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# Polarization and electron densities in the solar corona of 1980 February 16

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**Abstract**. The analysis of the blue and red photographs of the solar corona of 1980 February 16 taken through a double polarigraph is presented. The degree of polarization and the angle of magnetic vector have been calculated at various points and contours plotted. The polarization is found to be mostly radial. High polarization (> 60%) was observed in some regions which exhibit high coronal activity. Electron densities have been determined from the measured intensities and polarization in the two colours and then used for separating the K and F coronas. The mean variation of the intensity of the K corona with distance from the limb has been found to be identical in both colours, whereas the F corona has turned out to be redder throughout. Average variation of temperature derived from the observed mean density gradiant agreed with Newkirk's model in the inner region.

*Key words* : solar corona—polarization—electron densities

## 1. Introduction

It has been known for a long time that the light of the solar corona is highly polarized due to Thompson scattering of the photospheric light by the free electrons present in the corona (Ney *et al.* 1961). This explanation led to the prediction that the direction of the *E* vector in the electromagnetic wave should be tangential and of the *H* vector radial; this is usually referred as 'radial polarization'. However if the observed polarization is due entirely to Thompson scattering by free electrons the polarization should continue to increase at larger distances from the sun and approach some relatively high value. But contrary to theoretical expectations it was observed that the polarization of the corona reached a maximum value of about 40% at $r = 1.5R_\odot$, and decreased beyond that distance. The dilution of polarization was explained by Grotrian (1934), Allen (1947), Ohman (1947), and van de Hulst (1947) as due to the presence of another unpolarized component known as F corona to distinguish it from the electron or K corona. The F component is produced by the scattering of sunlight by the interplanetary particles. The polarization property of the corona is very useful in separating the K and F components and to determine the electron densities in the corona.

We report here our study of the polarization and electron densities in the corona observed during the total solar eclipse of 1980 February 16 at Japal-Rangapur observatory.

## 2. Observations and reduction

The double polarigraph used has been described by Anthony Raju (1981); with it the corona was photographed directly and also through three polaroids at two wavelengths, blue (λ 4200 Å) and red (λ 7000 Å), simultaneously. The polaroids were arranged such that their axes were oriented at 120° with each other. Since the measurement of polarization involves the determination of intensities of the same point of the corona in all photographs they were developed under identical conditions. The method of calibration to get absolute intensities and of scanning the photographs has been described by Anthony Raju & Abhyankar (1982).

Now by definition the degree of polarization is given by $P = (I_t - I_r)/(I_t + I_r)$ where $I_t$ and $I_r$ are the intensities of the tangential and radial components, respectively. Denoting the position angles of the plane of vibration by $\alpha$ and the three measured intensities by $a$, $b$, and $c$ for the three polaroids we can write (Fesenkov 1935; von Kluber 1958) :

$$a = I_t \cos^2 \alpha + I_r \sin^2 \alpha,$$

$$b = I_t \cos^2 (120^\circ - \alpha) + I_r \sin^2 (120^\circ - \alpha),$$

$$c = I_t \cos^2 (60^\circ - \alpha) + I_r \sin^2 (60^\circ - \alpha).$$

Then the degree of polarization is given by

$$P_{(K+F)} = \frac{2\sqrt{a(a-b) + b(b-c) + c(c-a)}}{a+b+c} \qquad \text{...(1)}$$

and the direction of H vector relative to the $a$ component by

$$\tan \alpha = \sqrt{3}\,\frac{c-b}{2a-b-c}. \qquad \text{...(2)}$$

The axis of polaroid no. 1 was found to make an angle of 14° with the heleographic north direction. Hence all the angles were suitably converted and expressed as position angles with respect to the heliographic north direction.

Equations (1) and (2) were solved, and the degree of polarization and the direction of polarization determined for a large number of points in the corona.

The contours of equal polarization based on the data are shown in figures 1 and 2 for blue and red wavelengths, respectively.

## 3. Characteristics of polarization

It is evident from figure 1 (for blue wavelengths) that there are two regions (marked by crosses) one in NE and the other in SW direction where high polarization (above 60%) is observed. Polarization is normal in other places. In figure 2 (for red

