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Study of High and Low Amplitude Wave Trains of Cosmic Ray Diurnal Variation during Solar Cycle 23

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Abstract. A detailed study has been conducted on the long-term changes in the diurnal variation of cosmic rays in terms of high and low amplitude wave trains event (HAEs/LAEs) during the period 1996–2008 (solar cycle 23), using the neutron monitor data from Kiel neutron monitoring station. As such, 17 HAE and 48 LAE cases have been detected and analyzed. These HAEs appear quite dominantly during the declining phase as well as near the maximum of the solar activity cycle 23. In contrast, the low amplitude events (LAEs) are inversely correlated with solar activity cycle. In fact, LAEs appear quite dominantly during the minimum phase of the solar activity. When we compare our results for diurnal phase with that observed on an annual average basis, we notice no significant diurnal phase shift for HAEs as well as for LAEs. Moreover, we find that the high-speed solar wind streams (HSSWS) do not play any significant role in causing these variations. These results are discussed on the basis of that observed in earlier cycles.

Key words. Cosmic rays—diurnal variation—high amplitude anisotropic events—low amplitude anisotropic events—solar cycle—solar wind speed.

1. Introduction

It is well known that cosmic ray diurnal anisotropy is caused by the co-rotation of cosmic ray particles with the magnetic field of the solar system. The long-term behaviour of cosmic ray diurnal anisotropy has been explained by Agrawal & Bercovitch (1993); Hashim & Thambyahpillai (1969); Ricker & Ahluwalia (1987); Singh & Badruddin (2006). The large day-to-day variability in the diurnal anisotropy (Rao *et al.* 1972; Ananth *et al.* 1974; Kane 1975) has been explained in terms of the change in the radial convection and field aligned diffusion of cosmic ray particles in interplanetary space. It has been reported that the enhanced diurnal variation or continuous wave of high amplitude anisotropy events (HAEs) exhibit maximum intensity in space around the anti-garden house direction and minimum intensity around the garden house direction. Similarly, waves of low amplitude anisotropy events (LAEs) have also been observed.

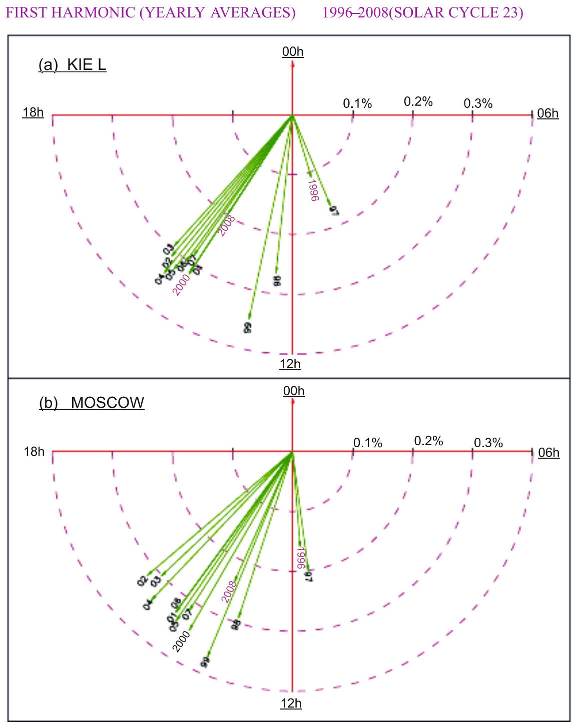

Figure 1. The harmonic dial representation of the annual average vectors of the first harmonic of the observed daily variation of cosmic rays of Kiel and Moscow N M stations for the years 1996–2008 (solar cycle 23).

A number of HAEs and LAEs have been observed with a significant shift towards later or earlier hours (Kumar & Chauhan 1996; Kumar *et al.* 1997; Mishra & Mishra 2007, 2008).

Changes have also been observed in the diurnal amplitude and phase during the high speed solar wind streams (HSSWS) coming from coronal holes (Iucci *et al.* 1981; Munakata *et al.* 1987). The diurnal variation might be influenced by the polarity of the magnetic field (Parker 1991), so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the sun. The occurrence of high amplitude days is found to be positively correlated with the sunspot cycle. Ananth *et al.* (1995) have examined the occurrence of a large number of high and low amplitude cosmic ray diurnal wave trains during two solar cycles (20 and 21) over the years 1965–1990 as a function of the solar activity. They concluded that low diurnal amplitude days show an inverse correlation with solar activity and have a maximum diurnal time along the ∼1500 h LT direction. Fluckiger (1991) attributed the enhanced diurnal amplitudes to changing conditions in the interplanetary space. During high speed solar wind streams (HSSWS), the amplitudes and phases of the diurnal variation are reported to be different from those of other days (Iucci *et al.* 1981; Munakata *et al.* 1987). Kane (2009) reported that HAE wave trains which can last for more than two days, their origin is not in parameters in or near-Earths environment. He has also reported that some of these events (generally short-lived, ∼4 days) did

