

Variations of Upper Cut-off Rigidity Of Cosmic Ray Diurnal Anisotropy

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Abstract: Using the experimental data of the high counting rate neutron monitor, the solar diurnal anisotropy of galactic cosmic rays has been investigated for the period 1986-2006. The most probable value of the upper cut-off rigidity of the diurnal variation shows a 22- years magnetic cycle variations with the lowest value at the sunspot minima of A>0 phase. Upper cut-off rigidity in solar cycle 22 and 23 is found to vary between 40 GV to about 100 GV. This is derived by using the minimum variance analysis between a few high and low latitude stations by including the set of variation coefficients. The derived amplitude of the diurnal anisotropy (in space) varies with a period of one solar activity (11-year cycle), whereas, the phase of the diurnal anisotropy displays an obvious 22-year magnetic cycle.

Keywords: Cosmic ray, Diurnal variation, Solar cycle, Solar magnetic cycle, Cut-off rigidity.

I. INTRODUCTION

The spatial anisotropy of the galactic cosmic radiation in the interplanetary medium is observed as the daily variation of cosmic ray intensity by the ground based detectors. The detector on earth scans the entire celestial sky during a period of 24 hours since the earth completes one revolution around its own axis once in 24 hours (a solar day). Many scientists (including Brunberg and Dattner, 1954), using the ground based detector system, have observed excess of particles arriving from the asymptotic direction 1800 hours local time. The amplitudes and phases of the harmonic components are generally derived by Fourier analysis using the hourly counts (Chapman and Bartels, 1940). A large difference in either the amplitude or the time of maximum between different stations shows that either the anisotropy is changing within 24 hours or the universal time effects are predominant.

At earth, the neutron monitors respond to an energy range from ≈ 1.5 GeV to a few hundreds of GeV. The existence of I, II and III harmonics of daily variations of cosmic rays have already been confirmed by various investigators. Their characteristics have been investigated by various workers both on theoretical as well as on experimental basis. A number of reviewers (Sarabhai and Nerurker, 1956; Dorman, 1957; Pomerantz and Duggal, 1971; Rao et al., 1971; Agrawal et al., 1981; Venkatesan and Badruddin, 1990) have dealt with this topic of the cosmic ray variation in detail. Initial theoretical ideas have been reviewed Parker (1958, 1963, 1967, 2001) in great details.

This means that in the vicinity of Sun, the particles corrotate with the Sun, thereby higher cosmic ray intensity is observed from a direction opposite to earth's orbital motion. Based on the concept of continuous emission of the solar wind and stretching with it the smooth IMF, Ahluwalia and Dessler (1962), proposed a model which could partially explain the average behaviour of diurnal variation. According to this model, whose mathematical formulation has been given, the cosmic ray particles, drift due to the electric field E ($E = V \times B$). The model predicts that, the source of the diurnal variation which is in the ecliptic plane is energy independent ($\beta = 0$). All particles, whose rigidity is below an upper cut off

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rigidity ($R_{\max} \approx 100$ GV), undergo complete co- rotation. The direction of anisotropy is perpendicular to the IMF direction. The amplitude of the anisotropy is proportional to the solar wind velocity.

II. DATA ANALYSIS

The available hourly pressure corrected neutron monitor data of Kiel, Moscow, Climax, Deep River, Tokyo, Haleakala and Huancayo with different cut-off rigidities obtained from websites ftp://ftp.ngdc.noaa.gov/stp/solar_data/cosmic_ray, have been subjected to harmonic analysis to derive the diurnal amplitude (in %) and diurnal phase (in hours), for an overall period of 21 years, during the years 1986-2006 and convert in space by using coupling fraction. These neutron monitor stations are so selected that they cover the major part of the earth's location. Certain days associated with universal time changes, such as Forbush decreases and large cosmic ray transient intensity variations are removed from the basic data, before calculating the average amplitude and phase for each year data and for each station. In general, the one sigma standard error of the mean for each annual average diurnal vector is $\approx 6\%$ of the amplitude value and hence most of the variations shown subsequently in various figures are significant.