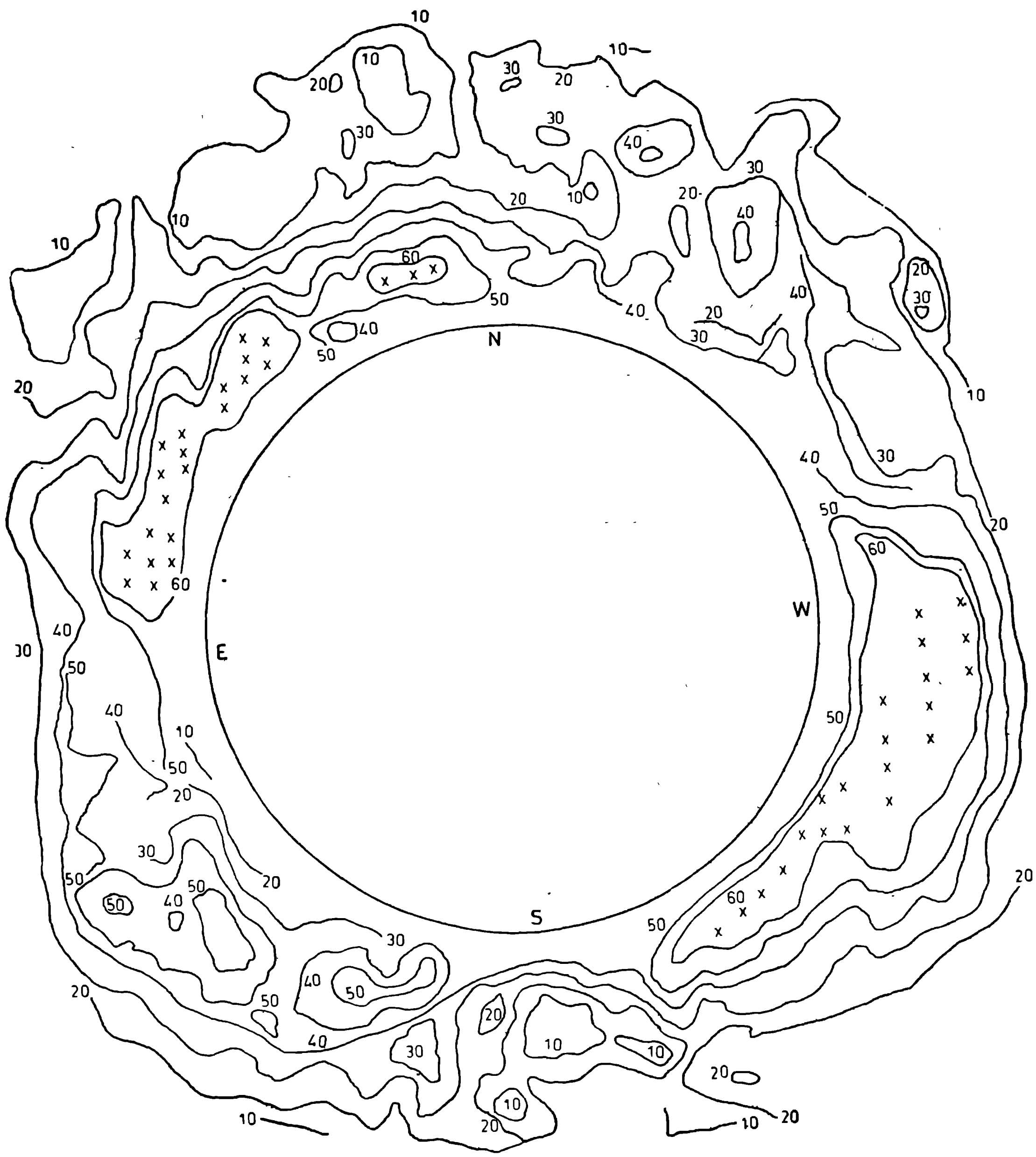


**Figure 1.** Polarization contours for the corona of 1980 February 16 (λ 4200 Å).

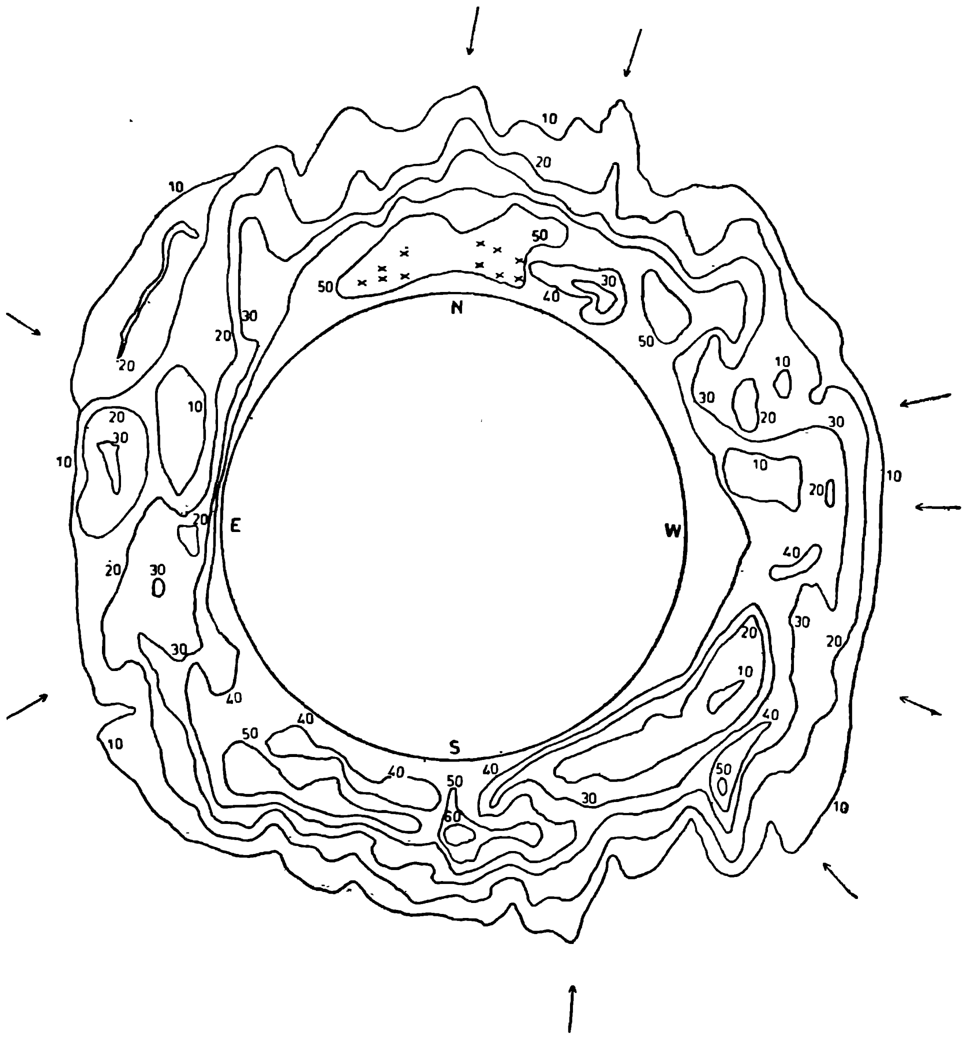


**Figure 2.** Polarization contours for the corona of 1980 February 16 in the red (λ 7000 Å).

wavelength) the region of high polarization (above 60%) is limited and confined to north direction only, and in general the polarization was lower than that in the blue. Differences are expected between the results for blue and red wavelengths because, as we shall see later, the contribution of the F corona is more in the red than in the blue.

In order to compare our results with the actual structure of the corona, we have examined a photograph of the corona taken during the same eclipse by J. L. Street & L. B. Lacey of High Altitude Observatory through a radially graded filter. It shows two loop like structures in the NE quadrant. The corona on the west limb was very complicated with many rays and streamers intermingling with each other. These were the regions where high polarization was observed in blue. The south limb was devoid of any activity and has a coronal hole in that region (J. Durst 1982 personal communication; Sivaraman 1981). This region was characterized by low polarization in the blue. Thus the regions of coronal activity and coronal hole are clearly projected in the polarization map of blue colour. Red