Kodaikanal Obs Bull (1988) 9, 89 98

# OPTICAL EMISSION FROM SOLAR CORONA

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**Abstract**

*In this article the methods to probe the solar corona are briefly described The discussion is confined to continuum and line radiation in the "optical" wavelength region ~ 0 3 μm to 1 1 μm*

## 1 Introduction

The mo t impre ive feature of solar eclipses is a luminous halo, surrounding the occulted disc of the Sun, known as coron Inspite of difficulties in its observation and interpretation the corona pre sents some of the most engaging problems in solar physics

The brightne s of corona amounts to only about one millionth of the brightne s of the solar di c It decrea es outwards very gradually such that no actual 'limit' can be indicated Thi re is probably a continuous tran ition from the corona to the zodiacal light Because of it extremely low surface brightness, the corona is best observed at total solar ec lip es

## 2 Optical Corona

I et us examine in some detail the coronal radiation in the optical region The spectrum of light emitted by the corona consists of a faint continuous background similar to that of the visual Sun and a number of sharp bright lines superimposed on the back ground continuum Thus, coronal optical radiation comprises of three components denoted by L, K and I The line radiation (L) mostly in the inner and middle corona constitute only about two perc nt of the total intensity The 'white light' which has nearly the same energy di tribution as the visual Sun is composed of a patially polarised continuou component (K) and an unpolarised or a weakly polarised faint (F) component that shows Fraunhofer lines Figure 1 shows the brightness of K and F coronas as a function of radial distance from the solar center

## 3 Optical Continuous Spectrum

As stated earlier most of the optical radiation from the corona is in the form of a strong pa tially polarised continuous spectrum The importance of polarisation measure ments of the corona was first emphasized by Schuster in 1879 Schuster pointed out that such inve tigation might give information on the size of scattering particles In 1905 Schwarschild attributed the polarisation of K co ona to Thomson scattering by coronal elelctrons Thomson cattering is wavelength independent and predicts that E vector in the electromagnetic wave should be in the direction perpendicular to the radius drawn from the Sun center I et $I_T$ be the intensity of tantentially polarised component $I_R$ be the intensity of the component whose E vector is along the radial direction The degree of polarislation may then be defined as

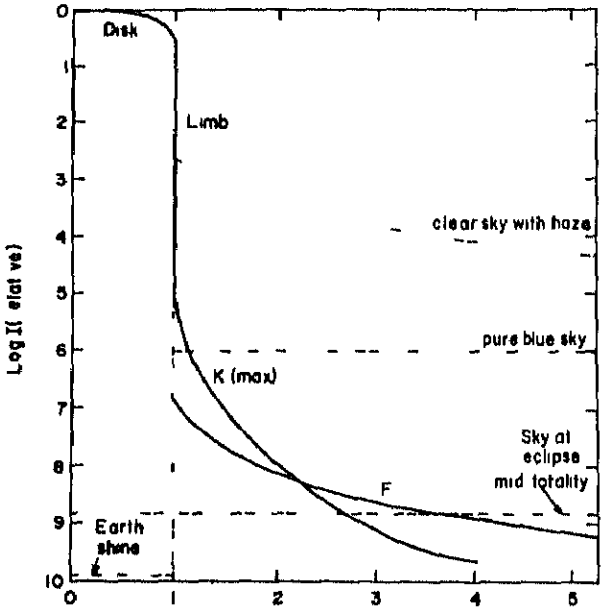


Fig.1 Brightness of the K and F continuum coronas relative to the solar disk and adjacent sky brightness The abscissa is in units of the solar radius (van de Hulst, 1953, Source University of Chicago Press)

