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Average Anisotropy Characteristics of High Energy Cosmic Ray Particles Approaching Solar Minimum*

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Long-term variability of the daily variation of cosmic ray intensity is discussed in terms of two hypotheses: the 22-yr field-aligned sinusoidal wave proposed by S E Forbush [*J. geophys. Res.*, **74** (1969), 3451] and the radial or field-aligned anisotropy mainly effective during alternate sunspot cycle superimposed on normal corotational anisotropy. As expected, no evidence is found for a positive cycle of 22-yr wave around 1964-65 minima as well as of complete phase reversal in diurnal vector even for a complete solar rotation in 1976 in contrast to that in 1954 at neutron monitor energies. Comparison of diurnal and semi-diurnal variations with the available solar wind velocity measurements provide further evidence of significant changes since 1971 and better understanding of the nature of semi-diurnal anisotropy. It is shown that the semi-diurnal anisotropy observed during days of higher A_p index may not be due to extra-terrestrial effect but of local origin.

1. Introduction

The hypothesis of 22-yr periodicity in the diurnal variation of cosmic ray intensity[1] was proposed as early as 1953. However, later till 1970, it was generally accepted that the diurnal anisotropy was mainly due to corotation and almost constant. This was so since 1957 (the IGY period) when the continuous operation of a number of neutron monitoring stations particularly sensitive to lower energies and free from atmospheric temperature vagaries[2,3] was started. In contrast, the meson telescope responding to higher energies and with much smaller diurnal amplitude has always recorded large variability with solar cycle. These observations have finite probability to include a small diurnal component due to the changes in atmospheric temperature at various altitudes up to the production layer of the unstable particles. However, recent neutron monitor observations showing a consistent diurnal phase shift[4,5] since 1971 and the detailed investigation of neutron monitor data for periods during 1954 by Thomson[6] have revived further interest in such studies. Moreover, the response of the diurnal vector to days with widely differing values of A_p was reported by Agrawal and Singh[7] to be having opposite senses in 1968 and 1973, even though the cosmic ray data were used only for days on which the diurnal vector was similar at 6 stations. The recent findings summarized by Svalgaard[8] indicate that there is a good correlation between A_p and solar wind velocity to justify the use of A_p index for such a statistical analysis. The analysis has been extended for further periods and also to include the semi-diurnal variation of cosmic ray intensity to understand their large variability.

2. Long Term Variation of Diurnal Anisotropy

The average characteristics of the diurnal component of cosmic ray daily variation has been obtained from a number of neutron monitoring stations operating at various latitudes and longitudes covering a wide range of cut-off rigidity using the modified variational coefficients and correction factors[9,10] for the period 1953-76. Even though during the period earlier to 1970 the rigidity spectral exponent (β) is essentially zero and the upper cut-off rigidity (R_{max}) varies only from 50 to 100 GV till 1970 with well defined and significant minimum variance,[3] yet both β and R_{max} remain indeterminate during the later period 1971-73 due to almost flat response of minimum variance with much higher values.[4] Nevertheless, to obtain the anisotropy values even for 1971-76, the same set of values are used. The yearly averages of diurnal amplitude and phase so obtained are plotted in Fig. 1.

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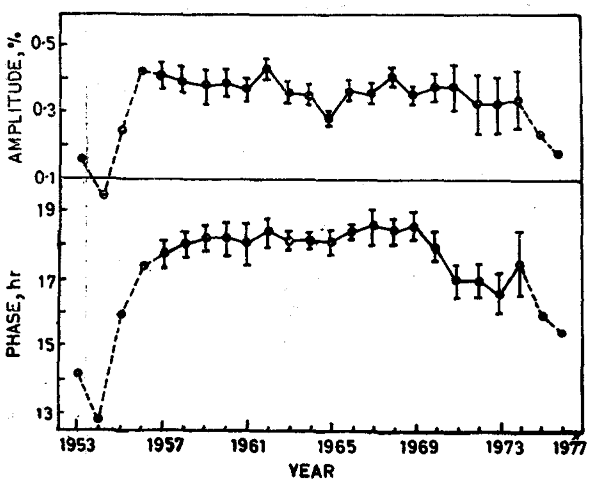

Fig. 1 — Plots of yearly averages of amplitude and phase of the diurnal anisotropy of cosmic ray intensity during the period 1953-76 (The values are obtained from neutron monitor observations together with their 1 σ standard error obtained from the observed vector at each station The dotted lines indicate the availability of data for a few stations; and the statistical error in these cases could be large)

A few remarks based on the above plot and further available data are as follows.

(i) The diurnal time of maximum (ϕ_1) was essentially constant for the period 1957-70 with $\phi_1 \approx$ 1800 hrs with no indication of any shift in ϕ_1 to later hours in sunspot minimum year of 1964-65.

