Kodaikanal Obs. Bull. (1986) 6

SOLAR OPTICAL OBSERVATIONS FROM KODAIKANAL AND FROM ECLIPSES

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Abstract

From an analysis of a long series of Calcium K specroheliograms taken at Kodaikanal, systematic changes in the sizes of supergranule cells have been found. The average cell size changes with the phase of solar cycle, being smaller at the maximum. Power spectral analysis of calcium plage areas indicates that chromospheric rotation rate at a fixed latitude varies over time scales ranging from the solar activity cycle down to about 2 years. The variation is of the order of 10% and is not correlated in different hemispheres.

The results of high resolution spectroscopy of the solar corona using multislit spectrograph at the total solar eclipses of 1980 and 1983 are also discussed. The line width measurements indicate that the turbulence might be a function of solar activity, being higher when the sun is more active. The line-of-sight velocities measurements show that there are no large scale localized differential mass motions in the corona and the solar corona co-rotates with the photospheric layers deeper down.

1. Introduction

The optical observations of the sun at Kodaikanal started as early as 1900 when a 6 inch Cooke telescope of 7 feet focal length was used for the visual study of sunspots. Image of the sun was projected on a graduated disc of 8 inch diameter and the position of spots marked on it (Kodaikanal Annual Report 1901). The heliographic latitudes and longitudes of spots were subsequently derived from these positions. The sunspots have been used to derive the rotation rate and differential rotation of the sun.

Apart from sunspots, there are other tracers of the solar cycle, for example, H-alpha activity, calcium K activity, magnetic field, and shape of solar corona. Since 1904 spectroheliograms light calcium K have been obtained using 60 mm image of the sun. (The sun as a star, i.e. in integrated $Ca^{+}K$ light, has been monitored since 1969). The spectroheliograms show a coarse network, calcium plages, and tiny bright points of about one arcsec size. Studies of this coarse network and its association with supergranulation, magnetic field, velocity fields etc. were made by Simon and Leighton (1964), who established a correspondence between supergranulation and bright emission network seen in calcium K spectroheliograms. The supergranules are of various sizes and shapes and have an average diameter of 32000 km and an average life time of 20 hours. The motion within each cell is mainly horizontal, proceeding from the centre toward the outer boundary with a velocity of 0.3-0.5 kms^{-1}. From the properties of these cells and their association with other solar phenomena Simon and Leighton (1964) concluded that supergranules are non-stationary convection currents originating perhaps at a quite deep level inside the convective envelope. We have tried to determine the sizes of these chromospheric network cells and their possible dependence on solar cycle.

2. Sizes of supergranulation

The supergranular area measurements were made for seven solar cycles starting from 1907 (Singh and Bappu 1981). The distribution of the cell sizes for each maximum and minimum is evaluated separately by fitting a normal distribution curve (Figure 1). The peak of the Gaussian gives a value of the area, from which a 'size' is taken as the diameter of a circle of equivalent area. These values represent the area of the the centre line of the emission boundary.

We have also measured the cell sizes, by auto-correlation method, on seven spectroheliograms representing solar minimum (Singh and Bappu, 1981). The mean value of the cell size determined this way is 32000 km, which agrees with the values similarly obtained by Rogerson (1955) and Simon and Leighton (1964) but is larger than the mean value (23000 km) derived from graphical procedure. It is as it should be. In the latter procedure, the peak of the emission intensity is taken to be the boundary of the cell. On the other hand autocorrelation technique involves a superposition of edges; the size value inevitably contains an additional length caused by the width of the cell boundary.

The width of the cell boundary was evaluated for the solar maximum and minimum. The mean values of FWHM derived from intensity tracings of the boundaries are in both cases 5700 ± 200 km. There is, thus no dependence of cell boundary width on solar cycle. If this additional width were to be added to the value of cell sizes derived from the areas one would obtain a mean size of 28700 km which is still short of the value derived from autocorrelation curves. The incompletely formed cells are likely to affect the autocorrelation curve values. Later Brune and Wohl (1982) and Kuveler (1983) from the measurements of velocity fields of individual supergranules have shown that mean area of the supergranule is 5.2×10^{14} m^2, i.e. a diameter of 26000 km, which agrees with our value.