III. DISCUSSION AND RESULTS

The cosmic- ray diurnal anisotropy vector (Amplitude and Phase) in free space (interplanetary space) can be estimated by calculating the observed diurnal vector at a certain location and then using the coupling fraction (CF) which couple the primary variational spectrum with the observed diurnal vector and also by assuming an upper limit of the rigidity above which the primary spectrum is not modulated (Dorman, 1974). **The upper limit of the rigidity (R_{\max}) is known as the upper cut-off rigidity.** Primary cosmic rays in free space, near Earth's orbit, are distributed anisotropically; there being a slight excess flux ($\sim 0.5\%$) from the local dusk (18 hour) direction. For a detector on the rotating Earth, this net flux from a single direction in space shows up as a sinusoidal diurnal variation in its hourly counting rate. The excess flux generates an energy- independent anisotropic flow from the 18-hr co-rotation direction with amplitude in space of $\approx 0.6\%$ (Pomerantz and Duggal, 1971; Rao, 1972). Nevertheless, an energy- dependent phase shift to the early hours in the diurnal time of maximum of the cosmic ray intensity has been reported since 1971 (Agrawal and Ananth, 1973). Many investigators including Ahluwalia and Riker (1987), have described how the amplitude (and phase) of the anisotropy vector (in space) can be derived from the observed diurnal variation amplitude (and phase) obtained for a given detector.

The effect of the geomagnetic field on the daily variation of cosmic rays has been found that the observed diurnal variation is dependent on the location of the neutron monitoring stations. As such, the observed values of the diurnal amplitude and phase differ very significantly from one station to other, even though, they are situated in the same latitude/longitude belt. Since the value of the rigidity spectral exponent (β) of the diurnal anisotropy has been quite often reported to be usually zero with maximum variability from -0.2 to $+0.2$, hence we have also assumed that the value of β , for the recent period also is not very different from that reported earlier (i.e. zero). Nevertheless, the value of R_{\max} has been shown to vary quite significantly during the period of eleven year solar cycle, with minimum R_{\max} during the minimum solar activity period (Ahluwalia and Sabbah, 1993 and references therein).

The limits of the upper cut-off rigidity (R_{\max}) variation have been reported from about 50 GV to about ~ 200 GV in different solar cycles (Sabbah, 1999; Ahluwalia, 2000). The variation of R_{\max} for the solar cycles 22 and 23 has been derived here by using the annual average values presented earlier. Using the expected combination of the results derived for the diurnal amplitude and phase for different stations, Yasue et. al., (1982) have given the expected fractional amplitude and geomagnetic bending for the values of $R_{\max} = 30, 50, 100, 200, 500,$ and 1000 GV. Using these values we have interpolated the values for many intermediate R_{\max} , such as 40, 60, 80, 120, 150 and 180, GV.

For all the above values of R_{\max} , the space values of diurnal anisotropy have been calculated for each year from 1986 to 2006 (solar cycle 22 and 23) by using the observed annual average diurnal variation for the stations Kiel, Moscow, Deep River, Climax, Tokyo, Huancayo, and Haleakala. The calculated values of the variance, obtained for each year (separately for amplitude and phase) have been obtained for each R_{\max} from the tabulated values. Many a times, the

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variance is too large for all R_{\max} because of one of the stations behaving erratically for both amplitude as well as phase. A critical examination of all the variances for all the years have shown that the space vectors of the diurnal anisotropy for the following stations and year should be excluded for the year while calculating the variance for the different values of R_{\max} : Huancayo (1986,1987,1991), Tokyo (1995, 1996), Haleakala (1991). It is noted that quite often only one low latitude station is included for the determination of the variance and the cut-off rigidity for the low latitude station is only ~ 13 GV. Hence the determination of the value of R_{\max} will be subjective because no neutron monitor is presently operating at cut-off rigidity >13 GV. Thus for each year, and for each R_{\max} , the calculated variance (with necessary exclusion of the station) has been plotted in figures 1 & figure 2, for solar cycle 22 and 23 respectively. The X-axis takes the value of R_{\max} , whereas, the Y-axis shows the variance separately for each year in these two figures. The best estimate of the minimum value of the variance for each year is shown by dashed vertical lines. The best estimate values of R_{\max} for which the variance is minimum is then used to calculate the average values of the diurnal anisotropy (in space), both for the case of diurnal amplitude and phase, for all the years in solar cycles 22 and 23. Thus the most probable values of the diurnal amplitude as well as the diurnal phase (in space) for all the years from 1986 to 2006, has been derived. These values are depicted in figure 3.

