COMPARISON OF COMPUTED FLUXES FOR Fe X AND Fe XIV LINES WITH OBSERVED VALUES AT 1980 ECLIPSE

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Abstract. Fluxes have been computed for Fe X (6374 Å) and Fe XIV (5303 Å) lines as a function of solar radii and at various coronal tempratures. The electron density derived from the white light corona during the total solar eclipse of 1980 were used in the computations. Fluxes in adjacent continua have also been computed. The computed ratios of line flux to the square of continuum flux at a coronal temperature of 1.6×10^6 K show a good fit with the observed values for Fe X line. Further, radiative excitation seems to dominate over collisional excitation beyond 1.3 solar radius.

1. Introduction

The information of continuum and line intensities on various locations in solar corona helps in understanding the physical processes and heating mechanism in the corona (Billings, 1966; Singh, 1985). Leibenberg *et al.* (1975) and Desai and Chandrasekhar (1983) have assumed only collisional excitation in order to derive the temperature and velocity structure in the solar corona. Singh (1985), however, from the multislit spectroscopy of solar corona taken during the 1980 solar eclipse, has shown qualitatively that radiative excitation is equally important in the inner corona and plays a greater role in the outer corona. In this paper, we compute the fluxes in the lines Fe X (6374 Å) and Fe XIV (5303 Å) and nearby continua by including both the processes and discuss the relative roles of collisional and radiative excitations. In Section 2 we consider the line-emission rates arising out of the forbidden transitions in Fe X and Fe XIV ions and the nearby continua. Relevant excitation rates are discussed in Section 3. Finally, in Section 4 we discuss the results of the eclipse observations in the context of the calculated line fluxes.

2. Emission Rates

2.1. Line emission

The line emission from a coronal ion can be expressed as

$$E_L = N_j A_{ji} h\nu_{ij}/4\pi \quad \text{erg cm}^{-3}\,\text{s}^{-1}\,\text{sterad}^{-1}\,, \tag{1}$$

where N_j is the number density of the upper level, j and i denote levels in the ground configuration, $h\nu_{ij}$ is the energy separation between the levels i and j, A_{ji} is the spontaneous transition probability. The number density N_j for Fe X ion (say) is given by

$$N_j(\text{Fe X}) = \frac{N_j(\text{Fe X})}{N(\text{Fe X})}\,\frac{N(\text{Fe X})}{N(\text{Fe})}\,\frac{N(\text{Fe})}{N(\text{H})}\,\frac{N(\text{H})}{N_e}\,N_e\,, \tag{2}$$

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where $N_j(\mathrm{Fe\,X})/N(\mathrm{Fe\,X})$ is the relative population of the jth level, $N(\mathrm{Fe\,X})/N(\mathrm{Fe})$ is the relative ion density of the Fe X ion. $N(\mathrm{Fe\,X})/N(\mathrm{Fe})$ values for different temperatures have been taken from Jordan (1969). A value of 7×10^{-5} is assumed for the relative abundance of iron, $N(\mathrm{Fe})/N(\mathrm{H})$ (Mason, 1975); N_e is the electron density.

Under coronal conditions, hydrogen and helium are fully ionized. Assuming 10% abundance for helium, we have for the ratio

$$\frac{N(\mathrm{H})}{N_e} = \left(1 + \frac{2N(\mathrm{He})}{N(\mathrm{H})}\right)^{-1} . \tag{3}$$