wavelength, which has more contribution from F corona, does not show this correlation. However the ray structure is more clearly shown in the red polarization map. A number of rays were visible in the coronal photograph and are denoted in the polarization map by arrows in figure 2.

The values of polarization averaged over all directions in the corona are shown in figure 3. The expected polarization for the van de Hulst model for maximum corona is shown. Although our values agree with those of the model in the inner regions, they drop off more rapidly in the outer regions. Such rapid decrease was observed earlier also by Khetsuriani *et al.* (1972), Koeckelenbergh (1977), and Sykora (1977).

The average angle of deviation, which is also plotted in figure 3 was more or less constant at $+10°$ in the red, but it decreased to $-15°$ in the blue, after attaining a maximum of $+18°$ at 1.5–1.6 $R_\odot$.

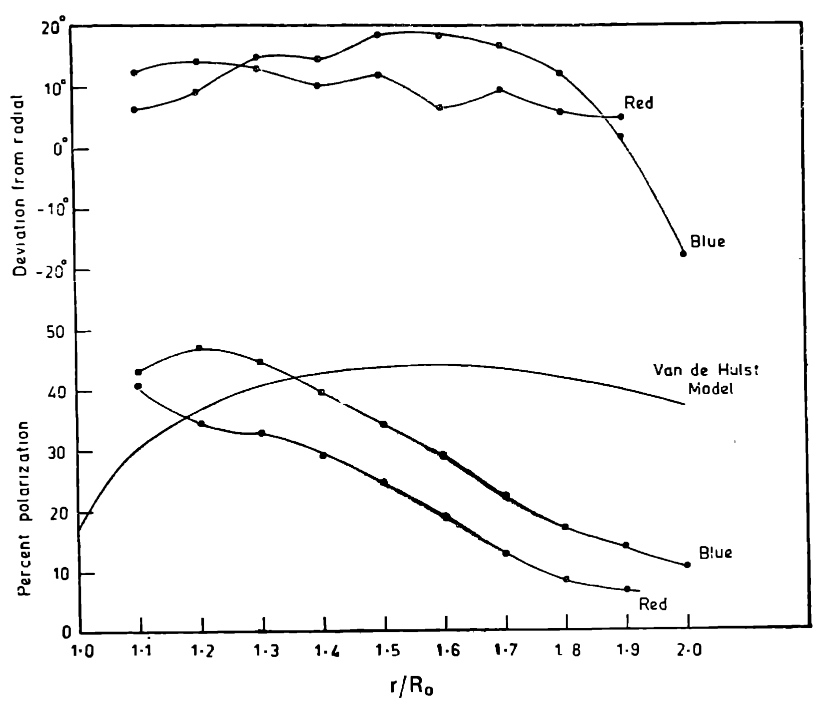


**Figure 3.** Variation of the average values and angles of polarization.

## 4. Electron densities

The procedure followed in the present analysis is that given by van de Hulst (1950 a) and adopted by von Kluber (1958) for the total eclipse of 1952 February 25. The principle of this method is to express the product of intensity $I$ and polarization $P$ as power series of the form $\Sigma(k_s r^{-s})$. It was found that the intensity could be expressed as