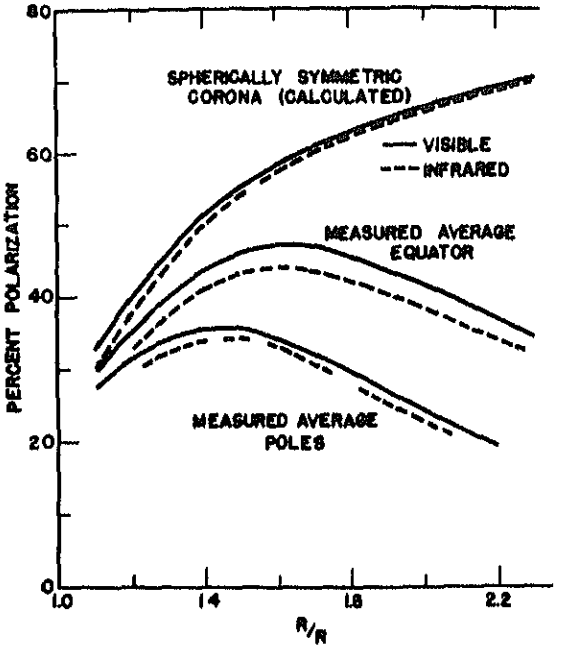


Fig.2 The observed polarisation is com with that calculated for pure electron tering (Source E P Ney, W F Huch, Kellogg W Stein and F Gillett, Ap J 616, 1961 University of Chicago Press)

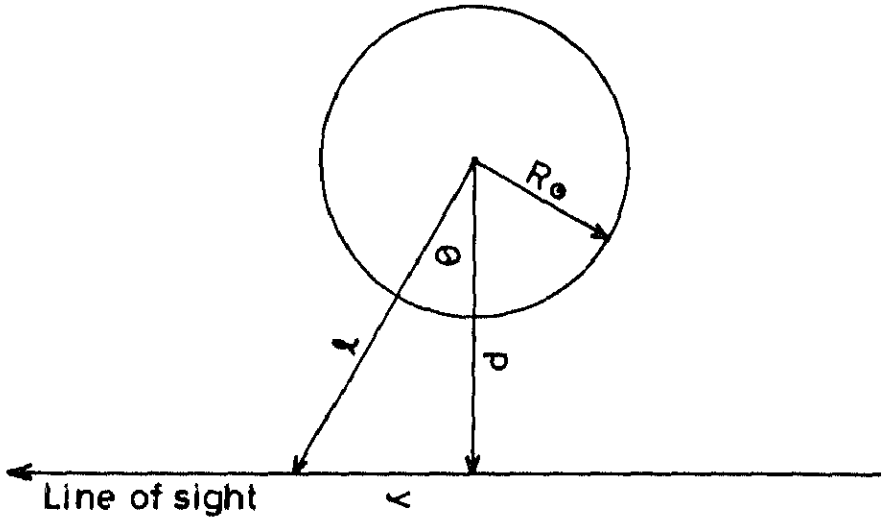


Fig.3 Geometrical representation of the observing aspect

$$P = \frac{(I_T - I_R)}{I_0} \tag{1}$$

where $I_0 = I_T + I_R$

In reality, the coronal continuum received by an observer is only partially polarized. This is because the Sun not being a point source, the contributions from volume elements along the line of sight add up to give rise to partial polarisation. The degree of polarisation in practice never exceeds about $45^0$.

Figure 2 shows the comparison of calculated and measured values of percentage of polarisation as obtained by Ney et al (1961) during the October 1959 eclipse. The rapid decrease of polarisation with distance indicates that some source other than electron scattering is responsible for continuum from outer corona.

If the partially polarised continuum of the inner corona arises primarily from electron scattering, as its faithful reproduction of the photospheric spectrum would indicate, very large electron velocities would be needed to wash out completely the dark Fraunhofer lines. The H and K lines of Ca II are almost completely obliterated. However the depression in the solar energy distribution beyond $\lambda$ 3800, caused by crowding together of many strong dark lines, is reproduced in the coronal spectrum. All individual lines appear to be smoothed out by fast moving scattering electrons. Grotrian (1934) obtained a thermal width for the scattering electron of the order of 60 Å to explain the observed effects. This implies an electron temperature of at least $3 \times 10^5$K.

Fraunhofer dark lines reappear beyond about one solar radius. They are weaker than in the solar spectrum but are of the same width as though a simple reflection of the solar spectrum were superimposed upon a continuum. Grotrian (1934) attributed the the F continuum to scattering by small particles related to those that cause zodiacal light. If one can assume that particles responsible for F continuum do not polarise the radiation then one can use polarisation measurements to separate K and F components. To carry out this separation, an additional requirement would be the assumption about density gradient of the K corona.