A plot of the cell sizes against sunspot number is shown in Figure 2. The cell sizes derived near the minimum phase do indicate a scatter but are systematically larger than those computed near the maximum phase. A linear fit to the data gives an inverse correlation between cell size and the sunspot number; the value of correlation coefficient is 0.861.

From an analysis of excellent pictures of the sun in broadband light Muller and Roudier (1984) and Keil (1985) find that the mean size of the granulation is smaller at the maximum phase than that at the minimum phase. Therefore, one can conclude that remnant magnetic fields play a role in the formation of convective cells. The changes observed in the size of the cells, following Chandrasekhar's (1955) limit, require about 15% changes in the magnetic fields, which are quite common during the two phases of the solar cycle.

3. Variation of Solar Rotation Rate

The calcium plage area measurements have been used to derive the solar rotation rate and its possible variation with time. Various techniques have been used to investigate the variation of rotation rate with time, e.g. (i) Spectroscopic measurements, (ii) rotation rate from sunspots, and (iii) rotation from calcium plage area.

Howard and Harvey (1970), Howard (1976), Belvedere et al. (1977), and Livingston and and Duvall (1979) have used spectroscopic data, while Neidig (1980) and few others have derived the rotation rate from sunspots. Howard and Harvey (1970) have indicated that rotation rates determined from sunspots may be uncertain because of difficulty in locating the same point from one time to the next. Howard et al. (1984) have developed a technique to determine the centre of a spot by fitting simple geometrical shapes to the sunspots but the method is still not free from uncertainties. Also recent measurements of individual sunspots have indicated that larger spots show slower rotation rate than the smaller ones (Howard et al. 1984). Power spectral analysis (cf. Knight et al. 1979; Bogard 1982) circumvents this problem. However, the results obtained from sunspot numbers may be affected by the differences between the rotation of different spot groups.

Stimets and Londono (1982) and Keil and Worden (1984) have done power spectral analysis of calcium K-index to compute the rotation rate of the sun.

Many years ago Hale (1908) showed that chromospheric features like calcium plages have rotation rate similar to the sunspots. Belvedere et al. (1977) concluded that large calcium K faculae rotate rigidly with the photosphere. Bappu and Sivaraman (1971) have shown that the time variation of total plage area on the visible disc of the sun has the definite signature of rotation. A Fourier analysis of calcium K plage area as a function of time of Singh and Prabhu (1985) has given a reasonably accurate rotation rate. We have used calcium K plage data over the entire visible disc for the period 1951-1981 to derive the rotation rate. If a day was cloudy, we took the mean of adjacent days for which data were available so as to form continuous data string. Raw power spectra were obtained for data strings of 512 days with a lag of 64 days in the successive data strings. Thus the data for 384 days are common to successive intervals. This was done to ensure continuous information about the chromospheric rotation period. A typical power spectra (Figure 3) of 512 days data show a conspicuous peak around 27 days (synodic). This is the most dominant peak and represents the solar rotation rate. A section of the data (1024 days) was analysed using different lags of 16, 19 and 24 days and computed rotation rates are plotted in Figure 4. It is evident that the adopted value of lag has no effect on the results obtained. The slow and steady changes in the rotation rate for lags of 16 and 19 days affirmed our faith in the reality of observed variation in the rotation period.

In order to understand the phenomenon better, we have analysed the data grouped into different latitude belts, considering only the 10°-15° and 15°-20° belts in both the north and south hemispheres where plages are seen almost throughout the solar cycle. The derived rotation periods as a function of time are plotted in Figure 5 for various latitude belts. We add for comparison the periods obtained from total active area over the entire visible disc and also from sunspot numbers. The mean synodic rotation periods in days are 27.2 ± 1.6 (15°-20°N), 27.4 ± 1.5 (10°-15°N), 27.9 ± 1.9 (10°-15°S), 27.5 ± 1.8 (15°-20°S), 27.9 ± 1.7 (total active area) and 27.8 ± 1.7 (sunspot numbers). Converting the mean synodic period between 1966-78 to sidereal rate we obtain a mean rotation rate of 14.11° day^{-1} from 10°-20°N and S belts, and 13.94° day^{-1} from integrated areas. These values may be compared with the mean chromospheric rotation rate of 14.39° day^{-1} derived by Livingston and Duvall (1979) for the same period but between latitude ±20°, i.e., including the equatorial belt. From Figure 5, it is obvious that the rotation period changes with time quasi-periodically. To estimate the periodicities of variation in rotation period, we carried out a further power spectral analysis of these periods for each latitude belt as well as for the total active area and for sunspot numbers. The power spectra of these show the multiplicity of the periodicities in the range 1-22 years. The time scales around 2, 7 and 11 years appear most frequently.