In the upper part of the diagram (3a), we have plotted the estimated (or most probable) values of the upper cut-off rigidity (R_{\max}), which is seen to vary from ≈ 40 GV to ≈ 100 GV. The figure very clearly demonstrates that the R_{\max} has a 22 year periodicity with minimum value in year 1996 (also in the adjoining years). In all other years, value of R_{\max} varies between 80 to 100 GV, which can not be taken to be very significant, because of the limited availability of only one or two low latitude neutron monitor stations data, that too with cut-off rigidity of only ~ 13 GV. The use of meson data (ground based and under ground) can help in this regard to better distinguish the value of R_{\max} . However, the meson data is usually affected by the atmospheric temperature variation and hence there again reliability could be questionable. In figure 3(b), we have plotted the values of the derived diurnal vectors (amplitude and phase in space) for the 1986-2006 period. The figure demonstrates that the amplitude (in space) of the cosmic ray diurnal anisotropy varies with a period of one solar activity (11-year) cycle, while the time of maximum (phase in space) of the diurnal anisotropy varies with a period of one solar magnetic cycle (22-year). From figure 3b, it is also evident that the maximum values of the diurnal amplitude is ~ 0.5 to 0.6% , where as the minimum value is $\approx 0.2\%$ (1996). Moreover, the diurnal phase is ~ 18 hour, except for the period from 1992 to 1999 where it is <17 hour, with minimum value < 15 hour in 1997. The theoretical models predict the diurnal amplitude in space $\sim 0.6\%$ with diurnal phase ~ 18 hour. As such, after every 11 - year there is anomalous decrease in the diurnal amplitude and also anomalous decrease in diurnal phase after every 22- years.