The line-of-sight intensity is given by

$$F_L(\mathrm{Fe\,X}) = R_\odot \int_{-\infty}^{\infty} E_L \,\mathrm{d}y \quad \mathrm{erg\,cm^{-2}\,s^{-1}\,sterad^{-1}} , \tag{4}$$

where y is the line-of-sight coordinate in units of the solar radius, $R_\odot$. Equation (4) can also be expressed as

$$F_L(\mathrm{Fe\,X}) = C(\mathrm{Fe\,X}) \int_{-\infty}^{\infty} \frac{N_j(\mathrm{Fe\,X})}{N(\mathrm{Fe})} N_e \,\mathrm{d}y , \tag{5}$$

where

$$C(\mathrm{Fe\,X}) = \frac{1.27 \times 10^{-9}}{\lambda_{ji}(\text{Å})} A_{ji} \frac{N(\mathrm{Fe})}{N(\mathrm{H})} \frac{N(\mathrm{Fe\,X})}{N(\mathrm{Fe})} R_\odot , \tag{6}$$

where $\lambda_{ji}(\text{Å})$ is the wavelength of the transition in Å. The fraction of the Fe X ion in the upper level of the ground term, $N_j(\mathrm{Fe\,X})/N(\mathrm{Fe\,X})$, is a function, in general, of electron temperature and electron density. We have computed $N_j(\mathrm{Fe\,X})/N(\mathrm{Fe\,X})$ for three special cases assuming isothermal conditions. Electron configurations are those given by Mason (1975).

We consider the following three cases.

Case I

The upper level of the ground term is populated by electron and proton excitations, and cascade transitions from excited levels. The upper level gets depopulated by spontaneous radiative transitions. Atomic data are again those given by Mason (1975).

Case II

The upper level of the ground term is excited by photospheric radiation and depopulated by spontaneous radiative transition. This case amounts strictly to a two-level scheme.

Case III

The upper level of the ground configuration is populated by electron and proton impacts, cascade transitions from excited levels, and by photospheric radiation. Depopulation is by spontaneous radiative transition.

The contribution of collisional de-excitation process to the total depopulation rate of the upper level of the ground term is estimated to be less than 2 percent for the electron density values under consideration. Therefore, we have neglected the collisional de-excitation term in all the three cases considered above.

2.2. Continuum emission

The continuum emission in the solar corona is essentially due to Thomson scattering of the photospheric radiation. The continuum flux at a particular wavelength is given by

$$F_K = \sigma_e J_0^\lambda R_\odot \int_{-\infty}^{\infty} N_e(\rho) W(\rho)\, \mathrm{d}y\,, \tag{7}$$

where σ_e is the Thomson scattering cross-section, ρ is the distance from the solar center in units of $R_\odot$, and J_0^λ is the mean solar intensity in erg cm^{-2} sterad^{-1} Å^{-1}. We have taken $J_0^\lambda = 2.46 \times 10^6$ for Fe X and 3.06×10^6 for Fe XIV (de Boer *et al.*, 1972). $W(\rho)$ is the geometrical dilution factor given by the following expression (cf. de Boer *et al.*, 1972):

$$W(\rho) = \frac{1}{2}\left[(1-u)\left(1-\left(1-\frac{1}{\rho^2}\right)^{1/2}\right) + \right.$$
$$\left. + \frac{u}{2}\left(1 - \rho\left(1-\frac{1}{\rho^2}\right)\ln\left(\frac{\rho+1}{\rho-1}\right)^{1/2}\right)\right], \tag{8}$$

where the limb-darkening coefficient u is 0.60 for Fe X, and 0.69 for Fe XIV (Allen, 1973).

The values of electron density $N_e(\rho)$ used in our computations are listed in Table I. These values are based on the curve (electron density versus radial distance) drawn by Dürst (1982) from the white light observations of the 1980 total solar eclipse.

3. Excitation Rates

Radiative rates: Assuming that the photospheric radiation is equivalent to that emitted by a blackbody with temperature T_R, the radiative excitation rates can be written as

$$R_{ij} = A_{ji} W(\rho) \frac{g_j}{g_i} [\exp(h\nu_{ij}/kT_R)^{-1}]^{-1}\,, \tag{9}$$

where g's are statistical weights.