With a view to determining if these changes are global or localized, we have computed correlation coefficients between the rotation period data for various belts. The correlation coefficients for 10°-15°N with 15°-20°N, and 10°-15°S with 15°-20°S belts are 0.576 and 0.605 respectively. For these values (n=170), the confidence level is better than 99%. We have also computed the cross-correlation function (Figure 6) which, for adjacent latitude belts, decreases with increasing phase lag. The secondary maximum around the 2 years phase lag in the cross-correlation function shows a good degree of coherence. On the other hand, the correlation coefficients between northern and southern latitude belts are much smaller (~0.1). This indicates that the changes in rotation occur on a latitude belt of width $\lesssim$10°, but the variations are not in a phase on a global scale. There is no north-south symmetry.

Three major conclusions appear from the above analysis:

(i) The calcium plage area provides an effective tool for deriving solar rotation rate.

(ii) The chromospheric rotation rate varies not only with solar activity cycle, but also on shorter time sclaes of the order of 2 and 7 years.

(iii) The rotation rate varies in phase over a fairly wide belt in latitude ($\gtrsim 10^{\circ}$ in width), but not on a global scale.

Howard and LaBonte (1980) have detected torsional oscillations on the sun with a period of 11 years. The wave-pattern of oscillations, which is symmetric about the equator, consists of four alternating zones of fast and slow rotation over each hemisphere. The whole pattern propagates from poles to equator with a time scale of about 22 years. The quasi-periodicities detected by us, however, do not appear to have a global pattern. The variation in rotational velocity can easily be induced by torsional oscillations on the sun (LaBonte and Howard 1982).

It will be interesting to compare the quasi-periodicities detected by us with the periodicities in other kinds of solar phenomena. Its existence in sunspot numbers was detected by Shapiro and Ward (1962). Sakurai (1979) found that the solar nuetrino flux for the period 1970-75 showed a periodicity of ~2.1 years and also correlated well with sunspot numbers. On the basis of more extensive data (1970-81), Haubold and Gerth (1983) detected a range of periodicities (0.53, 0.73, 1.27, 1.63, 2.13, 2.98, 4.90 and 8.33 yr), the 2.1 yr periodicity being the prominent one. Similarly, λ 10 cm flux data for the period 1947-78 analysed by Hughes and Kesteven (1981) showed periodicities of 2.1 and 3.0 yr. It is surprising to find the 2 year time scale so common between totally different types of observations. A physical explanation connecting all these diverse phenomena will certainly be challenging.

4. High Resolution Spectroscopy of Solar Corona

Apart from observing sun at Kodaikanal, a number of expeditions were planned to observe the corona. At the 1970 Mexico expedition Bappu et al. (1972) were able to detect H alpha line in emission indicating the existence of low temperature regions in the solar corona. The knowledge of the temperature and velocity structure of the corona plays a significant role in understanding the coronal heating mechanism and dynamics of the solar corona. Therefore, high resolution coronal spectra were obtained in [Fe X] line using a multislit spectrograph at the 1980 eclipse (Singh et al. 1982; Singh 1985). The analysis of the spectra has shown that large number of locations have half widths around 1.3 A which corresponds to a temperature of 4.6×10^{6} K if this width is entirely due to thermal motions. But the computations by Jordan (1969) indicate an ionization temperature of 1.3×10^{6} K for Fe X ion. It therefore becomes inadmissible to accept the high values of temperature inferred from line widths. Introducing a turbulence parameter, an additional line-broadening agency, in the kinetic-temperature equation and assuming temperature of 1.3×10^{6} K for Fe X ions, one finds turbulent velocities of 30 kms^{-1} from the line width of 1.3 A. This value is in good accord with that derived by Delone and Makarova (1969, 1975), Mariska et al. (1978) and Cheng et al. (1979).