$$I = \frac{A}{r^{2\cdot 5}} + \frac{B}{r^7} + \frac{C}{r^{17}} \text{ (red)} \qquad \ldots(3a)$$

and

$$I = \frac{A}{r^7} + \frac{B}{r^{17}} \text{ (blue).} \qquad \ldots(3b)$$

Similarly polarization $P_{K+F}$ was found to vary as power series of the form

$$P_{K+F} = X + Yr + Zr^2 + \frac{V}{r^{24}} \text{ (red)} \qquad \ldots(4a)$$

and

$$P_{K+F} = X + Yr + Zr^2 + \frac{V}{r^1} \text{ (blue).} \qquad \ldots(4b)$$

Since the observed polarization $P$ was not always radial, the polarization $P_{K+F}$ was equated with P cos $2\alpha$, where $\alpha$ is the angle of departure from the radial polarization.

The values of $A$, $B$, $C$, $X$, $Y$, $Z$, and $V$ for various directions were obtained by the method of least squares separately for the two colours. A set of typical values for red wavelength in the north direction is

$$A = 1.1550 \times 10^{-6} B_\odot,\ B = 1.6839 \times 10^{-6} B_\odot,\ C = 6.4719 \times 10^{-6} B_\odot,$$
$$X = 1.2161,\ Y = -0.8452,\ Z = 0.1379,\ V = -0.3056$$

(for details see Anthony Raju 1982).

From the expressions (3) and (4), the product $I.P_{K+F}$ was also expressed as another power series of the form $\Sigma(k_s r^{-s})$. Then

$$K_t - K_r = P_K K = I.P_{K+F} = \Sigma(k_s r^{-s}), \qquad \ldots(5)$$

from which we get the electron densities N(r) as

$$N(r) = \sum \frac{k_s}{r^{s+1}} \frac{1}{a_{s+1}} \frac{1}{C_e} \frac{1}{A(r) - B(r)}, \qquad \ldots(6)$$

where $a_n$; the constant $C_e$; and functions $A(r)$ and $B(r)$ are defined by van de Hulst (1950 a). $A(r)$ and $B(r)$ were calculated by setting Q equal to 0.796 and 0.485 for blue and red wavelengths, respectively.

Equation (6) was used for calculating the electron densities in various directions at intervals of 10° separately for the two colours. The electron density, averaged over all directions, is shown in figure 4; the van de Hulst model for maximum corona is also shown for comparison. It was gratifying to note that the average electron density was the same in the two colours, within experimental errors. Hence the electron density in the two colours was combined and contours of the average electron density are shown in figure 5. The number on each contour gives log $N_e$ for that contour.

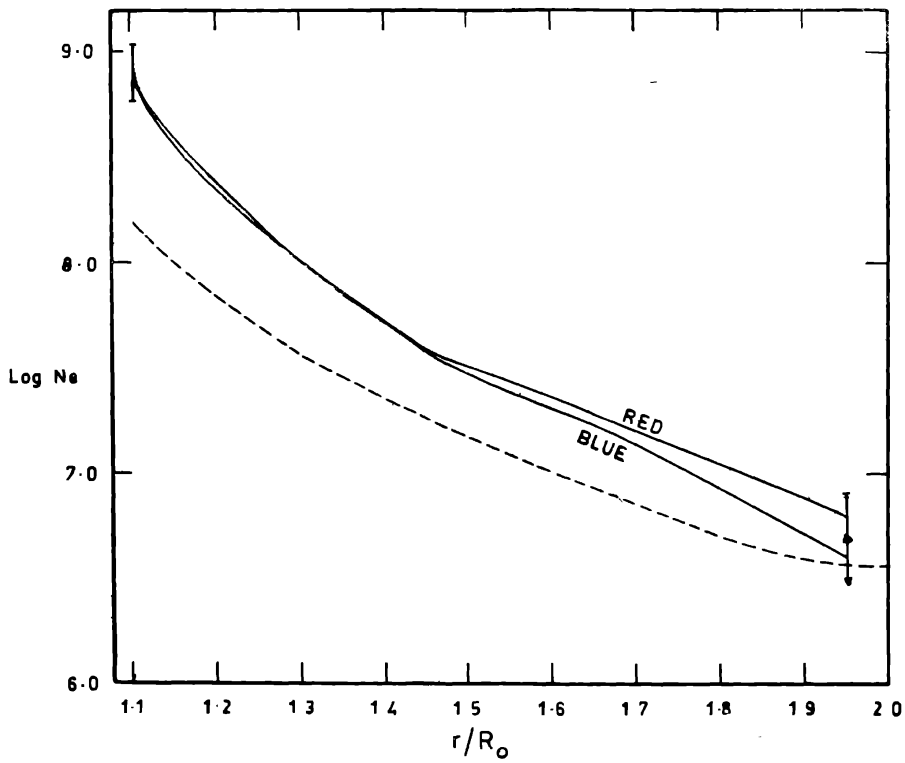


**Figure 4.** Variation of average electron density. The dashed curve represents van de Hulst's model.

## 5. Separation of K and F coronas

(a) *Intensities* : Following von Kluber (1958), the intensity of K component can be found as follows. As the values of $N(r)$ and $A(r)$ are known, power series was again formed for the product $N(r)\, A(r)\, C_e$ in the form

