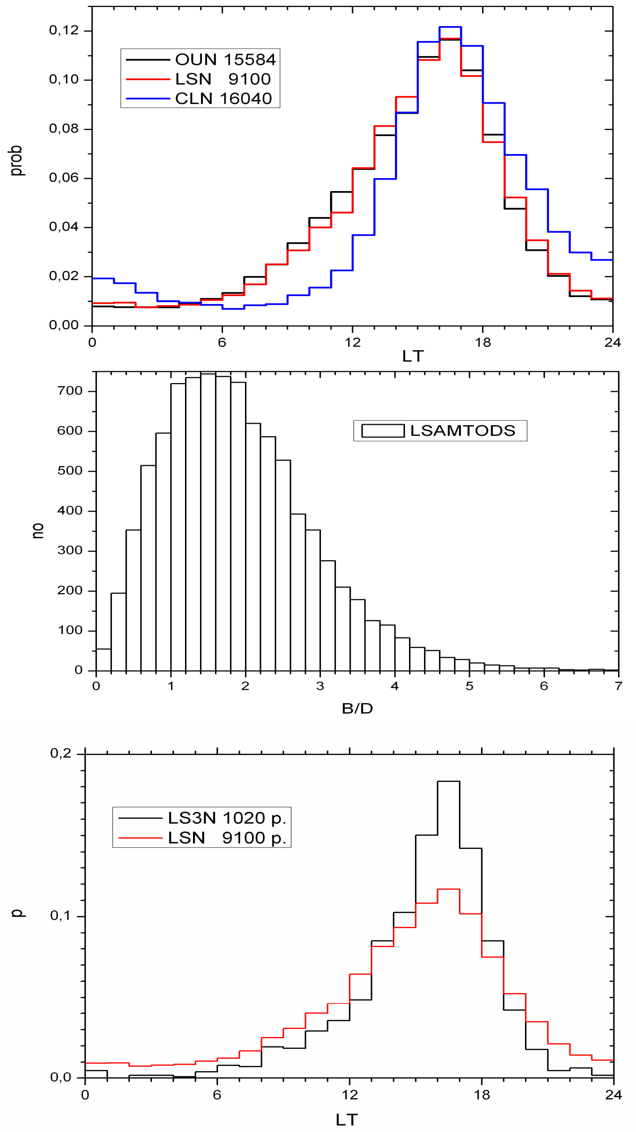

Fig. 2. Normalized distribution of probabilities of phases of diurnal variation at three NMs (upper panel). Number of days included is indicated. The middle panel shows the distribution of the ratio B/d for Lomnický Štít Neutron Monitor (LSN). The bottom panel displays comparison of normalized distributions of phases for all days (LSN) and for days when B/d > 3 (LS3N). B and d are defined by Eq. 1 and 2.

Similar changes (narrowing of phase distribution with increase of B/d) was found in all three data sets. However, the position of maximum phase is not changing. Thus, for reviews the whole data set is used just with excluding strong FDs and all GLEs observed at Oulu neutron monitor to deduce the temporal variations of diurnal wave and its relation to solar, interplanetary and geomagnetic parameters.

4. Long term behaviour of diurnal wave

The amplitude to average ratio is a useful parameter for review of diurnal wave contribution to cosmic ray time signal on long time scales (see figure 3). This, along with the phase evolution at the three neutron monitors, is displayed in figure 4. While the amplitude has 11-year variation, the phase has a different profile indicating the presence of solar magnetic cycle variation with 22 year quasiperiodicity which is seen both on Oulu and Climax data.