The line-of-sight velocities measured range between ±15 kms^{-1} and most of the locations have velocities less than ±5 kms^{-1}. These values agree well with the findings of Livingston and Harvey (1982). Therefore one may say that corona does not show any localised differential mass motion. The line-of-sight velocities grouped together on the eastern and western hemisphere indicate that the corona co-rotates with the photospheric layers.

The spectra obtained at this eclipse were indeed well exposed to give us reliable data on line and continuum intensities at large distances in the solar corona.

The behaviour of the line intensity and continuum intensity with radial distance indicates that for $R/R_{\odot} < 1.2$, mode of excitation of Fe X ions is more or less collisional; collisional as well as radiative excitation is equally important for $1.2 < R/R_{\odot} < 1.4$, and beyond $R/R_{\odot} = 1.4$ radiative excitation becomes more dominant (Singh 1985).

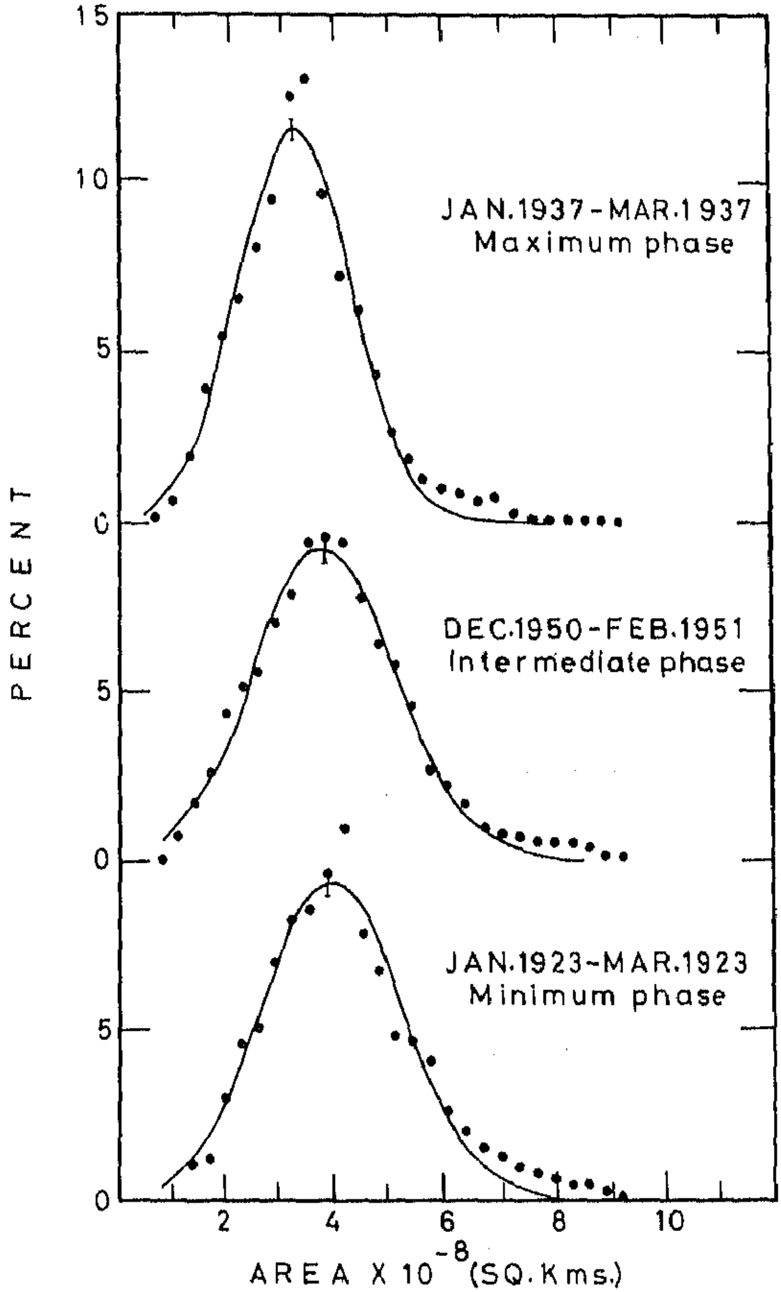

Fig.1. Frequency distribution of network area at solar maximum (1937), intermediate phase (1950-51) and solar minimum (1923). Curve drawn is the Gaussian fit to the frequency distribution.