We have seen above how one can infer, rather roughly, the temperature of the K corona from the observed effects of scattering K coronal electrons on the Fraunhofer spectrum. Let us now examine a simplified approach (Allen, 1963) to obtain electron density distribution from the continuum data. In his classic paper Van de Hulst (1950) found that the intensity distribution in the inner corona, after subtracting the continuum of F corona may be represented by an expression of the form

$$I(P) = \frac{1.12\rho}{p^7} + \frac{2.065}{p^{17}} \tag{2}$$

Figure 5 depicts the observing aspect and the various variables involved. $R_0$ is the radius of the Sun. Let $\varepsilon(\gamma)$ be the emissivity per unit volume per unit solid angle at a distance $\gamma$ from the centre of the Sun. If

$$\varepsilon(\gamma) = A_1 \gamma^{-a} + A_2 \gamma^{-b} \tag{3}$$

we have

$$I(P) = A_1 \int_{\infty}^{\infty} \frac{dy}{\gamma^a} + A_2 \int_{\infty}^{\infty} \frac{dy}{\gamma^b}$$

$$= I_1(p) + I_2(p) \tag{4}$$

With reference to figure 3, w have

$$I_1(P) = \frac{2A_1}{p^{a-1}} \int_0^{\pi/2} \mathrm{Sec}^{2-a}(\theta)\, d\theta$$

$$= \sqrt{\pi}\ \frac{\Gamma(a - \frac{1}{2})}{\Gamma(a/2)}\ \frac{A_1}{p^{a-1}} \qquad (5)$$

Similarly we get an expression for $I_2(P)$ in the form

$$I_2(P) = \sqrt{\pi}\ \frac{\Gamma(b - \frac{1}{2})}{\Gamma(b/2)}\ \frac{A_2}{p^{b-1}} \qquad (6)$$

Using Equations (2) (6) we get for the emissivity function the expre sion

$$\epsilon(\gamma) = \frac{j(\gamma)}{4\pi} = \frac{1\ 15}{\gamma^8} + \frac{4\ 157}{\gamma^{18}} \qquad (7)$$

However the actual values of $A_1$ $A_2$, a and b may vary from eclipse to eclipse

Here we have adopted a millionth of the Sun s brightnes as the unit of luminosity and the solar radius as the unit of length For isotropic radiation the cattering cro s section per electron is $0\ 65 \times 10^{-24} cm^2$ and the corresponding cattering coefficient per unit length (solar radius) is

$$S \quad 0\ 66 \times 10^{-24} R_0 N_e$$

$$= 4\ 60 \times 10^{-14} N_e \qquad (8)$$

The total amount of scattered energy follows from an integration of the incident intensity over all directions

$$j(\gamma) = S \int I_0 d\Omega = 4\pi S I_0 \qquad (9)$$

$\Omega$ is the solid angle subtended by the Sun at the point $\gamma$ in the corona, and $I_0$ is the incident intensity When $I_0$ is computed, $N_e$ may be found from Equation (7) In case of specific studies of solar eclipses reference can be made to van de Hul t (1950), Ney et al (1961) Durst (1982) and Sivaraman et al (1984)

## 4. Optical Line Emission

In the preceding section we had examined the continuous pectrum of the optical corona We now consider the diagnostics of the optical corona using emi sion lines On the faint continuous coronal spectrum are superposed a number of bright lines which did not seem to coincide with the emission spectrum of any known element In an attempt to explain the origin of these mysterious lines, astronomers went so far as to suggest the presence on the Sun of a new hypothetical element 'coronium' unknown on the Earth

The identification of the coronal emission lines was an outstanding achievement of spectroscopy The most conspicuous of these radiations is the green line $\lambda$ 5303 Å discovered independently by C A Young and W Harkness at the total solar eclipse of 1869 The other strong lines were $\lambda$ 6375 Å and $\lambda$ 6702 Å three infrared lines at $\lambda$ 7892 Å, $\lambda$ 10747 Å and $\lambda$10798 Å, and one in the ultraviolet at $\lambda$ 3388 Å More than thirty lines have been identified between $\lambda$ 3328 Å and $\lambda$11000 Å Many lines have been found in the far ultra violet

The mystery of these lines was explained by Swedish physicist B. Edlen in 1940. He ascribed these lines mostly to Iron, Nickel and Calcium atoms excited under rather unusual circumstances. These are forbidden lines of highly ionized atoms. The high level of ionization and large line widths are all indicative of gas kinetic temperature of about a million degree. The absence of other ionic stages of Iron, Nickel and Calcium are due to the fact that the relevant transitions fall in inaccessible part of the spectrum or transition probabilities are low. Although other elements are present in the corona under coronal conditions these elements have no forbidden or permitted transitions in the optical range.

