Anomalous behaviour of cosmic ray diurnal anisotropy during descending phase of the solar cycle-22

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Large anomalies have been detected in the characteristics of daily variation of cosmic rays during 1993 and 1994. The years 1993 and 1994, which fall in the descending phase of solar activity cycle-22, show the period of anomalous variation of diurnal waves particularly in the diurnal time of maximum. In 1992, the diurnal phase shifted to later hours at first, but anomalously recovered in 1993 and 1994, and then again shifted to early hours continuously since 1994 to 1997. The recovery of phase in 1993 and 1994 is quite significant and anomalous, and is not associated with any anomalous change in diurnal amplitude, which remains constant. Dependence of diurnal vector on the variation of *Ap* values are studied.

THE characteristics of the daily variation of cosmic ray intensity at relativistic energies have generally been studied using the hourly data recorded by ground-based high counting rate super neutron monitors[1–3]. These monitors are operating continuously for almost four decades at various locations on the surface of the earth, and their worldwide locations are well distributed both in latitude and longitude. The amplitude (in %) and the phase (time of maximum) of the first few harmonics of the daily variation of cosmic rays for these stations are generally derived by simple harmonic analysis[4–7]. The unusual high and low days of cosmic ray counts are eliminated from the study. These two low and high count rates are known as universal time changes, which influence the results. Days associated with large universal time changes in cosmic ray intensity (occurring simultaneously at all stations) are identified and rejected while deriving the averages. Considering all such data vagaries, neutron monitor data of Kiel station for the interval (1989–2003) have been used to study the response of the daily variation of cosmic rays in different phases of the solar cycle. The data of Kiel station have been compared with other high latitude stations for greater reliability[8–10]. A systematic study has been performed using geomagnetic disturbance index *Ap*, both on day to day as well as on an average basis, because both cosmic ray anisotropy and *Ap* are affected due to the variations in solar plasma parameters, which include solar wind as well as interplanetary magnetic field parameters. Nevertheless, we recognize that the cosmic ray variability is a phenomenon of large spatial extent, whereas the *Ap* index is a local effect limited to solar plasma variability near the earth's local interplanetary space[11,12].

The temperature and pressure-corrected hourly data of cosmic ray intensity from Kiel and Haleakala neutron monitors have been used to obtain the amplitude and phase of the harmonic component for each day by Fourier techniques, where the long-term change from the data has been removed by the method of 24-h moving average. Moving average is slide average technique, which shows the long-term

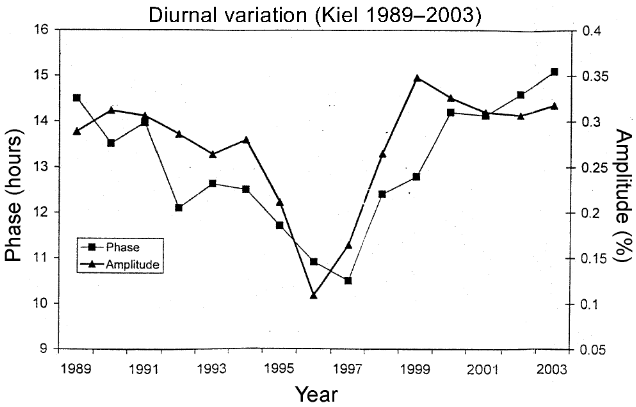

Figure 1. Yearly mean values of diurnal amplitudes and time of maxima (phases) for the period 1989–2003.