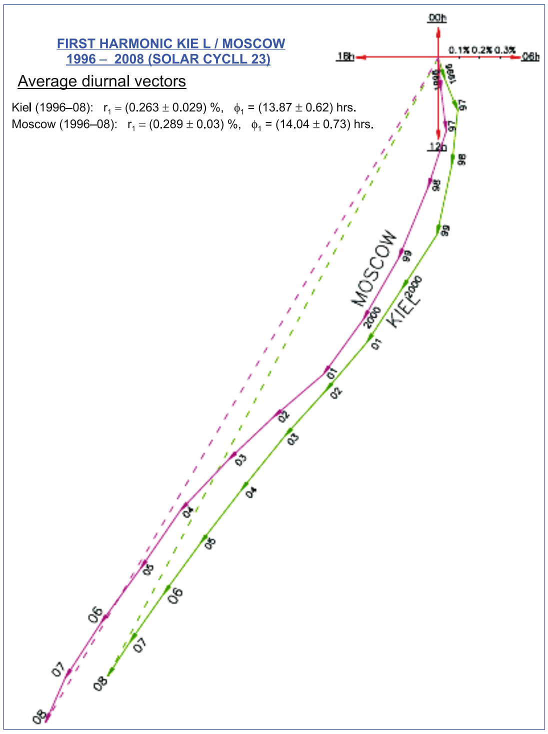

Figure 2. The vector addition diagram of the annual average vectors of the first harmonic of the observed daily variation of cosmic rays of Kiel and Moscow N M stations for the years 1996–2008 (solar cycle 23). The overall average values are also marked.

show some relationship with near-Earth interplanetary parameter, which could be due to chance coincidences.

2. Data analysis

Generally, cosmic ray intensity shows significant diurnal variations on a day-to-day basis with most probable amplitude of 0.4% to 0.5% at high and middle latitude neutron monitor stations; often with wave trains of high amplitude anisotropic events (HAEs) and low amplitude anisotropic events (LAEs). The pressure corrected hourly neutron monitor data of Kiel neutron monitor station (54.3°N, 10.1°E, cut-off rigidity 2.36 GV) and Moscow neutron monitor station (55.4°N, 37.3°E, cut-off rigidity 2.39 GV) obtained from websites ftp://ftp.ngdc.noaa.gov/stp/solar_data/comic_rays/ and http://omniweb.gsfc.noaa.gov/form/dn1.html, are subjected to a simple harmonic analysis technique for deriving the amplitude and maximum time of diurnal anisotropy vectors on each individual day for 13 years during the epoch 1996–2008 (solar cycle 23). The days associated with Forbush decreases and large cosmic ray transient intensity variations are removed from the basic data and from the average diurnal variation vectors obtained from the individual days, to avoid UT effects. Based on the observed diurnal variation vectors at Kiel, the individual days are classified into two

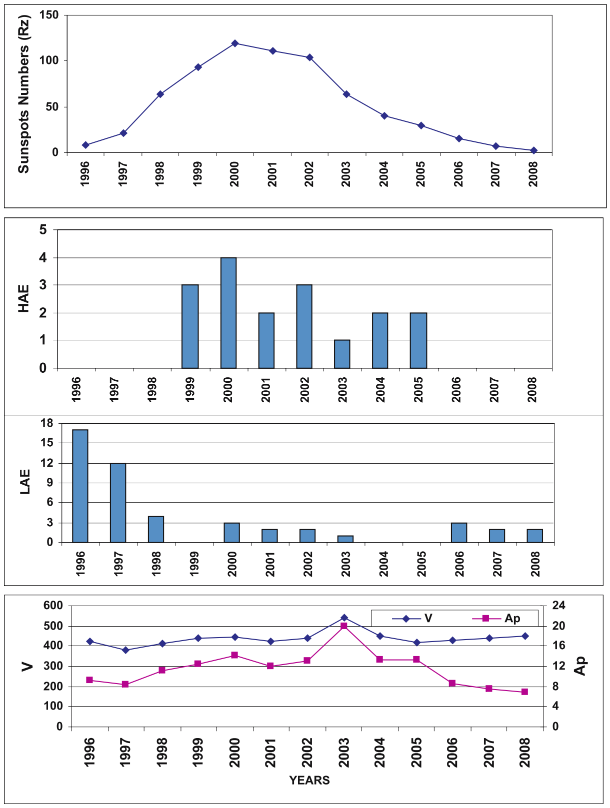

Figure 3. The frequency distribution of the annual values of the occurrence of high and low amplitude diurnal wave trains plotted along with the solar activity represented by the sunspot number (Rz). The figure also shows the solar cycle dependence of Ap and V.

groups as follows:

(i) Four (or more) consecutive days with observed diurnal amplitude $\geq 0.6\%$; these are the high amplitude days (HAEs).