The line at λ 5303 Å has been observed to change by a factor of two in an hour. The level of excitation of the corona usually changes relatively slowly. Waldmeier found this green line to be especially useful as an indicator of coronal excitation. The total emission in λ 5303 Å and λ 6374 Å closely follow sunspot cycle, although the λ 6374 Å maximum at the solar cycle maximum is more irregular and less pronounced than for λ 5303 Å. The intensity of emission in the lines λ 5303 Å and λ 6374 Å is determined mostly by electron density, even though both electron density and temperature are higher at sunspot maximum than at minimum. Based on coronagraphic studies Lyot and Waldmeier showed that coronal lines have different spatial distribution. There are regions of relatively low excitation where the λ 6374 Å [FeX] line is prominent, so called the red regions. Then there are regions, so called the green regions, where the λ 5303 Å [FeXIV] line and other high excitation lines are prominent.

Table 1 shows the grouping of prominent coronal lines into three groups in relation to solar activity.

**Table 1**

Representative Line Grouping by Relation to Solar Activity
(Courtesy, E. G. Gibson, The Quiet Sun, 1973, NASA SP 303, Washington, D. C.)

| Group | Characteristic | Wavelength Å | Ion | Ionization energy, eV |
|---|---|---|---|---|
| I | Prominent during solar minimum and in quiet regions | 3533 | V X | 206 |
| | | 3987 | Fe XI | 262 |
| | | 6374 (red line) | Fe X | 235 |
| | | 7892 | Fe XI | 262 |
| II | Prominent during solar maximum and in active regions | 3388 | Fe XIII | 330 |
| | | 3643 | Ni XIII | 350 |
| | | 4232 | Ni XII | 321 |
| | | 5303 (green line) | Fe XIV | 355 |
| | | 7060 | Fe XV | 390 |
| | | 8024 | Ni XV | 430 |
| | | 10747 | Fe XIII | 330 |
| | | 10798 | Fe XIII | 330 |
| III | Prominent in regions of very high excitation, e.g. during flares or above large spots | 3327 | Ca XII | 392 |
| | | 3601 | Ni XVI | 455 |
| | | 4086 | Ca XIII | 655 |
| | | 4351 | Co XV | 412 |
| | | 4412 | A XIV | 687 |
| | | 5446 | Ca XV | 820 |
| | | 5694 (yellow line) | Ca XV | 820 |
| | | 6740 | K XIV | 717 |

Let us examine in some specific form the diagnostic aspects of line emission at optical wavelengths.

a) **Temperature diagnostics :** One can infer temperature of corona from spectroscopic data connected with processes such as ionization, excitation, line broadening etc. The temperature we speak of is the kinetic temperature of ions or electrons. Since collisions influence all the above mentioned processes

i) One way of inferring kinetic temperature is to perform ionization equilibrium calculations Here we obtain the relative abundance of various ionic stages of an element as a function of kinetic temperature From such calculations we find that a given ionic stage is abundant over only a narrow temperature range Therefore the presence of lines of a given ion say, Fe XIV in the coronal spectrum would specify the value of the kinetic temperature though not precisely, of the coronal emission region Figure 4 illustrates the relative abundance of Iron ions and Calcium ions as function of temperature obtained by ionization equilibrium calculations (Landini and Monsignori Fossi 1972)

ii) In another method kinetic temperature can be inferred from line width measurements Line profile of an optically thin line can be expressed as

$$I(\Delta\lambda) = I_0 \exp\left[ -\left(\frac{\Delta\lambda}{\Delta\lambda_D}\right)^2 \right] \tag{10}$$

where

$$\Delta\lambda_D = \frac{\lambda_0 [2kT_{ion}/m_{ion}]^{\frac{1}{2}}}{c} \tag{11}$$