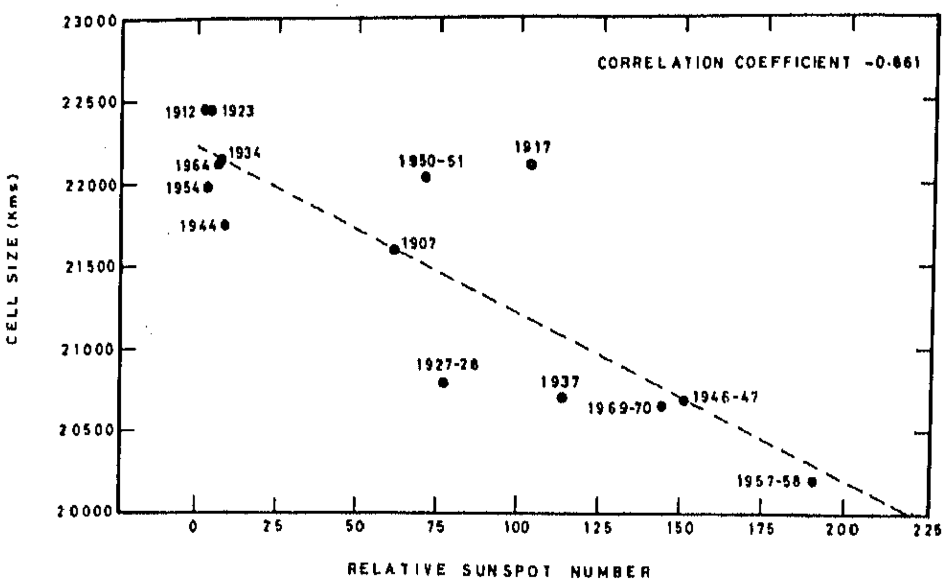

Fig.2. Variation of 'cell size' with sunspot number. The year sampled is marked against each point. A linear fit shows inverse correlation.

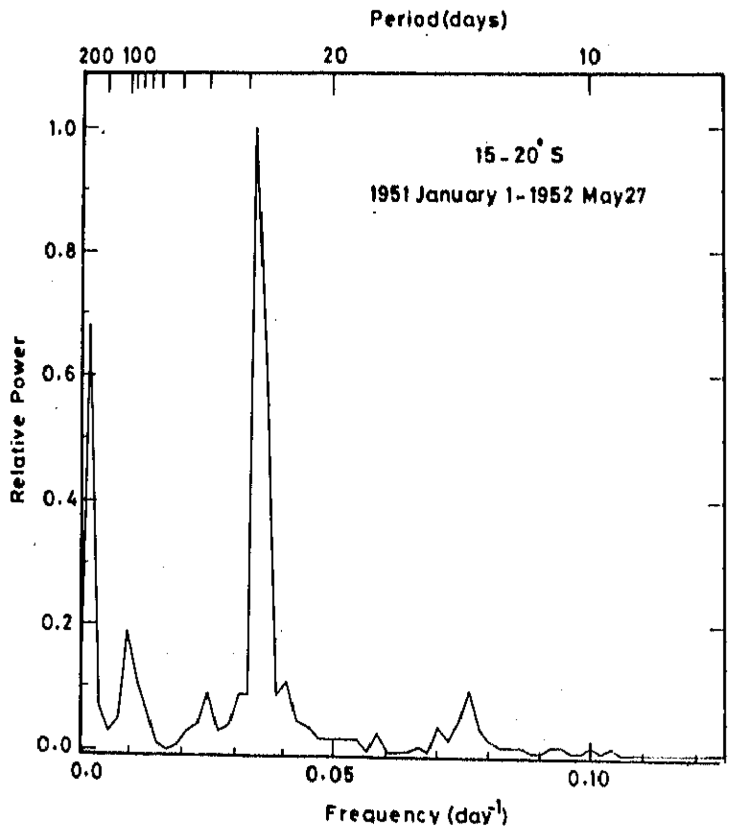

Fig.3. A typical raw power spectra of 512-day data showing clearly the rotation period.