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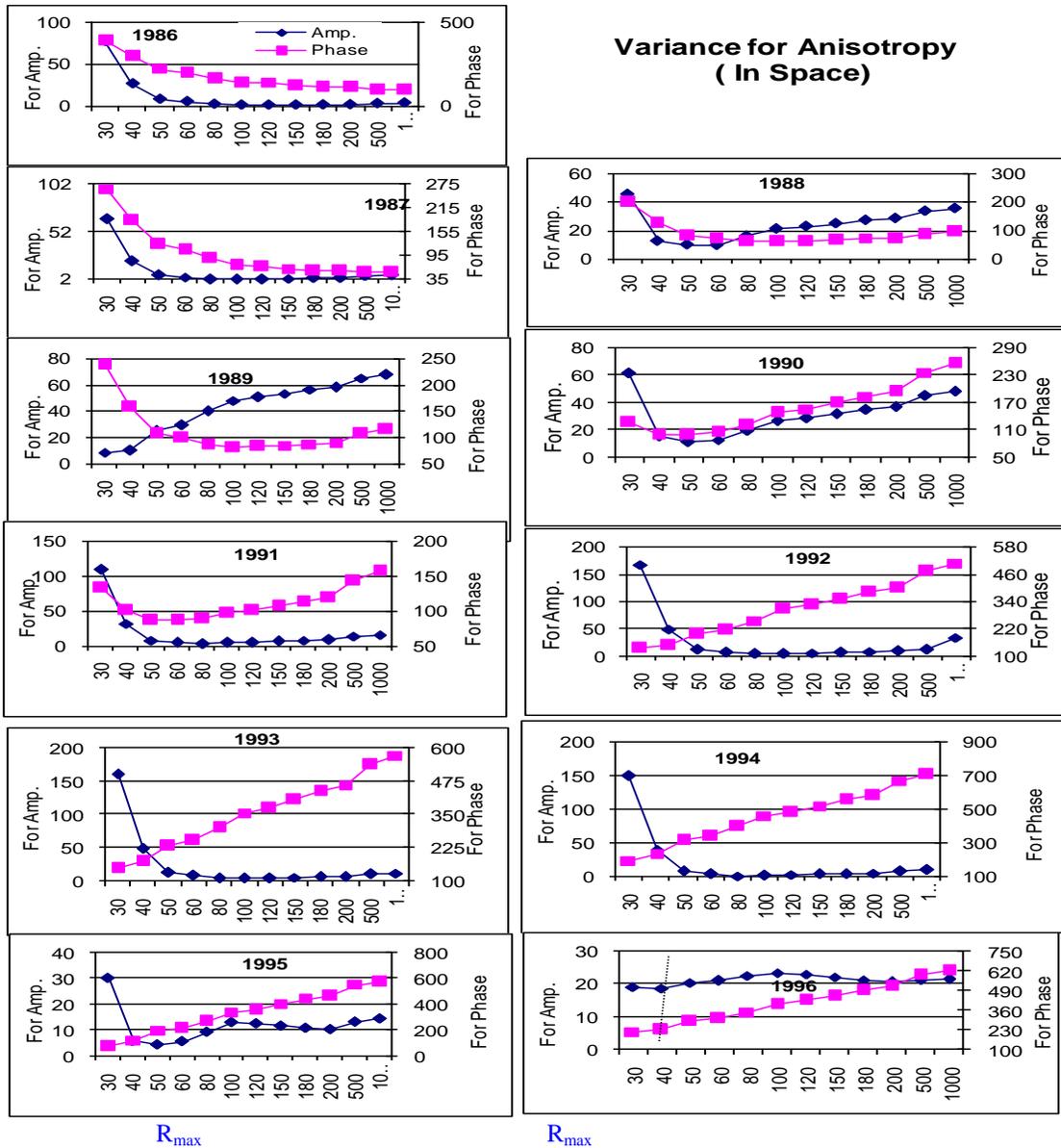


Figure 1: Shows in the linear plot, variance for diurnal anisotropy amplitude and phase (in space) with different upper cut-off rigidity, for the years 1986- 1996 (solar cycle 22).