(ii) The value of ϕ_1 shifted to earlier hours since 1971 with minimum value of 1976, but at no time, even for one solar rotation it was in the early morning hours,[5] even at high cut-off rigidity monitor such as Tokyo-Itabashi in Japan.

(iii) In contrast to the above, the shift in ϕ_1 was much larger during 1954 minimum and consecutively for 3 months the vector pointed itself in the morning hours.[6] However, this may not be surprising as the minimum of 1954 was least active. Nevertheless, the situation and time coincidence of the IMF polarity was of the right phase to have produced similar effects during Aug.-Sep. 1976.

(iv) The average diurnal amplitude $r_1 \approx 0{\cdot}4\%$ when modified with the constant factor of $\approx 1{\cdot}5$ suggested by Subramanian[11] yields theoretically expected amplitude of $\approx 0{\cdot}6\%$. This value is reduced significantly during all the solar minima with varying degree, but is almost constant during other periods, even in 1971-74 when the value of ϕ_1 changed significantly.

Recently, Pomerantz[12] has summarized the long-term variability of the diurnal anisotropy and have inferred that the data are consistent with a sunspot cycle corotational anisotropy superimposed with a

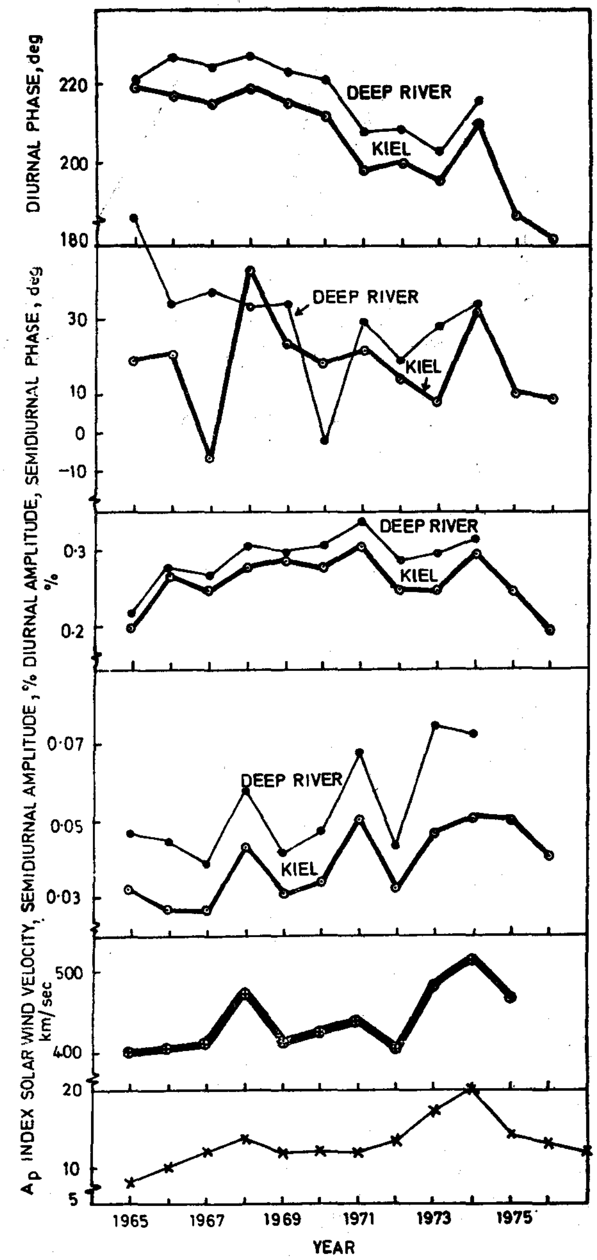

Fig. 2 — Plots of yearly averages of amplitude and phase of the diurnal and semi-diurnal variations of cosmic ray intensity for two stations alongwith the yearly mean solar wind velocity and A_p index for the period 1965-76

22-yr field-aligned wave proposed by Forbush[13] earlier and theoretically conjectured by Levy[14] and Svalgaard and Wilcox[15] based on 22-yr solar magnetic cycle. Whereas the models are highly speculatives it is also difficult to produce 22-year wave with its positive wing in 1964-65 using neutron monitor data alone because no evidence of phase $\phi_1 > 1800$ hrs is present during this period. However, one can view the same phenomenon in terms of a radial or field-aligned anisotropy away from the sun