$$N(r)\, A(r)\, C_e = \Sigma l r_s^{-(s+1)}. \qquad \ldots(7)$$

Then

$$K_t = \sum \frac{l_s}{r^s} a_{s-1}, \qquad \ldots(8)$$

Equations (8) and (5) give the intensities of the K and F coronas; their variations averaged over all directions are shown in figures 6 and 7, respectively

(b) *Polarization* : Since the values of $I$, $P$, and $\alpha$ at various points in the corona are known, the intensity of polarized light was calculated using the formula $I_p = IP \cos 2\alpha$. The isophotes of the polarized light are shown in figure 8. In addition, the polarization of the K corona was also calculated from $P_K = P_{K+F} \times I_{K+F} \cos 2\alpha / I_K$. The values of polarizaton of K corona in the red from this equation are shown in figure 9.

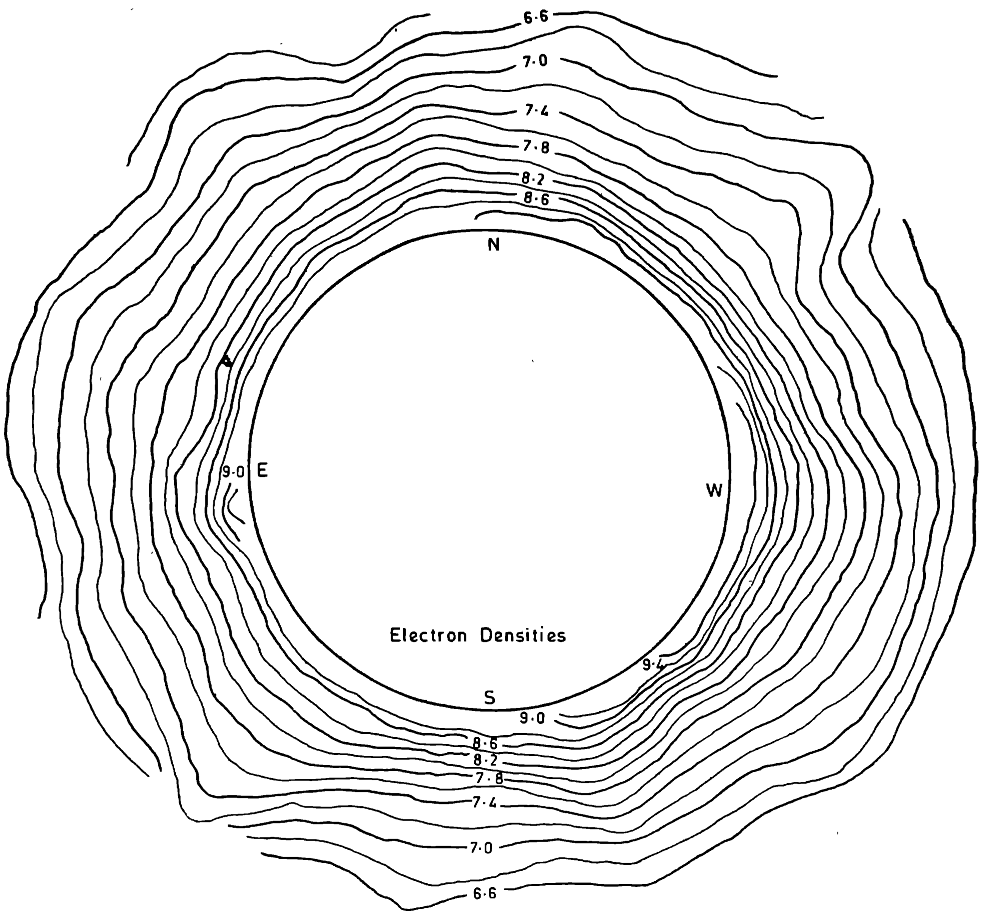


**Figure 5.** Electron density contours; the numbers are for log $N_e$.

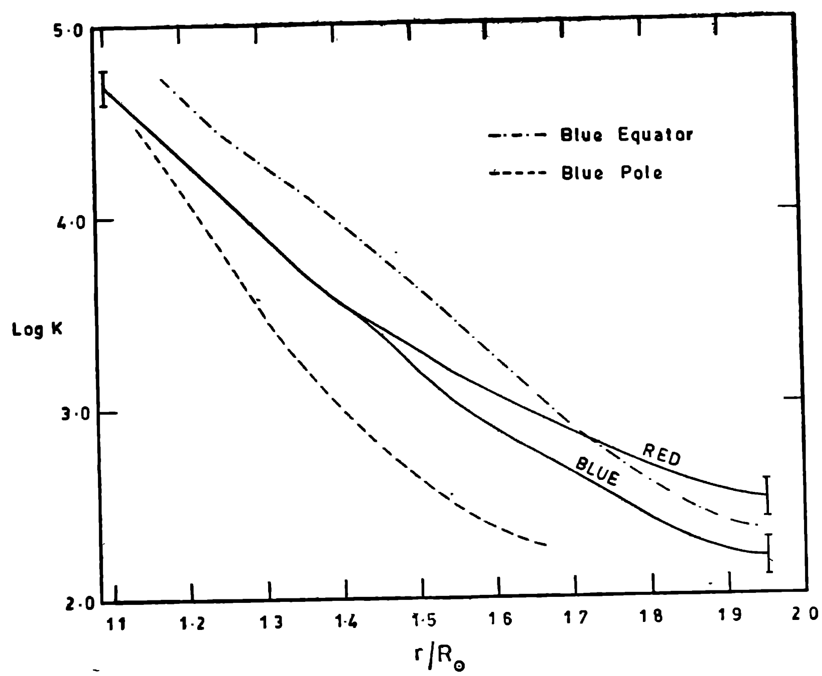


**Figure 6.** Average variation of K corona in units of $10^{-6}B_\odot$. Variations along the equatorial and polar radii are also shown.