(ii) Four (or more) consecutive days in which the observed diurnal amplitude is $\leq 0.2\%$; these are the low amplitude days (LAEs). Our classification shows that there are as many as 17 high amplitude wave trains and 48 low amplitude wave trains occurring during our study period. For each event, the average diurnal variation is then determined by vector averaging of the diurnal variation derived for each individual day of the event.

3. Discussion and results

In Fig. 1, we show the harmonic dial for the annual average vectors of the first harmonic of the daily variation of cosmic rays, for (a) Kiel and (b) Moscow neutron monitor stations, for the period of 1996–2008 (solar cycle 23). For the Kiel and Moscow neutron monitors, the diurnal amplitude, as clearly seen from this figure, is low during the time period of solar minimum (1996, 2008). In fact, the diurnal amplitude is high

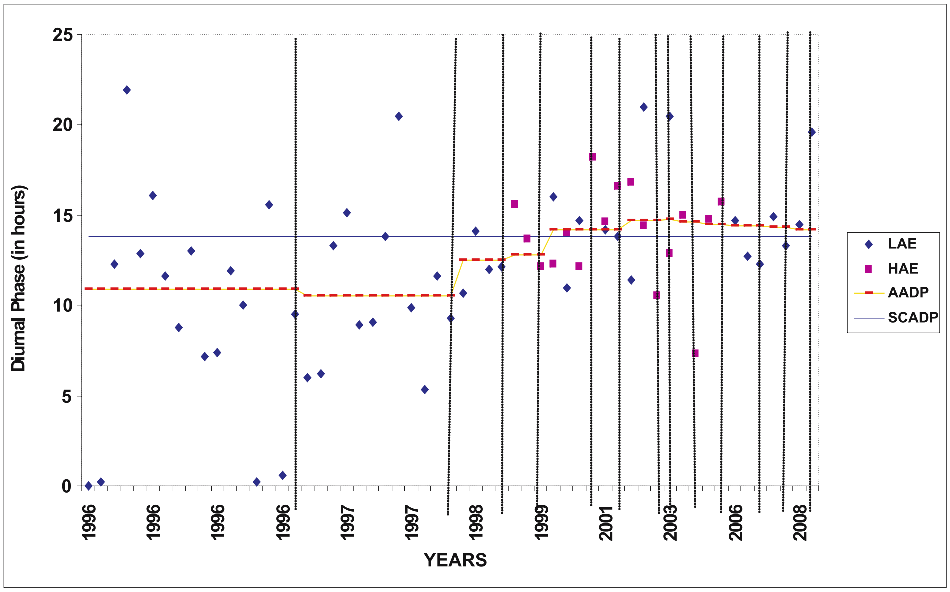

Figure 4. The magnitude of the diurnal phase (time of maximum) of cosmic ray intensity for Kiel neutron monitor station for various events (HAE: high diurnal amplitude events; LAE: low diurnal amplitude events) observed during the years 1996–2008, in solar activity cycle 23. AADP refers of annual averages shown by dashed lines for each year, whereas SCADP refers to overall average of diurnal phase for the whole solar cycle. Note the significant increase of diurnal phase from 1996 onward till 2008.

from the year 1999 (near solar activity maxima) and remains high thereafter. In this cycle, the diurnal phase does not shift to earlier hours during the declining phase of solar activity. Further to harmonic dial representation, Fig. 2 shows the vector addition diagram of annual average vectors of the first harmonic of the daily variation of cosmic rays, for the Kiel and Moscow neutron monitor stations, for the years 1996–2008 (solar cycle 23). From this figure, we very clearly notice that the diurnal phase has continuously moved to later hours from the beginning of solar cycle 23, with a somewhat increasing trend in the diurnal amplitudes. The overall average diurnal vector for the complete solar cycle 23 for Kiel and Moscow neutron monitor stations have also been deduced and these are found to be:

$$\text{Kiel}: \quad r_1(1996\text{–}2008) = (0.263 \pm 0.029)\%, \quad \Phi_1 = (13.87 \pm 0.62)\,\text{h}.$$

$$\text{Moscow}: \quad r_1(1996\text{–}2008) = (0.289 \pm 0.03)\%, \quad \Phi_1 = (14.04 \pm 0.73)\,\text{h}.$$

We have presented the data together in Fig. 2, to show the differences (if any) in the variation of diurnal variation from two similar high latitude stations (Kiel and Moscow) and to bring out the observed similarities between the two high latitude stations, Kiel and Moscow. As such, we can select any one station for further analysis, as both stations are running parallel to each other.