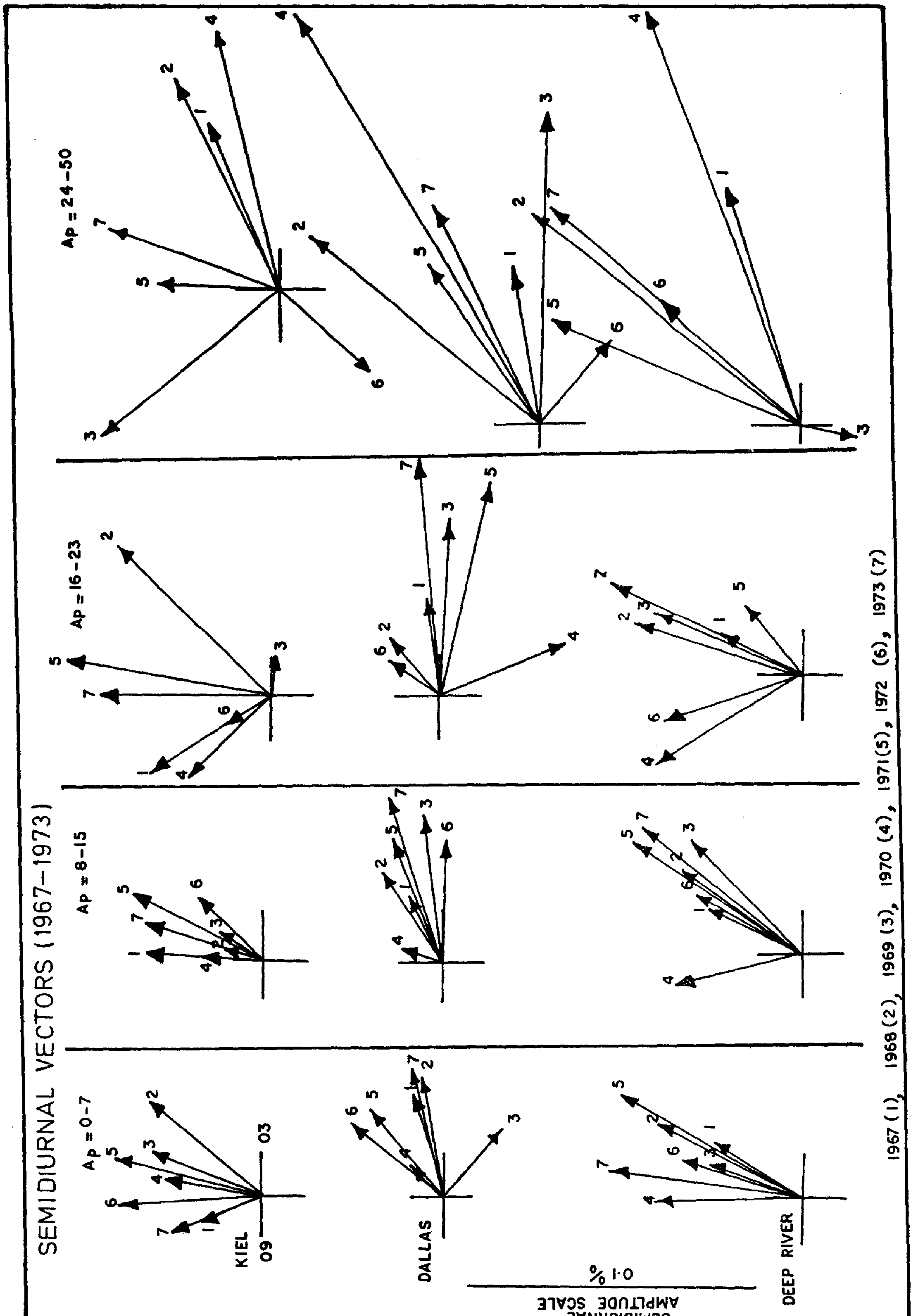

Fig. 3 — Plots showing average behaviour of semi-diurnal vectors for four different groups of A_p index values for three stations during the period 1967-73, each of the 7 years being represented by numerals 1 to 7 in order

and operating only during alternate cycle, the magnitude of which is mainly determined by off-ecliptic phenomena.[16] Further analysis is required using data from equatorial neutron monitors for recent periods to find the detailed characteristics of the anisotropy before drawing any further conclusion.

3. Relationship between A_p and $r_2-\phi_2$

As mentioned earlier, the statistical relationship between A_p and $r_1-\phi_1$ on a day-to-day basis was found to change drastically during 1968 and 1973. It is, therefore, natural to look for the relationship between A_p and semi-diurnal variation if any, as well as to extend the analysis for further period for diurnal variation. Fig. 2 shows the long-term variability of the associated parameters from 1965 to 1976. Except for some indications for an increase in semi-diurnal amplitude in 1973-76 directly related with A_p or solar wind velocity, none of the other values shows any correlation with A_p or solar wind velocity on a long-term basis. It is implied that on a long-term basis A_p and solar wind velocity are well correlated.[8]