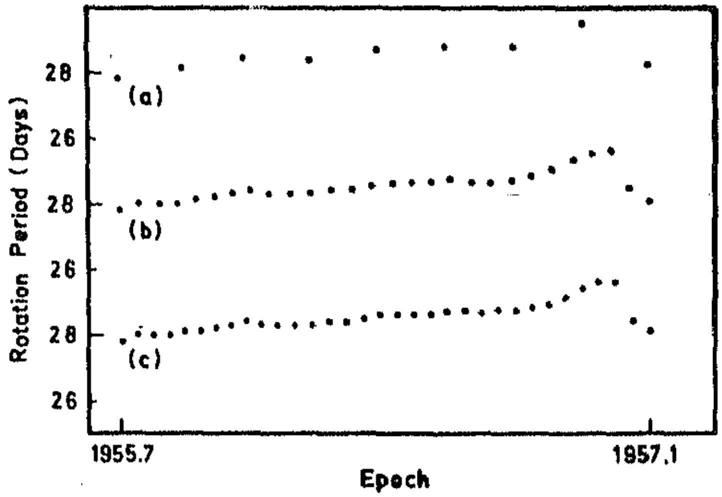

Fig.4. Rotation period (synodic) as a function of epoch is plotted with different phase lag. (a) of 64 days; (b) of 19 days; and (c) of 16 days.

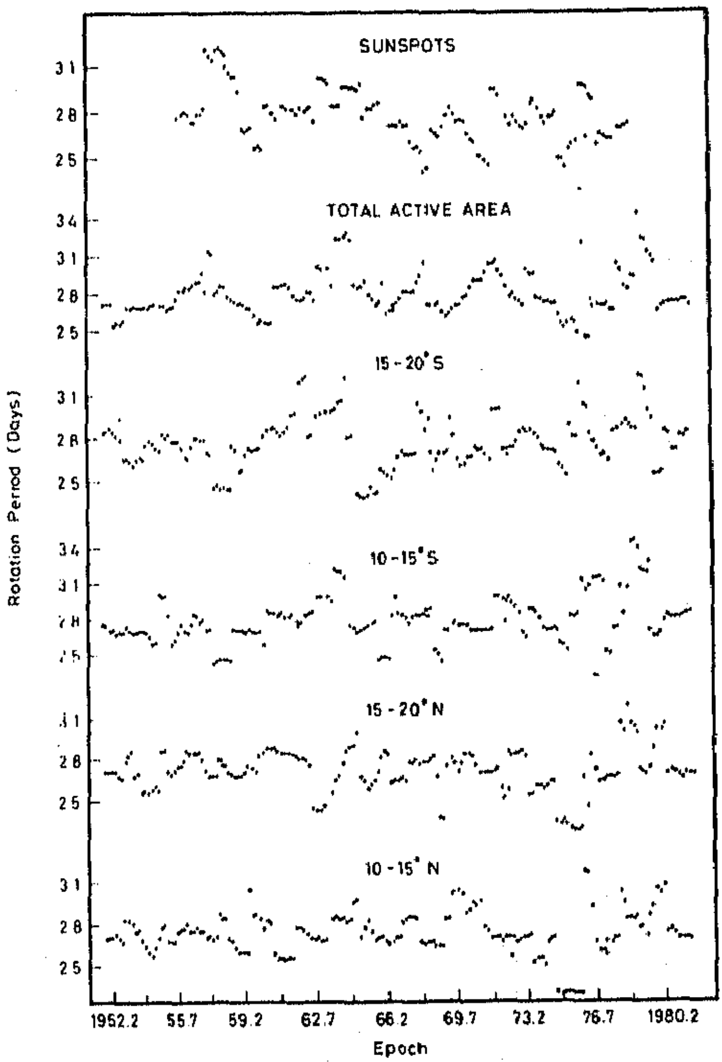

Fig.5. Variation of the (synodic) rotation period with time, derived from the sunspots, total active area, and active area at different latitude belts.