Collision rates: Electron collisional excitation rates are given by the following expression (Mason, 1975):

$$C_{ij} = \frac{8.63 \times 10^{-6}\, \Omega_{\mathrm{eff}}(i,j)}{T_e^{1/2} g_i} \exp\left(-\frac{h\nu_{ij}}{kT_e}\right) cm^3\, s^{-1}\,, \tag{10}$$

where T_e is the electron temperature. $\Omega_{\mathrm{eff}}(i,j)$ is the effective collision strength as given

TABLE I

Electron density N_e as a function of ρ in units of $R_\odot$

ρ	$N_e \times 10^{-8}$	ρ	$N_e \times 10^{-8}$
1.10	151.991	1.15	110.262
1.20	81.113	1.25	59.670
1.30	45.773	1.35	33.206
1.40	24.771	1.45	19.403
1.50	15.739	1.55	12.502
1.60	10.355	1.65	8.381
1.70	6.579	1.75	5.412
1.80	4.545	1.85	3.739
1.90	3.162	1.95	2.565
2.00	2.278	2.05	2.009
2.10	1.772	2.15	1.552
2.20	1.350	2.25	1.207
2.30	1.043	2.35	0.940
2.40	0.842	2.45	0.746
2.50	0.677	2.55	0.605
2.60	0.553	2.65	0.501
2.70	0.448	2.75	0.415
2.80	0.384	2.85	0.359
2.90	0.334	2.95	0.309
3.00	0.289	3.05	0.269
3.10	0.249	3.15	0.234
3.20	0.218	3.25	0.207
3.30	0.196	3.35	0.186
3.40	0.176	3.45	0.166
3.50	0.158	3.55	0.152
3.60	0.146	3.65	0.140
3.70	0.132	3.75	0.126
3.80	0.120	3.85	0.115
3.90	0.110	3.95	0.105
4.00	0.100	4.05	0.096
4.10	0.092	4.15	0.089
4.20	0.086	4.25	0.083
4.30	0.080	4.35	0.077
4.40	0.075	4.45	0.073
4.50	0.071	4.55	0.069
4.60	0.067	4.65	0.065
4.70	0.063	4.75	0.061
4.80	0.059	4.85	0.057
4.90	0.055	4.95	0.053
5.00	0.051		

by Mason (1975). It includes the effect of electron excitation to excited configurations followed by radiative decay to the ground term levels.

For proton collision rates we have assumed, for numerical simplification, a constant value of 1.34×10^{-9} cm^3 s^{-1} corresponding to a temperature of 1.5×10^6 K for Fe X ion and 1.39×10^{-9} cm^3 s^{-1} at a temperature of 2×10^6 K for Fe XIV ion (Mason, 1975). Proton number density is given by Equation (3).

4. Comparison with Observations

The observations giving the information on continuum and line intensities are very few. The coronal spectra obtained near the limb, mostly for the identification of coronal lines (Aly, 1953; Jefferies *et al.*, 1971; Bappu *et al.*, 1972; and Singh *et al.*, 1983) yield intensities at a fixed solar radius. Therefore, these observations cannot be used to study the behaviour of the ratio of line to continuum intensity as a function of solar radius.

The interferograms of solar corona have been taken at number of total solar eclipses and in only very few cases have been used to study the continuum and line intensities