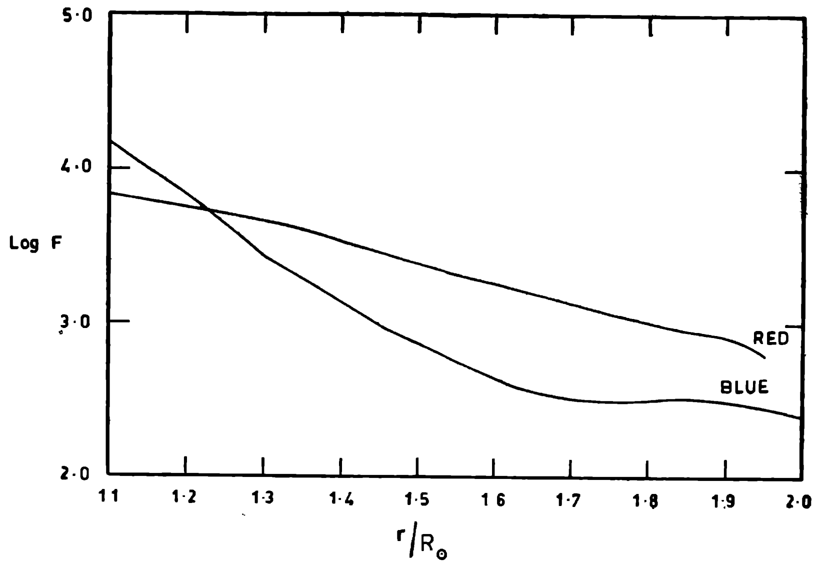


**Figure 7.** Average variation of F corona in units of $10^{-6}B_\odot$.

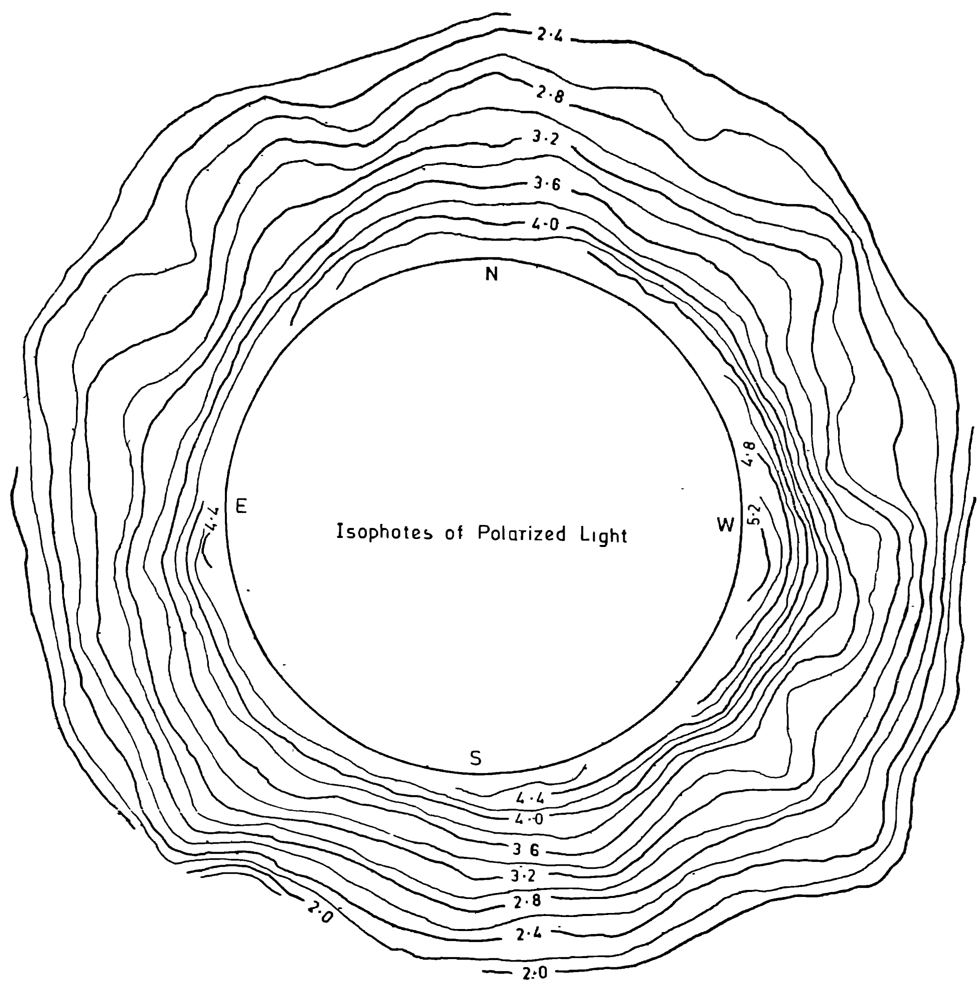


**Figure 8.** Isophotes of polarized light in red, the numbers are log $K_P$ in units of $10^{-6}B_\odot$.

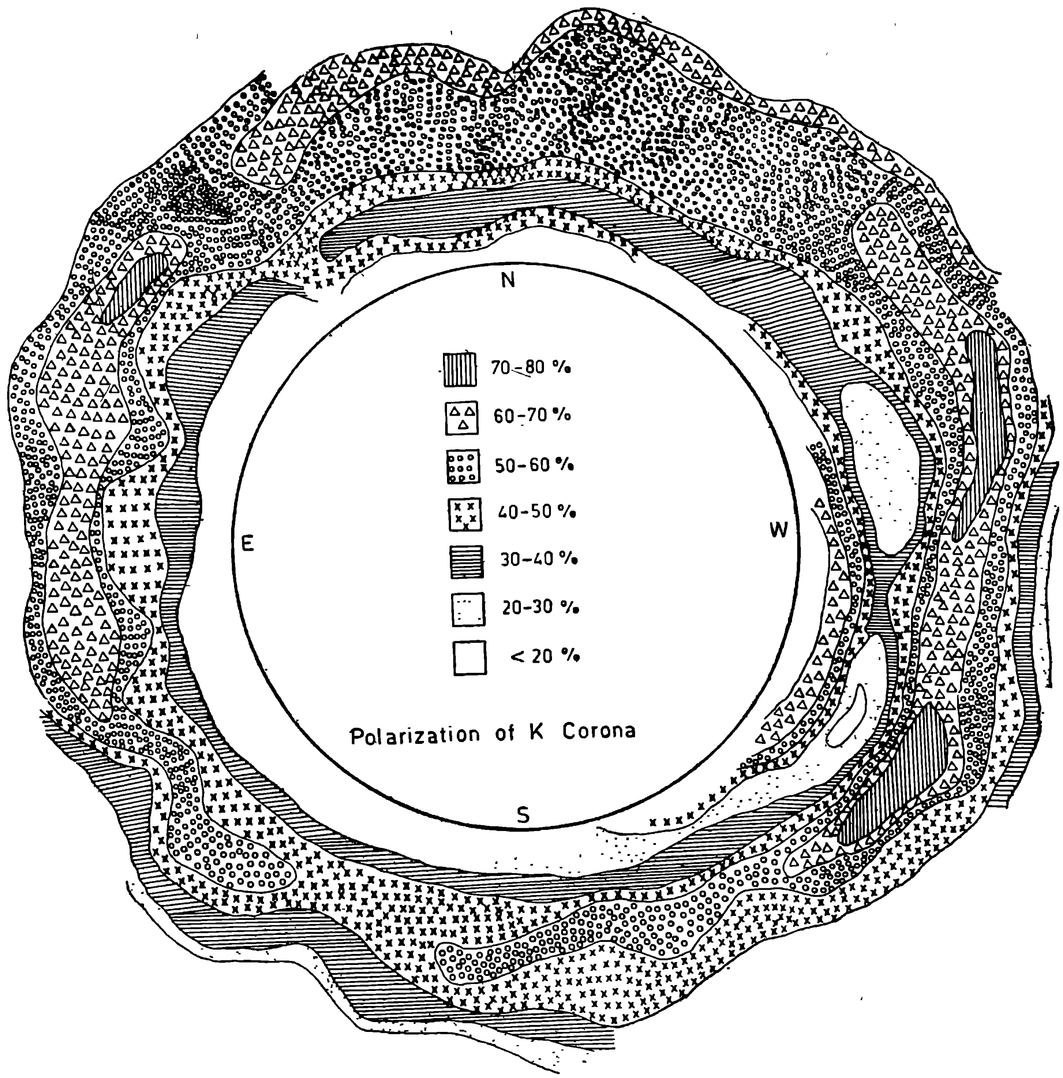


**Figure 9.** Polarization of K corona in the red.

## 6. Electron temperature

One of the methods to determine the temperature of the corona is to use the density gradient, assuming hydrostatic equilibrium (Billings 1966) :

$$\frac{GM}{r^2} N\mu m + k \frac{d}{dr}(NT) = 0.$$

It has been pointed out by van de Hulst (1950b) that this equation reduces to the form

$$\frac{T_1}{T} = \frac{d}{d(1/r)} \ln N + \frac{d}{d(1/r)} \ln T,$$

where $T_1 = g_\odot R_\odot \mu m/k$; $g_\odot$ is the acceleration of gravity at the solar surfae; $\mu$ the mean molecular weight; $m$ the mass of unit atomic weight; and $k$ the Stefan-