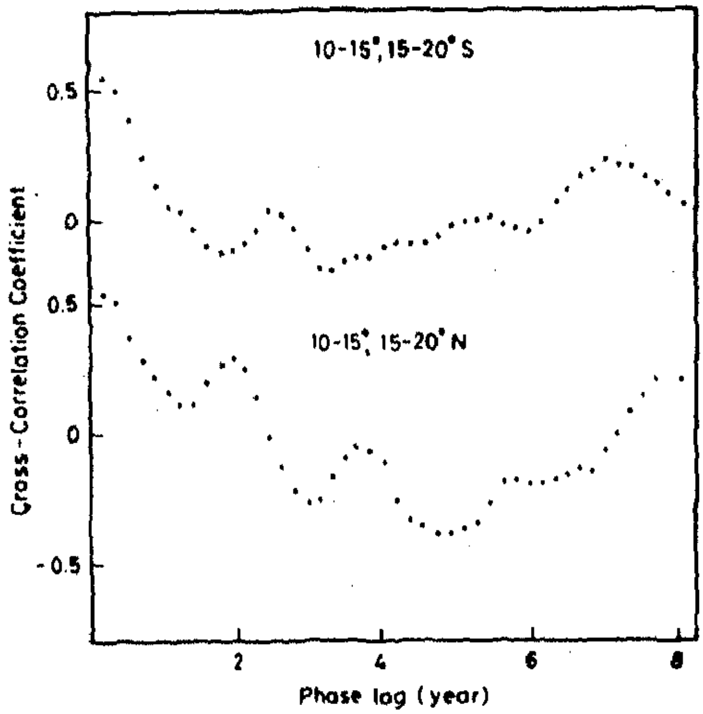

Fig.6. Cross-correlation coefficient at adjacent latitude belts.

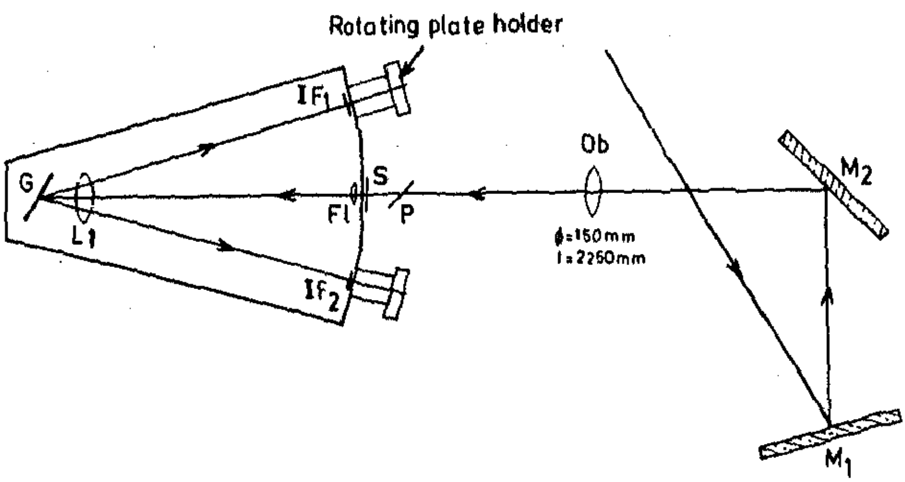

Fig.7. A schematic sketch of the experimental set up for observing 6374 Å and 5303 Å lines simultaneously. M_1 and M_2 are flat mirrors. Ob=Objective; P=pelicle beam splitter; S=multislit; Fl = field lens; L_1=Collimator; G=grating and IF_1 and IF_2=interference filters.