In Fig. 3, we show the frequency distribution of the occurrence of high and low amplitude wave trains by also plotting the sunspot number (Rz) during solar cycle 23 (1996–2008). The high amplitude events are found in maximum number during

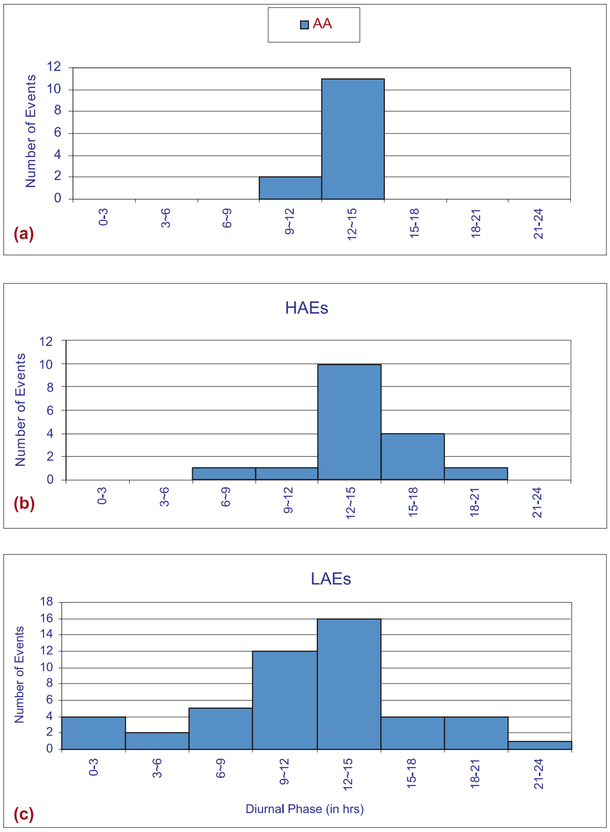

Figure 5. Histograms showing the distribution of diurnal phase in bins of 3 h, **(a)** on for annual average basis, for **(b)** high and for **(c)** low amplitude events during solar cycle 23.

the maximum solar activity period and in the declining phase of the solar activity. Moreover, the low amplitude events (LAEs) are inversely correlated with solar activity. In Fig. 4, we have plotted the average diurnal phase for each event as well as the annual average diurnal phase to compare the variability for the entire period. In figure 4, we have plotted the average diurnal phase for each event as well as the annual average diurnal phase to compare the variability for the entire period. From this figure, we observed that the high amplitude events (HAEs) show the time of maximum in the same direction as the annual average for that year with some indication of phase shift to later hours. Similarly, no significant diurnal phase shift is observed for LAEs also, though here again some indication is seen for phase shift to earlier hours. In fact all the events have their diurnal phase almost in the same direction as their annual averages for both HAEs and LAEs. Such a result shows that as the annual average diurnal phase shifts from low values to high values with the progress of the solar cycle, the event averages also consonantly shift to higher diurnal phase values. Such a result obtained for solar cycle 23 seems to be a little different than that reported earlier. In Fig. 5, we have plotted the frequency histograms of diurnal phases in bins of 3 h from where we do notice some indication that the HAE's phases are slightly shifted to later hours as compared to annual averages, whereas LAEs do not show any significant difference from the annual averages. However, it would be worth investigating how the annual diurnal phase has varied during different periods in those stations. We have also investigated if there is any relationship of these events with the solar wind speed and with the geomagnetic field index (Ap). Here again we find that no significant change in the solar wind speed or Ap has been observed during the events of solar cycle 23.

4. Conclusions

From the above discussion of observation and results we conclude that:

- Diurnal phase for HAEs and LAEs varies with the diurnal phase on annual average basis. The direction of observed diurnal variation for HAEs lies along the $\sim$12–18 h direction, whereas for LAEs it lies between 9 and 15 h direction. The annual average phases are concentrated mostly in the 12 to 15 h direction, 9 mainly in the 15 h direction).
- High amplitude events (HAEs) appear quite dominantly during the declining phase, as well as near the maximum of the solar activity cycle 23.
- The low amplitude events (LAEs) are inversely correlated with solar activity cycle.
- The HAEs and LAEs do not reveal any correlation with the solar wind speed V or geomagnetic index, Ap (on annual average basis).
- During solar activity minima of 1996, 1997, the yearly average diurnal phase shifted to earlier hours, which is not at all noticed in the other solar minima of 2008, where diurnal phase does not shift to earlier hours. In contrast, we have found that the annual average diurnal amplitudes show a significant decrease during the solar activity minima and maximum found during the declining phase of the solar cycle.
- The high speed solar wind streams do not play any significant role in causing these HAEs and LAEs.

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