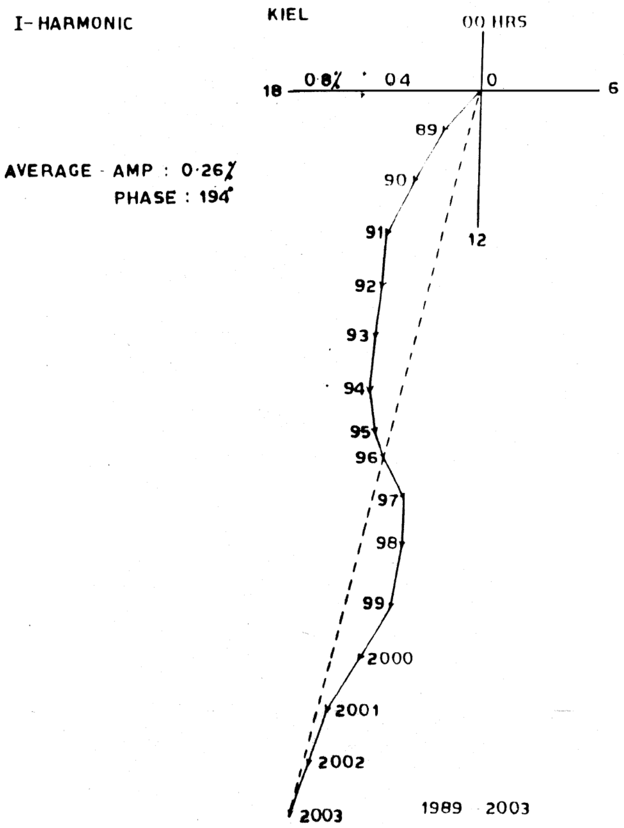

Figure 2. Yearly average vectors for diurnal variation of cosmic ray intensity observed by neutron monitor at Kiel for 1989–2003.

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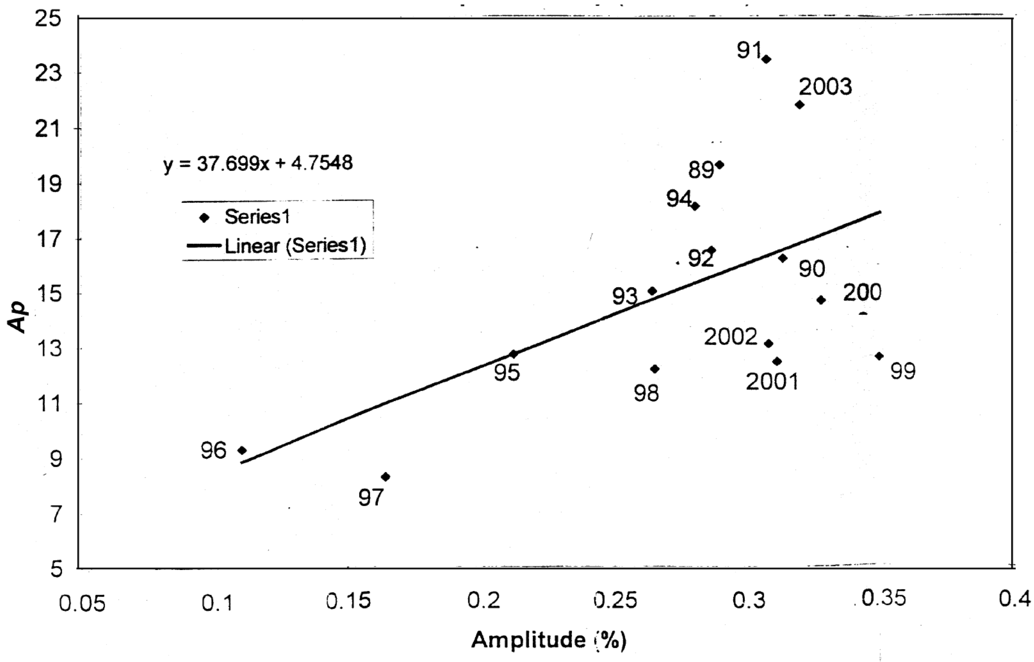

Figure 3. Correlation between yearly mean values of diurnal amplitudes and *Ap* index for the period 1989–2003.

profile of a dataset. In this way we can exclude the short-term fluctuation of noise in a dataset. The days of Forbush decreases have been removed from the analysis to avoid associated superposed variation in cosmic rays. A complete computer program was used for calculating the harmonics of each day during the period 1989–2003. The yearly mean values with their standard errors have been obtained from these daily vectors. Geomagnetic disturbance index *Ap* can be a good proxy of the interplanetary conditions. In fact, it has been demonstrated that the *Ap* index is highly correlated with the mean fluctuations in the amplitude of the interplanetary magnetic field, which in turn is related to the diffusive component of the convection–diffusion theory.