$\Delta\lambda_D$ is Doppler width, $m_{ion}$ is ionic mass, $\lambda_0$ is rest wavelength But observationally, one finds that $T_{ion}$ is somewhat larger than $T_e$, the elelctron temperature i e line are nonthermally broadened To explain excess broadening the a tronomers have introduced, for want of better information, a microturbulent thermal broadening pecified by an RMS speed $\zeta_{turb}$ One then writes for the modified $\Delta\lambda_D$ the expres ion

$$\Delta\lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2kT_e}{m_{ion}} + \zeta^2_{turb}} \tag{12}$$

with two or more line profiles $\zeta_{turb}$ and $T_e$ can be separated Since they influence line width separately depending upon the ionic mass

iii) A very reliable and powerful method, though not at optical wavelengths to obtain the kinetic temperature of the corona is to observe the width of scattered Lyman α line of hydrogen This is so because the hydrogen atom being light their thermal motions contribute more than non thermal motions in broadening the scattered Lyman α line Kohl et al (1980), Withbroe et al (1982) have obtained Lyman α line profile at several heights in the corona using a rocket borne spectrograph, and on analy i have obtained variation of coronal proton temperature with height

iv) We may estimate electron kinetic temperature from line intensity ratio Here the requirement is that the energy interval between the upper levels of the two transitions should be greater than the energy equivalent of the temperature being measured This method is not particularly useful for coronal conditions at optical wavelengths For details one may refer to the paper by Dwivedi (1987) in these proceedings

b) **Electron density diagnostics** Line intensity ratios provide a powerful tool to infer electron densities in the emission regions For sake of illustration, let us consider lines emitted by Fe XIII This ion has five levels in the ground state The various important lines in the optical range are shown in the figure 5 Assuming steady state conditions one can compute ground term level populations after considering the relevant excitation and de excitation processes, as a function of electron density and temperature Knowing the level populations we obtain the various line intensities Flower and Pineau des Forets (1973) have obtained intensity ratios for Fe XIII ion as a function of electron density at $T_e = 2 \times 10^6$ (Figures 6 and 7) Knowing the observed ratios one can read off from these curves the electron density value for the emission region