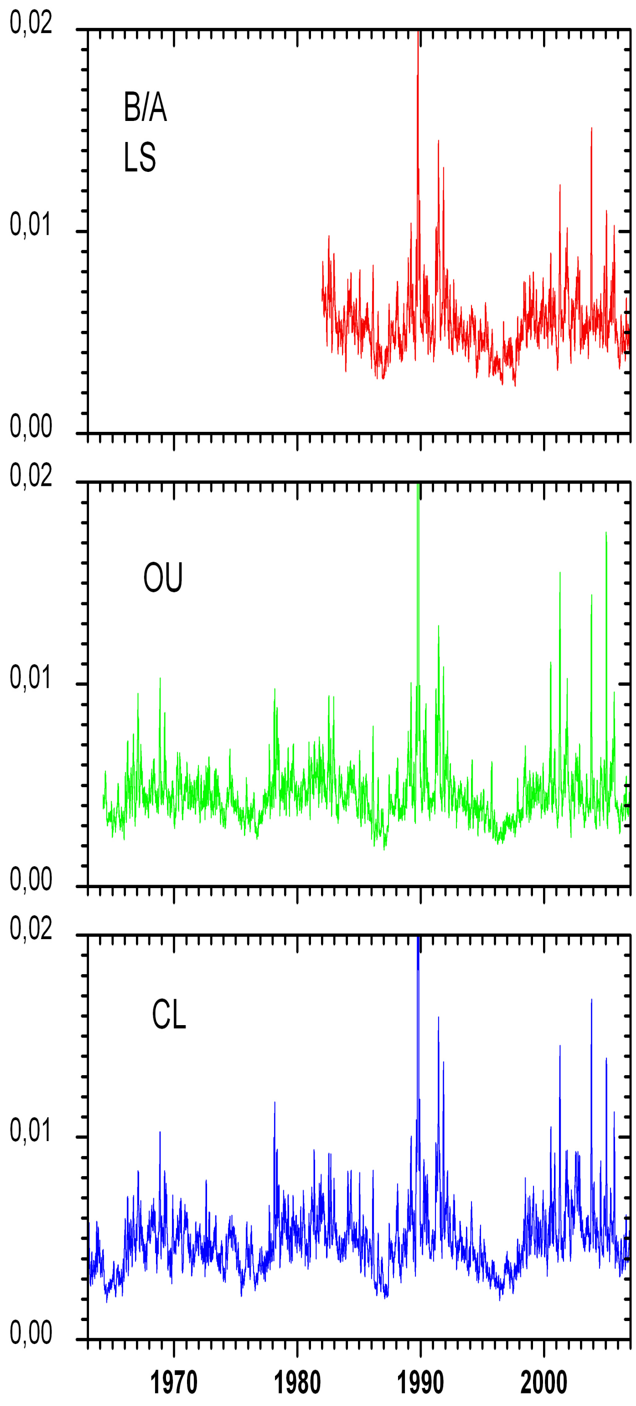

Fig.3. The long term evolution of the amplitude to average (B/A) ratio. All data sets are smoothed by 27 neighbour points. Values B and A are obtained from Eq. 1.

fitted at the three neutron monitors are significant. For Oulu versus Climax the linear correlation coefficient r=0.78 (15232 points), for Lomnický Štít vs Climax r=0.77 (8939 points) and for Lomnický Štít vs Oulu r=0.75 (8939 points). Out of the checked relations of the amplitude of diurnal wave with various parameters, the most significant one was found with the value of total IMF. It is shown in figure 5.

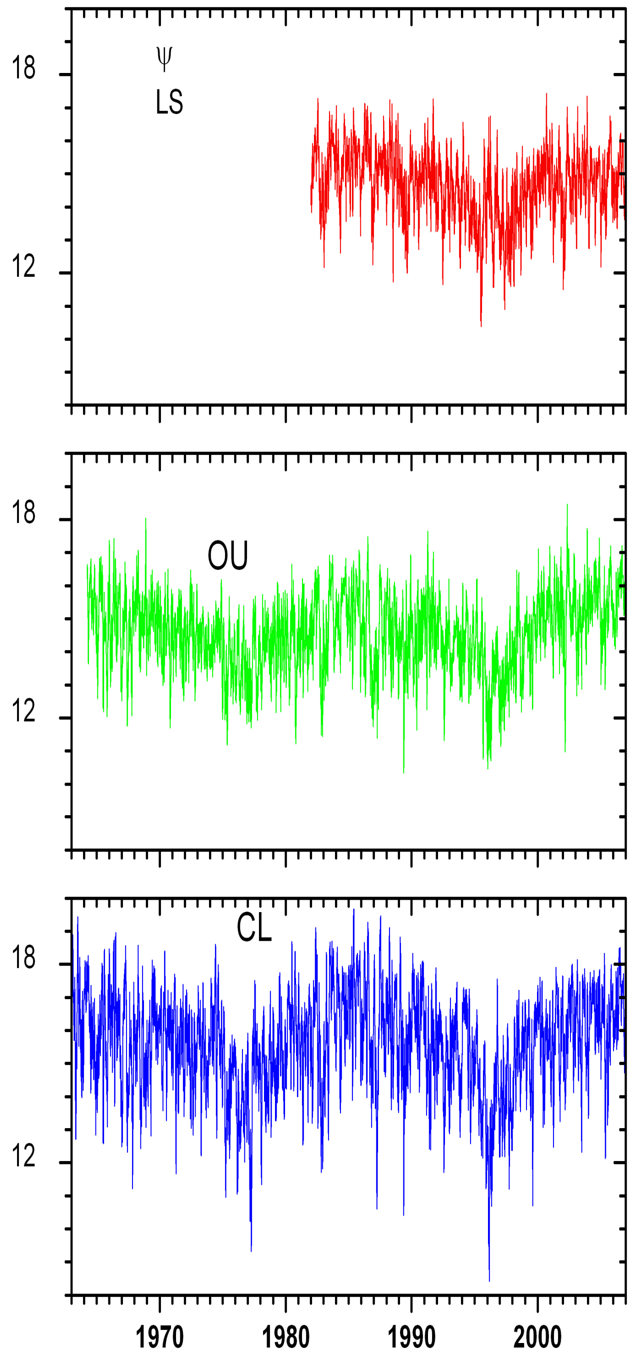

Fig. 4. The long term evolution of the phase (ψ in Eq. 1) of diurnal wave. Data are smoothed by by 27 neighbour points