The year-to-year variations in diurnal amplitudes and phases for the period 1989–2003 are illustrated in Figure 1. The amplitude of the diurnal variation displays an 11-year cyclic variation, with minima occurring near sunspot minima (1996) and maxima occurring near sunspot maxima (1989 and 1991). Using the neutron monitors cosmic ray researchers observed every day counts to an excess of particles arriving from the asymptotic direction 1800 local time. It has been found that in the vicinity of the sun, the cosmic ray particles corotate with the sun; thereby higher cosmic ray intensity is observed from a direction opposite to that of the earth orbital motion. In this way, a 24-h wave is formed from the cosmic ray hourly counts and named as diurnal variation (first harmonics of cosmic ray anisotropy). The diurnal amplitudes and phases are derived from the daily vectors, which are derived from the harmonic analysis technique. The yearly mean values of the amplitude and time of maxima of diurnal variation of cosmic rays derived the daily vectors for each year. The observed yearly vectors are shown in Figure 2, as a vector addition diagram for Kiel neutron for the interval 1989–2003. Large anomalies have been detected in the variational characteristics of the diurnal anisotropy during the years 1993 and 1994, while investigating the results for the period 1989–2003. The period 1993–94 falls in the descending phase of the solar activity cycle-22. The recovery of diurnal phase in 1993 and 1994 is quite significant and is not associated with any anomalous change in diurnal amplitude, which remains constant. It has been generally found that the diurnal phase shows a 11-year variational cycle from one maxima to another. In earlier results, the diurnal phase shows a decreasing trend during the solar cycle[13–15]. In our study, we noticed a phase shift to early hours in 1992, but it anomalously recovers in 1993 and 1994 and then again shifts to early hours. The recovery of phase in 1993 and 1994, which is also not associated with change in amplitude, is known as anomalous behaviour. Cross-correlation between the annual averages of *Ap* and amplitude of diurnal variation of cosmic rays for the period 1989–2003 has been plotted in Figure 3. It is found that the behaviour of diurnal amplitude and phase during the descending phase of solar activity in the previous solar cycle-22 and during the present solar cycle-23 is quite different. The most noticeable difference is seen in 1989, 1991 and 2000–02. The *Ap* value is exceedingly large in 1991, but without any significant increase in diurnal amplitude. The analysis on a day-to-day basis reveals yet another anomaly in between *Ap* and cosmic ray daily variation. In this analysis, we have shown diurnal variation during the periods of low as well as high *Ap* values. As already known, geomagnetic *Ap* index is highly correlated with solar wind velocity[16]. Therefore, low *Ap* values indicate the quite interplanetary medium as well as low solar wind speed. In this