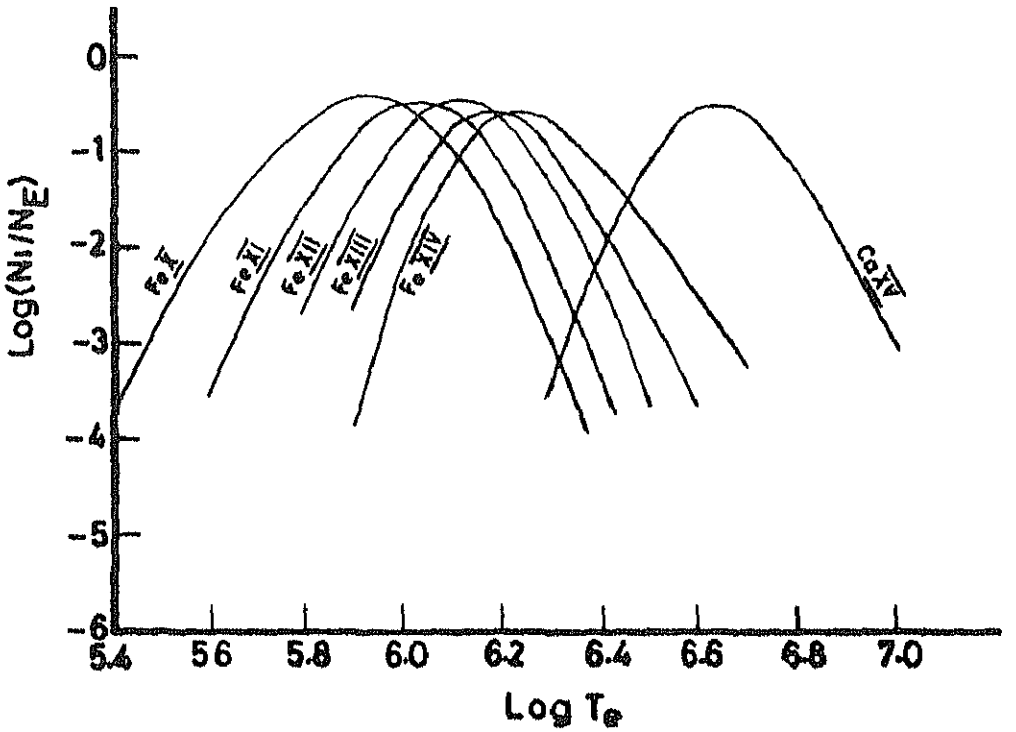


Fig.4. Relative abundance of Iron ions and CaXV ion as a function of electron temperature (Landini & Monsignori Fossi, 1972)

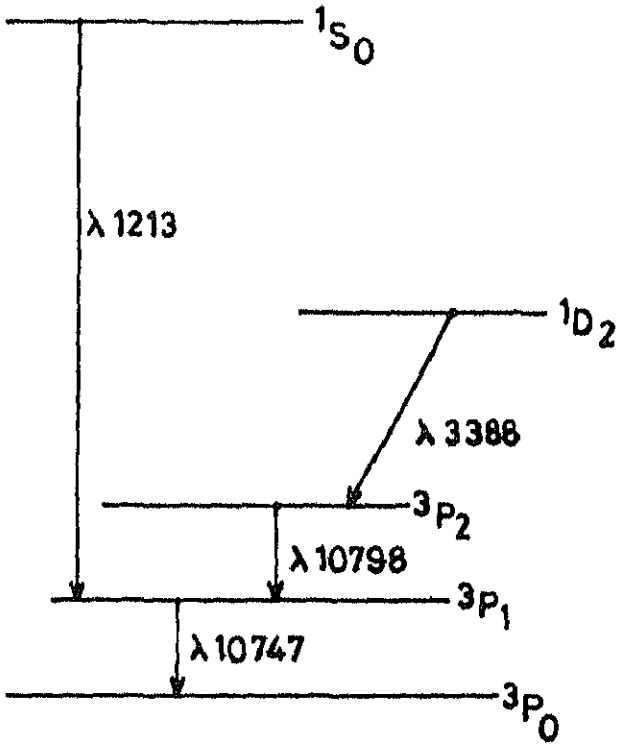


Fig.5 Term diagram for the $3s^2 3p^2$ configuration of Fe XIII The transitions which have been identified in the coronal spectrum are indicated

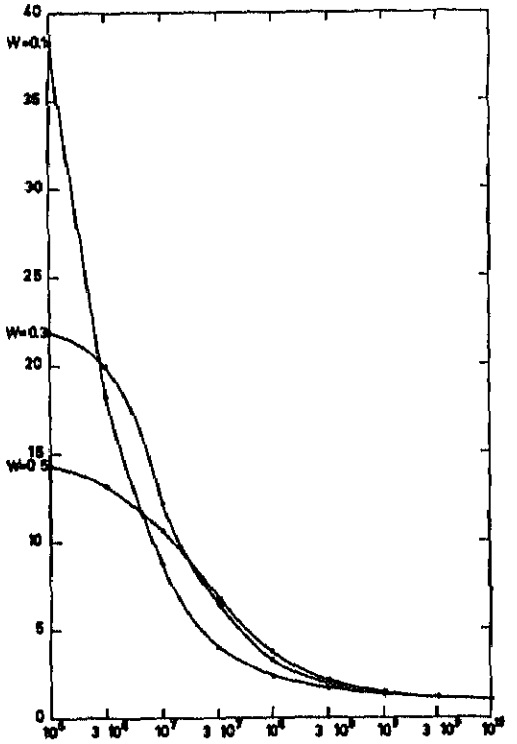

Fig.6. Ratio of the intensities of the infrared lines I(λ 10747)/I(λ 10798) as a function of $N_e$ (cm $^{-3}$) for a range of values of W (dilution factor) and for $T_e = 2 \times 10^6$ K (Courtesy D R Flower and G Pineau des Forets, 1973)