To obtain the relationship between the A_p index and semi-diurnal variation on day-to-day basis, only those days have been considered for which there is inter-station agreement in diurnal variation to avoid the effects of universal time related changes. The days are then divided into 4 groups according to increasing value of A_p index (0-7, 8-15, 16-24 and 24-50). Days with $A_p>50$ are also excluded. The vector average values for each group and for each year from 1967-73 are plotted in Fig. 3 for three stations showing consistency among them. It is observed that for low A_p groups the dispersion from one period to another is least, both in amplitude and phase, and can be easily shown to be consistent with a free space anisotropy perpendicular to IMF with amplitude 0·1% at these energies.[17,18] However, the dispersion is large for the two high A_p index groups particularly for the group $A_p = 24\text{-}50$. It is also noticed that the amplitude (r_2) increases with A_p, a result consistent with earlier findings.[19,20] Since the error bars associated with the vectors in Fig. 3 have not been worked out, it is not possible to ascertain the physical significance of these relationships. Nevertheless, it appears that the vectors associated with high A_p values having large amplitude and large scatter are composed of real extra terrestrial anisotropy, and that the variation of terrestrial origin,[21] which could be due to universal time variations cut-off rigidity changes, correlated with D_{st} variations and/or due to inadequate atmospheric pressure correction.

4. Discussion

Since the long-term variation of diurnal anisotropy at high energies plays a very crucial role in defining the interplanetary medium both in and out of ecliptic plane, it is essential to understand that the anisotropy observations from both neutron and meson monitors lead to similar results and that they, when taken together, help in extending the energy range. Presently, it is not possible to do so and this requires further data from equatorial monitors. Similarly, the models are too speculative and require realistic observations from out-of-ecliptic regions to explain both the isotropic and anisotropic observations of cosmic ray intensity. Planned off-ecliptic probe is expected to provide plasma and field values basic to these models.

5. Conclusions

The analysis presented earlier leads to following conclusions.

(i) The long-term change in diurnal anisotropy at neutron monitor energies is more consistent with a radial outward flow during alternate cycles in addition to normal corotational anisotropy.

(ii) The semi-diurnal amplitude and phase have not changed very significantly except in later periods associated with high values of solar wind velocity or A_p index.

(iii) The semi-diurnal amplitude and phase associated with low values of A_p are more coherent and are probably representative of the true extra-terrestrial anisotropy, whereas the large variability during high A_p days and the significant increases in amplitude with the increase in A_p, could be related to their terrestrial origin.

(iv) The analysis for relationship between A_p and $r_1-\phi_1$ leads to similar conclusion reported previously, i.e. till the year 1970, in general, the rotation of diurnal vector is anticlockwise with r_1 being high during high A_p days. However, since 1971-76, either the vector rotates clockwise with no appreciable change in r_1 or the change is insignificant in between various groups of A_p days which are not understood presently.

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References

1. Thambyahpillai T & Elliot H, *Nature, Lond.* **171** (1953), 918.

2. Pomerantz M A & Duggal S P, *Space Sci. Rev.*, **12** (1971), 75.
3. Rao U R, *Space Sci. Rev.*, **12** (1972), 719.
4. Agrawal S P & Singh R L, *Proceedings of the 14th international cosmic ray conference, Munich*, Vol. 4 a (1975), 1193.
5. Agrawal S P, Singh R L, Nigam S K & Sharma R M, *Proceedings of the 15th international cosmic ray conference, Plovdiv*, Vol. 4 (1977), 26.
6. Thomson D M, *Planet. Space Sci.*, **19** (1971), 1169.
7. Agrawal S P & Singh R L, *Proceedings of the 14th international cosmic ray conference, Munich*, Vol. 4 b (1975), 1235.
8. Svalgaard L, *Coronal holes and high speed wind streams*, edited by J B Zirker (University Press, Colorado) 1977, p. 371.
9. Rao U R, McCracken K G & Venkatesan D, *J. geophys. Res.*, **68** (1963), 345.
10. Mori S, *Nuovo Cim.*, **B 58** (1968), 1.
11. Subramanian G, *J. geophys. Res.*, **76** (1971), 1093.
12. Pomerantz M A, *Upper atmosphere research in Antarctica*, edited by Lanzerotti & Park (American Geophysical Union), **29** (1978), 12.
13. Forbush S E, *J. geophys. Res.*, **74** (1969), 3451.
14. Levy E H, *J. geophys. Res.*, **81** (1976), 51.
15. Svalgaard L & Wilcox J M, *Nature, Lond.*, **171** (1953), 918.
16. Quenby J J & Hashim A, *Planet. Space Sci.*, **17** (1969), 1121.
17. Rao U R & Agrawal S P, *J. geophys. Res.*, **75** (1970), 2391.
18. Subramanian G, *Can. J. Phys.*, **49** (1971), 34.
19. Ahluwalia H S, *Proc. Phys. Soc.*, **80** (1962), 472.
20. Sandstrom A E, *Cosmic Rays* (North Holland, Amsterdam), 1965.
21. Kane R P, *J. geophys. Res.*, **80** (1975), 470.