Boltzmann constant. The above equation can be put in the final form (Hepburn 1955) :

$$\frac{6.9 \times 10^6}{T} = \frac{d}{d(1/r)} \log eN_e + \frac{d}{d(1/r)} \log T.$$

Assuming the radial temperature change to be small, the second term in the above equation can be neglected and the temperature can be determined from the slope of the log $N_e$ versus $1/r$ curve. The resulting temperature variation obtained from the average density distribution is shown in figure 10. The temperature according to Newkirk's (1967) model is also shown in the figure. One can see that there is a good agreement in the inner region.

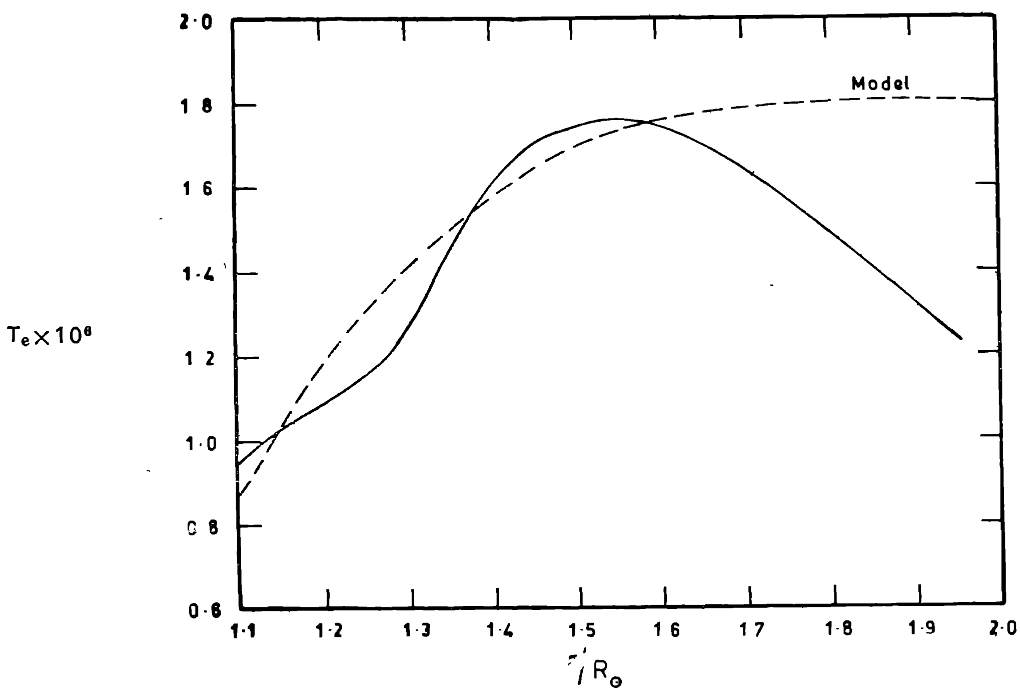


**Figure 10.** Average variation of temperature in the corona. Newkirk's (1967) model is also indicated by the dashed curve.

## 7. Discussion

The electron density contours (figure 5) show that the density is higher in the coronal active regions such as streamers, rays etc. than at other places. The electron density in the south appears to be low, confirming the presence of a coronal hole in that region. The average electron density of figure 4 is high compared to the van de Hulst model. Such high electron densities were observed earlier also during the maximnm phase. Ney *et al.* (1961) and Newkrik (1961) indicated that during 1957–59 period, densities of 1.4 to 2 times the van de Hulst model were observed, and attributed to the increased level of solar activity.

The average intensity of the K corona (figure 6) is the same for both the colours, although it becomes slightly reddish in the outer regions. This shows that the true corona has almost the same colour as that of the sun. On the other hand, the F corona (figure 7) was redder throughout. On integrating the intensity of the F corona it is found that $I_F = 6.2161 \times 10^{-6} B_\odot$ in the red and $I_F = 4.8526 \times 10^{-6} B_\odot$ in the blue. Thus the variation of F corona with the wavelength has been found to be $\lambda^{0.49}$, as compared to $\lambda^{0.5}$ obtained by van de Hulst (1950a).

The isophotes of the K corona and contours of polarized light in red correspond in a better way to the structure of the corona than the isophotes of the total light. The contours of density and polarized light thus represent the structure of the corona satisfactorily.

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