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LETTER TO THE EDITOR

The change in the upper limiting rigidity for the cosmic ray diurnal intensity variation from 1965–1971

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Abstract. The change in the upper limiting rigidity for cosmic ray particles undergoing diurnal modulation has been studied for the period 1965–1971 using neutron monitor and muon telescope observations. The limiting rigidity is shown to vary from a minimum value of about 35 GV in 1965 to a maximum of about 125 GV in 1970.

The solar diurnal variation of cosmic rays is explained as arising mainly from the corotation (Parker 1964, 1967, Axford 1965) of the cosmic ray particles with the interplanetary magnetic field attached to the sun. The nature of this anisotropy has been studied using detectors sensitive to different primary energies (Duggal *et al* 1967, Jacklyn *et al* 1969) and it has been established that the characteristics of the anisotropy vary with time. Jacklyn *et al* (1969) using data from neutron monitors, inclined telescopes and underground muon detectors have determined, for the period 1958–1966, the upper limiting rigidity R_u of the particles which undergo diurnal modulation. They found a variation in the value of R_u with time which appears to follow the cycle of solar activity. During the present cycle, the study of diurnal variation and the change in R_u have been extended by Ahluwalia and Ericksen (1969), Ahluwalia (1971), Agarwal *et al* (1971) and Speller (1972) all working with muon detectors. Their results also indicate a variation in the upper limiting rigidity with time.

The present work investigates whether the diurnal anisotropy measured by neutron monitors behaves in a similar way. The upper cut-off rigidity for the quiet day diurnal variation has been calculated for the period starting from 1965, the minimum of the present solar cycle, to 1971, when the solar activity was at a maximum. NM 64 data from five mid-latitude stations (Deep River, Churchill, Kiel, Kerguelen and Leeds) and one equatorial station (Kula) have been used. In addition, muon data from Deep River and London were used. The general method outlined by Jacklyn *et al* (1969) was followed.

Using the neutron monitor and meson observations, yearly diurnal vectors for 1965–1971 were calculated from unfiltered data, after eliminating days of Forbush decrease, flare increases and also those days where the correlation coefficient between the observed hourly values of a single station and the best fit diurnal curve derived from the data of all the stations was less than 0·5. Large amplitude wave trains were also rejected. The annual mean diurnal variation for 1965 was very small for all detectors.

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The diurnal anisotropy is usually represented by

$$\frac{\Delta J(R)}{J(R)} = \begin{cases} \alpha R^{\beta} & \text{for } R < R_u \\ 0 & \text{for } R > R_u \end{cases}$$

where R is the magnetic rigidity, α the free space amplitude of the anisotropy and R_u the upper limiting rigidity for diurnal modulation.

The value of the exponent β has been found to be zero for the diurnal anisotropy by most previous workers. In the present work, five different values of β ranging from $-0{\cdot}2$ to $+0{\cdot}2$ have been tried and within statistical uncertainty $\beta = 0$ is found to give the best fit.

The free space anisotropy α, which should be the same for all detectors, can be calculated from the observed diurnal variation in any detector (Rao *et al* 1963) using appropriate variational coefficients. The coefficients for some neutron monitors have been calculated by McCracken *et al* (1965) assuming a fixed upper cut-off of 500 GV. Mori (1968) has also determined variational coefficients for mesons as well as neutrons for different upper cut-off rigidities. His values are consistently lower than those of McCracken *et al.* This difference may have been caused by their slightly different normalizations. The variational coefficients used in the present work recalculated for each detector, following Rao *et al* (1963), using the appropriate vertical threshold rigidity for the stations and varying the values of R_u, the upper cut-off rigidity. The neutron monitor coupling coefficients were taken from Lockwood and Webber (1967) and for muons from Cooke and Fenton (1971). For Kula (altitude 1000 m) the high altitude curve of Lockwood *et al* was used. The normalization in the calculations was made by assuming that the isotropic intensity spectrum extends up to infinity instead of 500 GV (Rao *et al* 1963).

It is well known that the lower energy part of the cosmic ray spectrum changes considerably from solar minimum to solar maximum and to allow for this a modified form of the coupling coefficient curve was used for the neutron data from 1967 to 1971, although the final calculated values of R_u were found to be insensitive to this modification. For the period 1965–1971 the calculated values of α for each detector for varying values of R_u were plotted for each year. The results for 1966 are shown in figure 1. Ideally, all the curves should intersect at a single point corresponding to identical values of R_u and α for the year. The value of R_u and the corresponding α, which showed the least scatter, was taken as the best estimate.

The calculated values of R_u and α are given in table 1. The uncertainties represent the upper and lower limit of the cut-off values derived from graphs such as figure 1, and are determined by the way the curves intersect. The values of R_u are also shown graphically in figure 2 with the results of other workers.

The upper limit of the rigidity of the cosmic ray particles undergoing diurnal modulation, as determined from neutron monitor data during the present solar cycle, shows a variation with time which corroborates the results obtained from muon data only. The observations show that the cut-off rigidity undergoes a significant variation through the solar cycle and is loosely connected with the gross changes in the solar activity shown for example by the sunspot numbers.