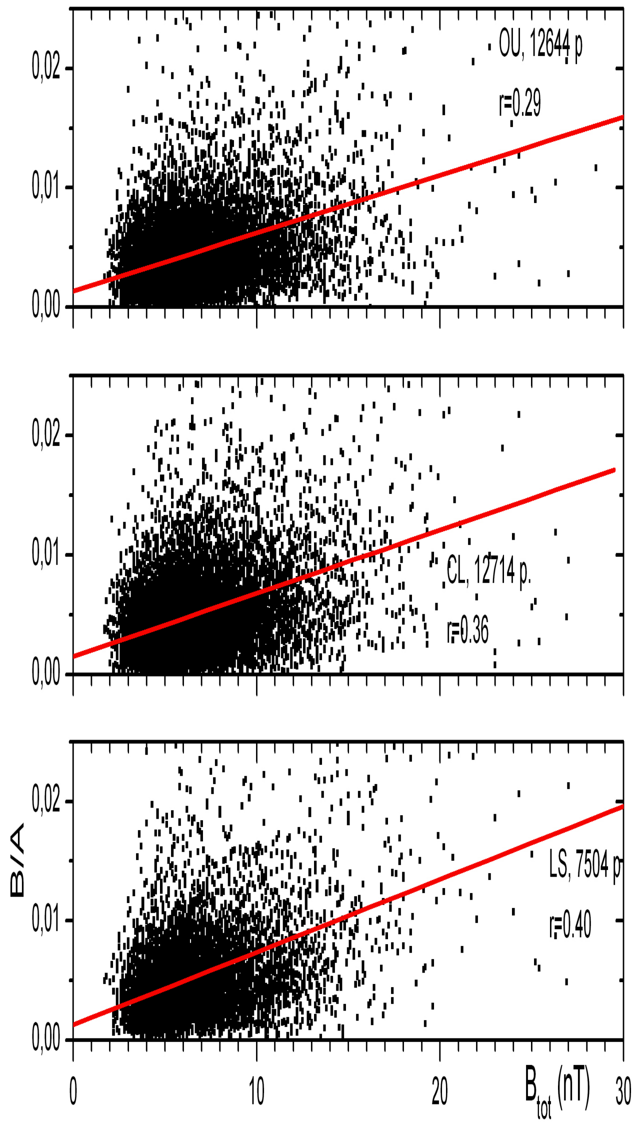

Fig.5. Scatter plot of amplitude/average of the diurnal wave fit versus the magnitude of interplanetary magnetic field vector. The linear correlation coefficients and number of days is labeled for data of the three neutron monitors.

5. Relations to solar, interplanetary and geomagnetic characteristics

The data set constructed allows to check various dependences of diurnal wave characteristics to solar, interplanetary and geomagnetic activity parameters. The mutual correlations between the amplitudes of diurnal waves

Splitting the data into the subsets for A>0 and A<0 did not reveal the different connection to IMF magnitude for the two polarities of solar magnetic field. While for amplitudes the sign of the changes with B_{tot} is clear, the changes of phases at the three monitors do not provide clear pattern if the whole data set is analyzed. Only a slight tendency with increase of

B_{tot} towards earlier hours is seen in linear fit, but also the shape of distribution is changed.

Regarding the north-south polarity of IMF neither the amplitude nor the phase was found different in the whole data set.

The relation of amplitude to the solar wind velocity is significantly different from zero assuming the large data set, but its values are smaller than those with B_{tot}. For Climax r=0.12 (12716 days), for Oulu r=0.17 (12794 days) and for Lomnický Štít r=0.19 (7335 days). No clear relation of the phase to solar wind speed was found.

There is also non-zero correlation between the amplitude of the diurnal wave and Kp index obtained. For Oulu r=0.15 (15232 days), for Climax r=0.22 (15688 days) and for Lomnický Štít r=0.24 (8939 days).

The non-zero correlations of the amplitude are obtained also with sunspot number, namely r=0.15 for Lomnický Štít (8939 days), r=0.18 for Climax (15688 days) and r=0.12 for Oulu (15232 days). However the dependences on Kp and on sunspot number are not casual, because of their mutual relations to IMF and solar wind which are affecting the modulation of cosmic rays in the heliosphere.

6. Conclusion

The data set constructed allows the detailed study of diurnal wave characteristics of cosmic rays in relation to solar, interplanetary and geomagnetic characteristics. The statistical study based on it using neutron monitor measurements at Lomnický Štít, Oulu and Climax confirmed on extended data set the earlier findings of other authors and indicated that (a) narrower phase distribution with non-significantly changed position of maxima is obtained at all three stations when the amplitude to dispersion ratio is increasing; (b) while amplitude of diurnal wave has ~11-year variation, the phase profile is more complicated and it is related most probably to ~22-year period of solar magnetic field polarity; and (c) the significant parameter controlling the amplitude of the diurnal wave is B_{tot} of IMF. For the three NMs no clear difference in the dependence of diurnal wave amplitude and of the phase on the daily average IMF value, solar wind velocity and geomagnetic indices is observed which may be related to the cut-off or position of the individual NMs.

The extension of the data set with other neutron monitor and muon telescope data can be a useful tool for clarifying the dependences obtained here for three neutron monitors, at different energies of primary cosmic rays.

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