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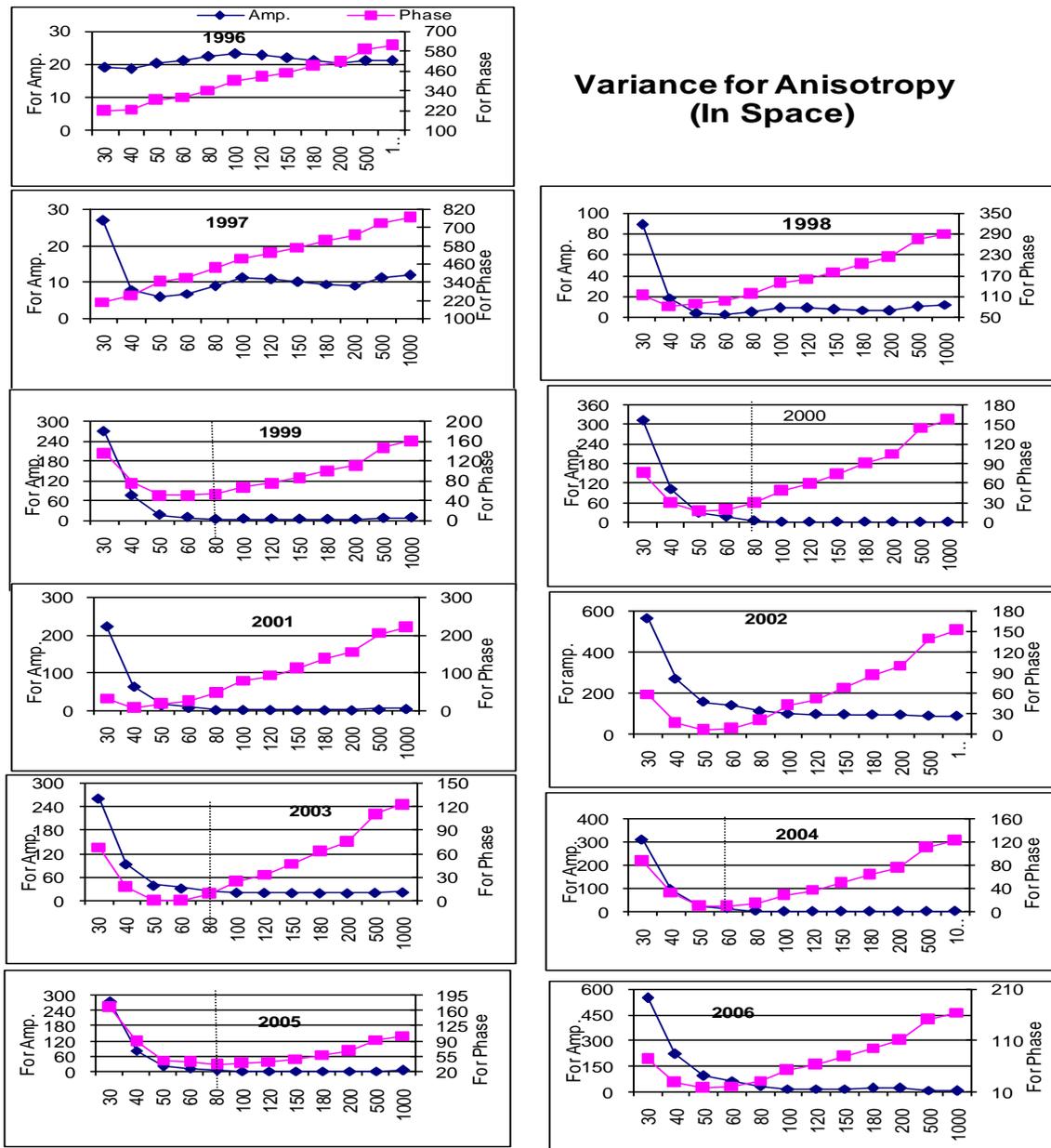


Figure 2: Shows in the linear plot, variance for diurnal anisotropy amplitude and phase (in space) with different upper cut-off rigidity, for the years 1996- 2006 (solar cycle 22).