In the present work as well as in the work of the other observers (Ahluwalia 1971, Speller 1972) the observations show that the cut-off rigidity increases from a low value (30–55 GV) in 1965 to a value of 125–140 GV in 1969–1970. The value of R_u

then drops to about 90 GV in 1971. This agrees well with the general form of the variation of the total cosmic ray intensity. The value of α remains constant within statistical error at $0{\cdot}412 \pm 0{\cdot}013$.

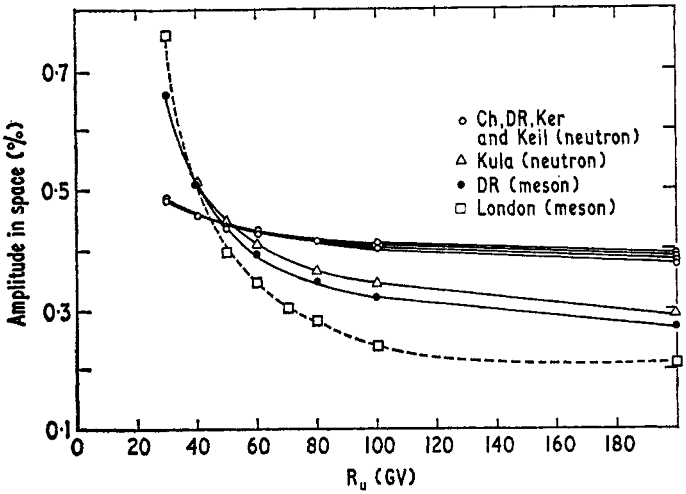

Figure 1. The 1966 free space amplitude of the diurnal variation against the upper limiting rigidity (R_u) of particles which undergo diurnal modulation for neutron monitors at Churchill (Ch), Deep River (DR), Keil, Kerguelen (Ker) and Kula, and for meson telescopes at Deep River and London.

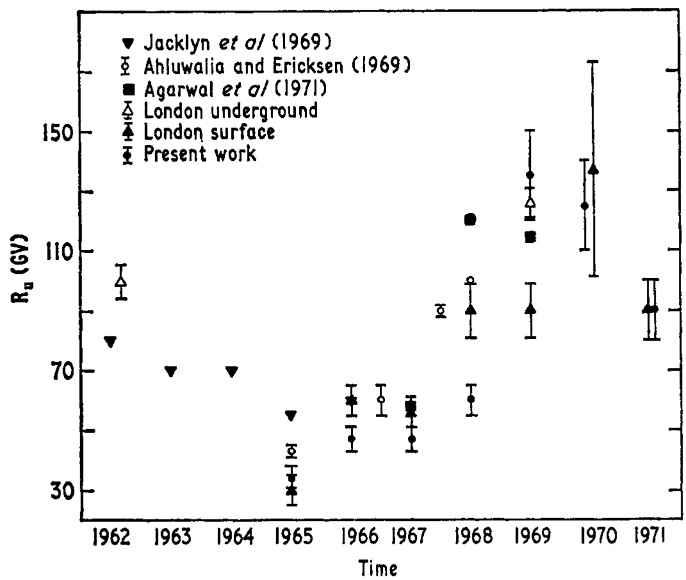

Figure 2. The upper limiting rigidity (R_u) of particles which undergo diurnal modulation for the period 1962–1971.

The mechanism which controls the limiting rigidity in diurnal modulation is not yet understood. The variation of R_u with the solar cycle leads us to examine the various parameters most likely to change with solar activity, eg solar wind velocity and density,

Table 1. The calculated values of the upper limiting rigidity for diurnal modulation (R_u) and the free space amplitude of the anisotropy (α).

Year	R_u (GV)	α
1965	34±5	0·37±0·03
1966	45±5	0·44±0·03
1967	47±7	0·43±0·05
1968	60±5	0·46±0·06
1969	135±15	0·38±0·07
1970	125±15	0·43±0·06
1971	90±10	0·42±0·05

the energy density of the interplanetary magnetic field irregularities etc. However, these show no systematic variations during the solar cycle (Gosling *et al* 1971, Mathews *et al* 1971).

For the co-rotation of the cosmic ray particles to be most effective it is necessary for the particles to gyrate in an interplanetary magnetic field which maintains the same direction over a complete orbit. However the direction of the field is determined by the sector structure which has been shown to vary with time. The sectors are narrow in 1965–1966 (which may reduce the limiting energy of the particles which co-rotate) and wider in 1967–1968 (Wilcox and Colburn 1970, Iucci and Storini 1973, private communication). In addition to the variation in width of the magnetic sectors, the strength of the field itself has been observed to vary with time, increasing with solar activity (Iucci and Storini 1973, private communication). This also will contribute towards increase of R_u with solar activity.

Iucci and Storini estimate that these two effects together may be expected to increase the upper cut-off rigidity by a factor of about 3 from 1965 to 1968. This is to be compared with the observed change, a factor of about 2, reported here for the same period.

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