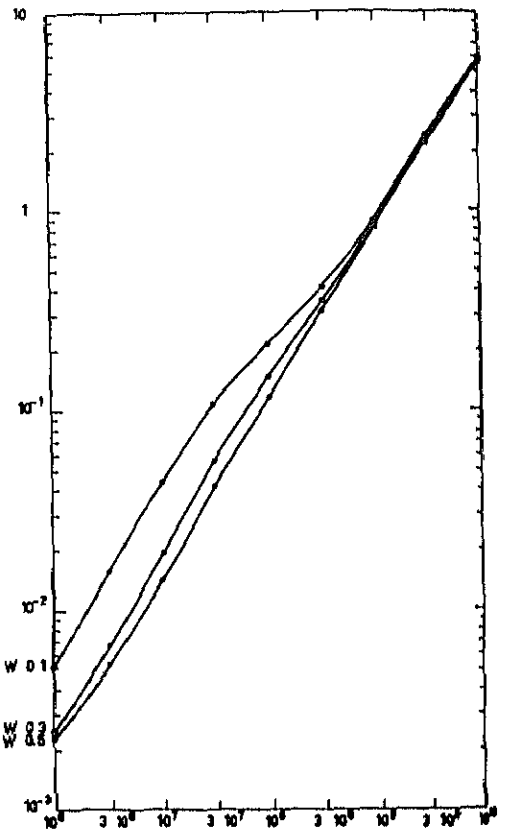

Fig.7 Ratio of the intensities of the lines I(λ 3388)/I(λ 10747) as a function of $N_e$ (cm $^{-3}$) fo a range of values of W (dilution factor) and $T_e = 2 \times 10^6$ K (Courtesy, D R Flower and G Pineau des Forets, 1973)

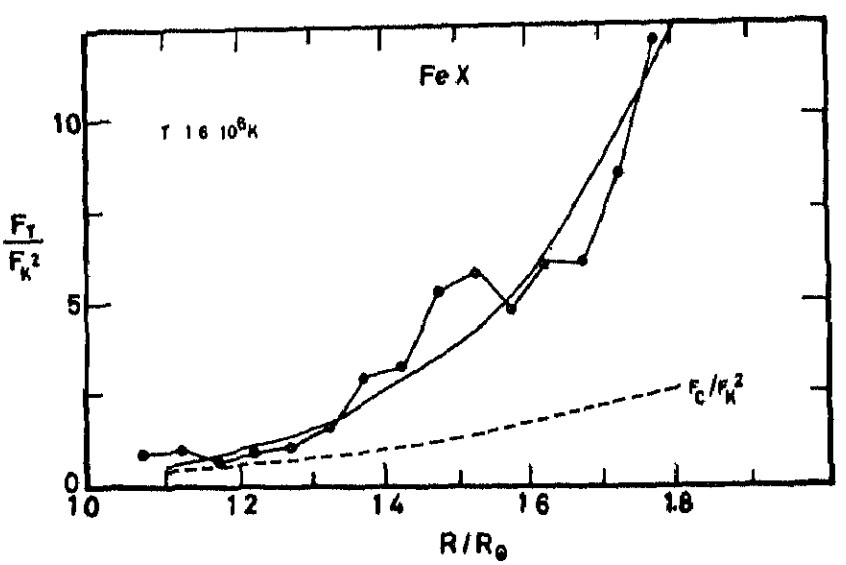


Fig.8 Continuous curve represents computed ratios of the line flux to the square of continuum flux as a function of radial distance for FeX (6374 A) line at coronal temperature for $1.6 \times 10^6$K Filled circles indicate the observed ratios for the average corona Dotted curve represents computed ratios for the line flux, due to collisional excitation only, to the square of continuum flux (Raju & Singh, 1987)

In another method we examine the ratio of line intensity and the continuum flux. The continuum flux is due to scattered photospheric radiation by coronal electrons in the emission region. The line flux is proportional to $N_e^2$ and the continuum flux varies linearly with electron density. The line to continuum flux would then vary linearly with electron density. This method is useful only for isolated emission region with constant electron density and temperature and when the line is excited purely by electron collisions. When the above constraints are removed then this method cannot be used. This is clearly demonstrated in Figure 8 (Raju and Singh, 1987).

In conclusion, various methods have been outlined in this article for probing the solar corona using continuum and line radiation, at optical wavelengths. It might be appropriate at this stage, to cite a very recent review article on the spectroscopy of the solar corona by Zirker (1987).

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