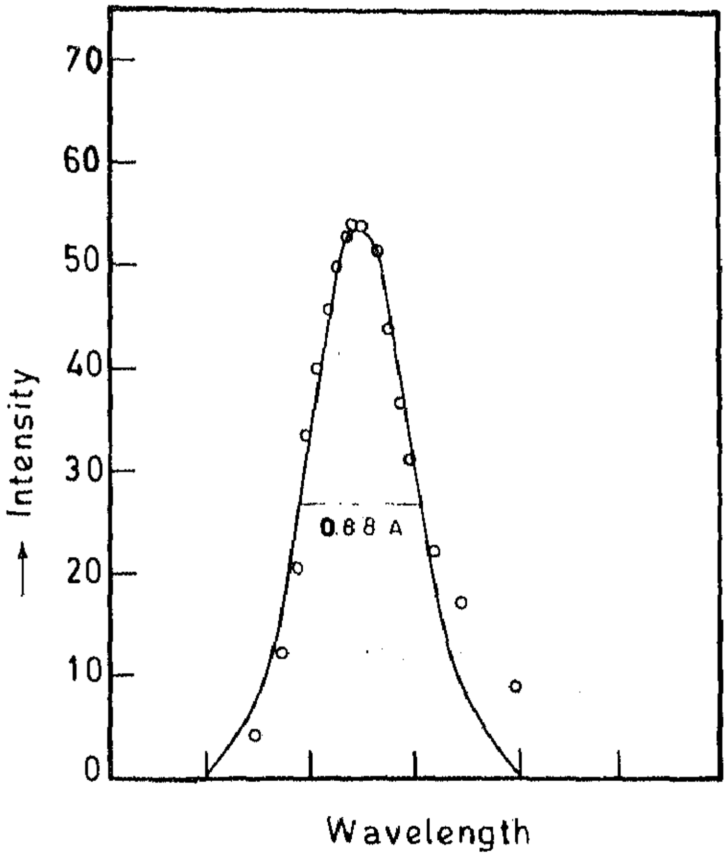

Fig.8. A typical observed line profile of 5303 Å line. Full line curve is the best Gaussian fit to these data points.

While doing the analysis of the spectra obtained at the 1980 eclipse, need was felt to collect the data on two emission lines simultaneously during an eclipse. The high resolution spectra of solar corona on two emission lines would enhance our knowledge manyfold about the dynamics and physical nature of the corona. With this aim we used the multislit technique to obtain the coronal spectra simultaneously in two lines 6374 A [Fe X] and 5303 A [Fe XIV] at the 1983 eclipse (Singh 1984). The experiment was set up at a site very close to the central path of totality, near Paciran in East Java. A schematic sketch of the epxerimental set up is shown in Figure 7. The coelostat and the spectrograph were adjusted so that the solar equator was approximately in a direction parallel to the length of the slits. The sky was covered with thin cirrus clouds during the phase of totality. Four spectra were obtained in each wavelength. Unfortunately the spectra, in 6374 A are underexposed and hence not very useful. Here we discuss the results of the analysis of 5303 A line spectra.

These spectra provide informatin mostly in the equatorial regions of the corona ranging from 1.04 to 1.24 $R_{\odot}$. One of the typical observed line profiles (open circles) and the best Gaussian fit to these data points (full line) are presented in Figure 8. The FWHM measured from free hand curves and the Gaussian curves agree with each other well. The line widths vary from 0.6 to 1.4 A with most frequent value of 0.9 A corresponding to a kinetic temperature of 3.1×10^6 K. Ionization equilibrium computations by Jordan (1969) show that Fe XIV ions are most abundant at the temperature of 2.3×10^6 K. Once again using similar arguments of maximum availability of Fe XIV ions at 2.3×10^6 K as done earlier for Fe X, one can infer a mean turbulence of about 16 $\mathrm{kms^{-1}}$. The fact that the corona was more active in 1980 than in 1983, coupled with the fact that the mean level of turbulence is correspondingly smaller in 1983, indicates the possibility of the variation of turbulence with activity of the sun.

Another multislit experiment was performed at the 1983 eclipse to sample the data only in 6374 A [Fe X] line on the polar regions of the solar corona. The aim was to determine the flow pattern near the poles. Spectra near the poles were too small in extent to permit a study of the flow pattern, and the spectra near the east and the west limb were not intense enough to permit an evaluation of the temperature structure. We could determine only the velocity structure and the coronal rotation from 6374 A emission line.

The wavelength of the red coronal line was derived at 57 locations, including 28 on the east limb and 25 on the west limb, ranging from 1.09 to 1.17 $R_{\odot}$. All the values of the wavelength were corrected for the rotational velocity of the sun and then used to derive the mean wavelength of the red line. The mean value turns out to be 6374.604 ±0.03 A, in good agreement with the value of 6374.596±0.02 A derived at the 1980 eclipse and with the value determined by Jefferies et al. (1971). The line of sight velocity measurements show that most of locations have velocities less than ±5 $\mathrm{kms^{-1}}$. This indicates that the corona is remarkably quiet confirming the findings of Livingston and Harvey (1982) and Singh et al. (1982).

The mean values of wavelength on the east and the west limb indicate that the solar corona co-rotates with the photospheric layers, thus confirming the results of the 1980 eclipse.

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