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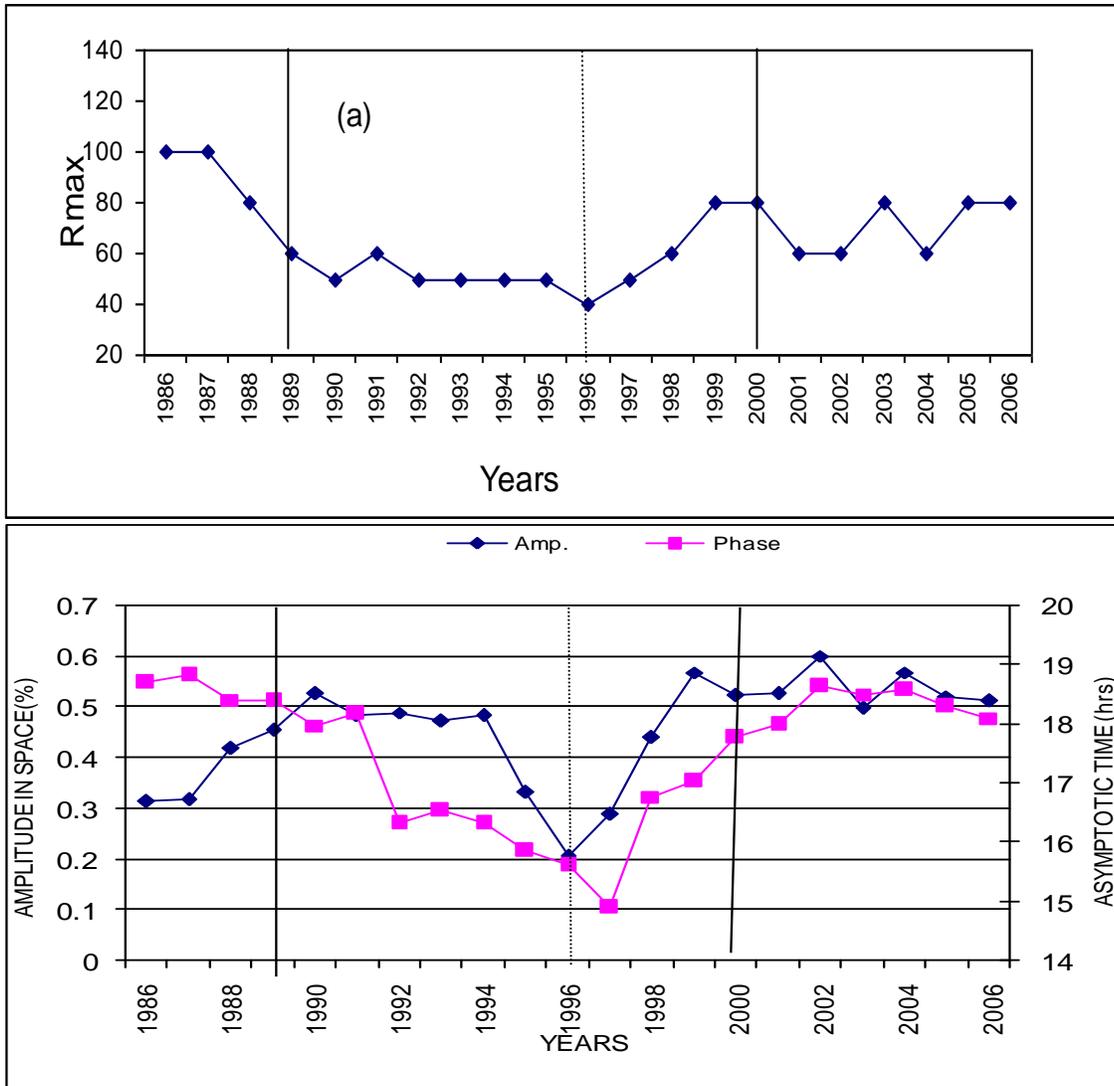


Figure 3:(a)Shows the most probable values of the upper cut- off rigidity (R_{max}), and (b) the amplitude and the phase of diurnal anisotropy(in space), during the period 1986-2006. The continuous vertical lines mark the year of maximum solar activity, whereas the dotted vertical line mark the year of minimum solar activity as well as the start of the new solar cycle

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IV. CONCLUSIONS

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

1. The most probable value of the upper cut-off rigidity of the diurnal variation shows a ~ 22- year magnetic cycle variation with the lowest values at the sunspot minima of A>0 phase. Upper cut-off rigidity in solar cycles 22 & 23 is found to vary between 40 GV to about 100 GV. This is derived by using the minimum variance analysis between a few high and low latitude stations by including the set of variational coefficients.
2. The derived amplitude of the diurnal anisotropy (in space) varies with a period of one solar activity (11-year) cycle, whereas, the phase of the diurnal anisotropy displays an obvious 22 year magnetic cycle.
3. The years of maximum and minimum values from the yearly average diurnal amplitudes (in space) and diurnal phase (in space) have been observed as under:
 - (i) Maximum diurnal vector amplitude (1999) 0.545 % (16.8 hrs.)
 - (ii) Minimum diurnal vector amplitude (1996) 0.228% (15.8hrs.)
 - (iii) Maximum diurnal vector phase (1987) 18.8hrs. (0.31%)
 - (iv) Minimum diurnal vector phase (1997) 14.9hrs. (0.289%).

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