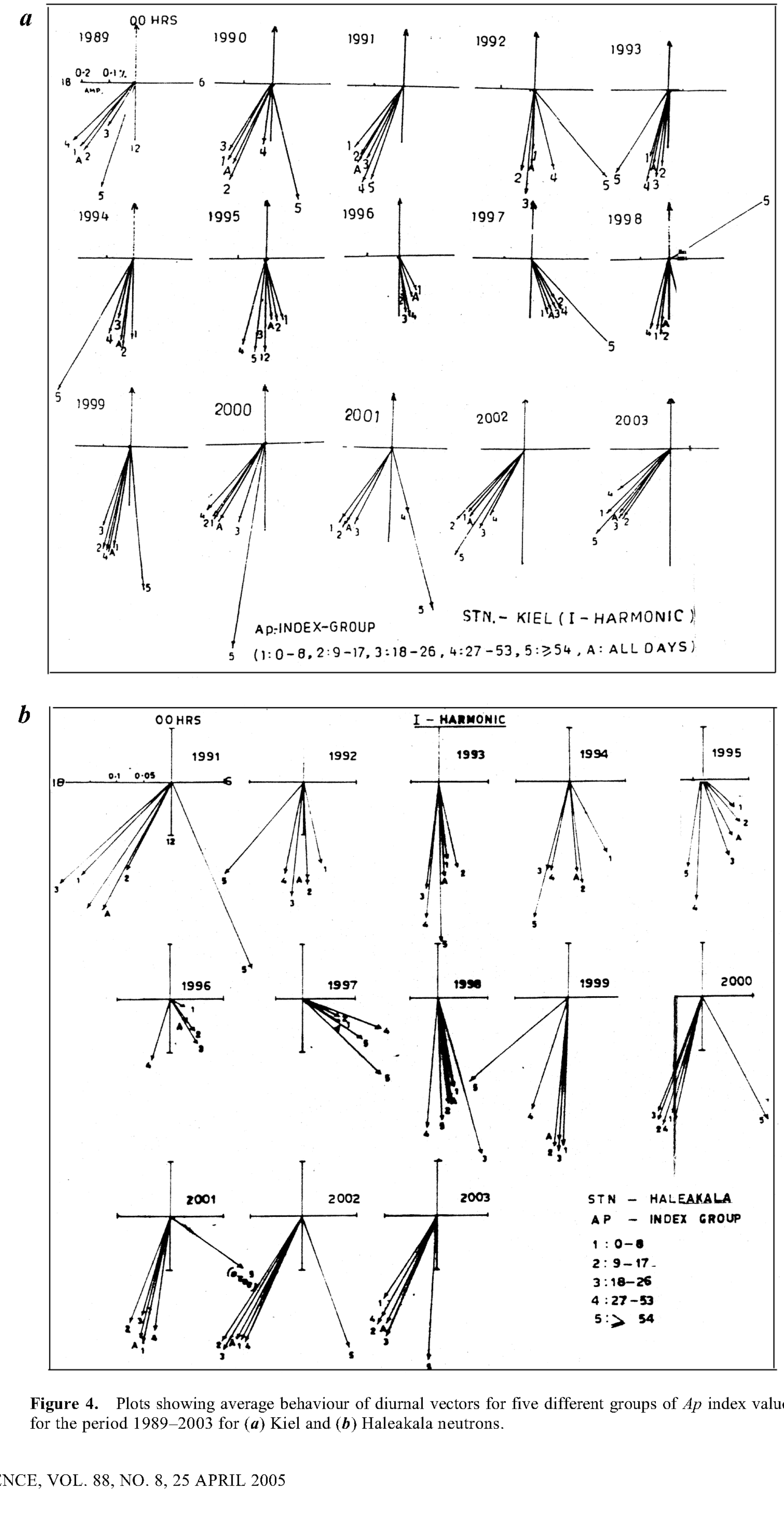

Figure 4. Plots showing average behaviour of diurnal vectors for five different groups of *Ap* index values for the period 1989–2003 for (***a***) Kiel and (***b***) Haleakala neutrons.

way, we can also derive the influence of solar wind on daily variation of cosmic ray anisotropy. To obtain the relationship between the *Ap* index and diurnal variation on a day-to-day basis, only those days have been considered for which there is inter-relation agreement in diurnal variation to avoid the effects of universal time-related changes. Kiel neutron monitor (cut-off rigidity ≈ 2.97 GV) data have been used to derive the daily vectors of cosmic ray anisotropy. The days are then divided into five groups according to increasing value of *Ap* index (0–8, 9–17, 18–26, 27–53 and ≥ 54). The vector average values for each group and for each year from 1989 to 2003 are plotted in Figure 4 *a*. It is observed that for low *Ap* index groups, the dispersion from one period to another is least, both in amplitude and phase. However, the dispersion is large for the high *Ap* index groups, particularly for group *Ap* ≥ 54. With increase in the value of daily geomagnetic disturbance index *Ap*, we find that during the period of high sunspot activity (1989–92 and 1997–2002), the diurnal variation rotates anticlockwise, i.e. when *Ap* is high the diurnal phase is smaller, contrary to that observed on long-term basis shown here by considering annual averages. Nevertheless, during the decline phase of solar activity (1993–96), the diurnal vector rotates clockwise with the increase in the value of *Ap*, which is in accordance with the findings on annual average basis. A similar analysis has been done for cosmic ray data from Halekala neutron monitor station (cut-off rigidity ≈ 13.01 GV). The vector average values for each group and for each year from 1991 to 2003 are plotted in Figure 4 *b*. For Haleakala neutrons, we also observe similar to Kiel neutrons, lesser dispersion from one period to another for low *Ap* values.

The dispersion is also high for high *Ap* groups. A critical comparison of Figure 4 *a* and *b*, shows that dispersion of high *Ap* groups, particularly 5 is quite different in Haleakala, than that from Kiel.

To conclude, the value of diurnal phase shifted to later hours in 1992. The values of diurnal time of maxima (phase) are abnormally shifted to later hours in 1993 and 1994. However, diurnal amplitudes remain constant during these years. This is also evident from the fact that diurnal amplitudes are maximum during high solar activity periods. Diurnal variation of cosmic ray intensity has clearly demonstrated the significant 11/22 year changes. The diurnal amplitude and phase associated with low *Ap* values are more coherent. The large variability during high *Ap* days and the significant increases in amplitude with increase in *Ap* values are found for both the Kiel and Haleakala neutrons. Diurnal variation rotates anticlockwise during the period of high solar activity. However, it rotates clockwise during the declining phase of solar activity.

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