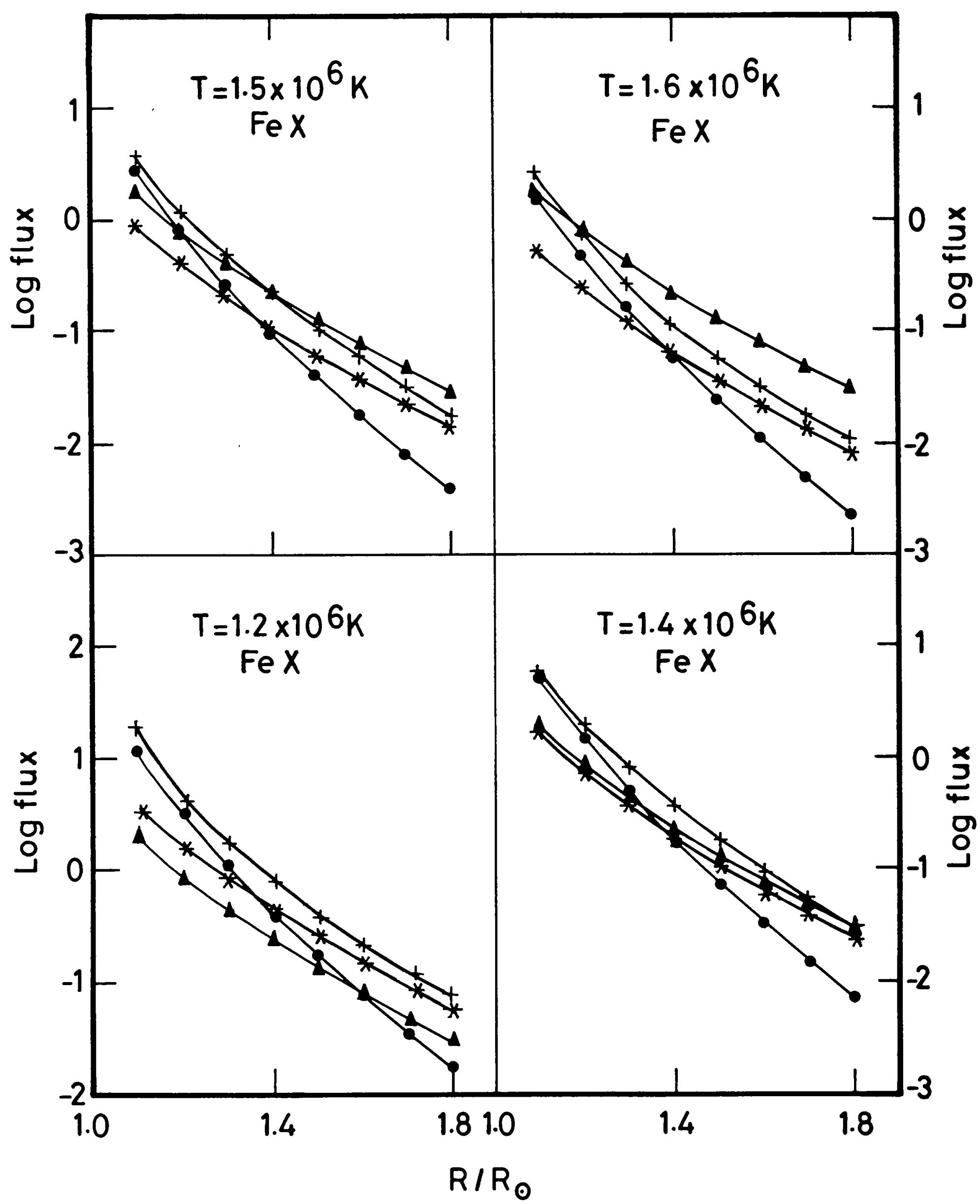

Fig. 1. Variation of the flux of Fe X (6374 Å) line as function of radial distance. ▲, ●, ∗, and + represent continuum, collisional excitation part, radiative excitation part and total flux (radiative + collisional) in the line, respectively. Temperature parameter is indicated in each sub-section.

(Leibenberg *et al.*, 1975; Desai and Chandrasekhar, 1983). The values of the ratio of the line to continuum intensities obtained from interferograms may not be truly representative, since continuum intensity will depend upon the percentage transmission and passband width of the interference filter, whereas the line intensity will depend only on percentage transmission of the interference filter used during the observations.

The other technique for determining the line and continuum intensities in the solar corona is to obtain the high-resolution spectra using multislit spectrograph as has been done by Livingston and Harvey (1982) for the study of coronal flow, who have used an interference filter of 100 Å pass bandwidth to record the coronal spectra. Thus, in the recorded spectra, the spectrum due to one slit is superimposed on the spectrum of

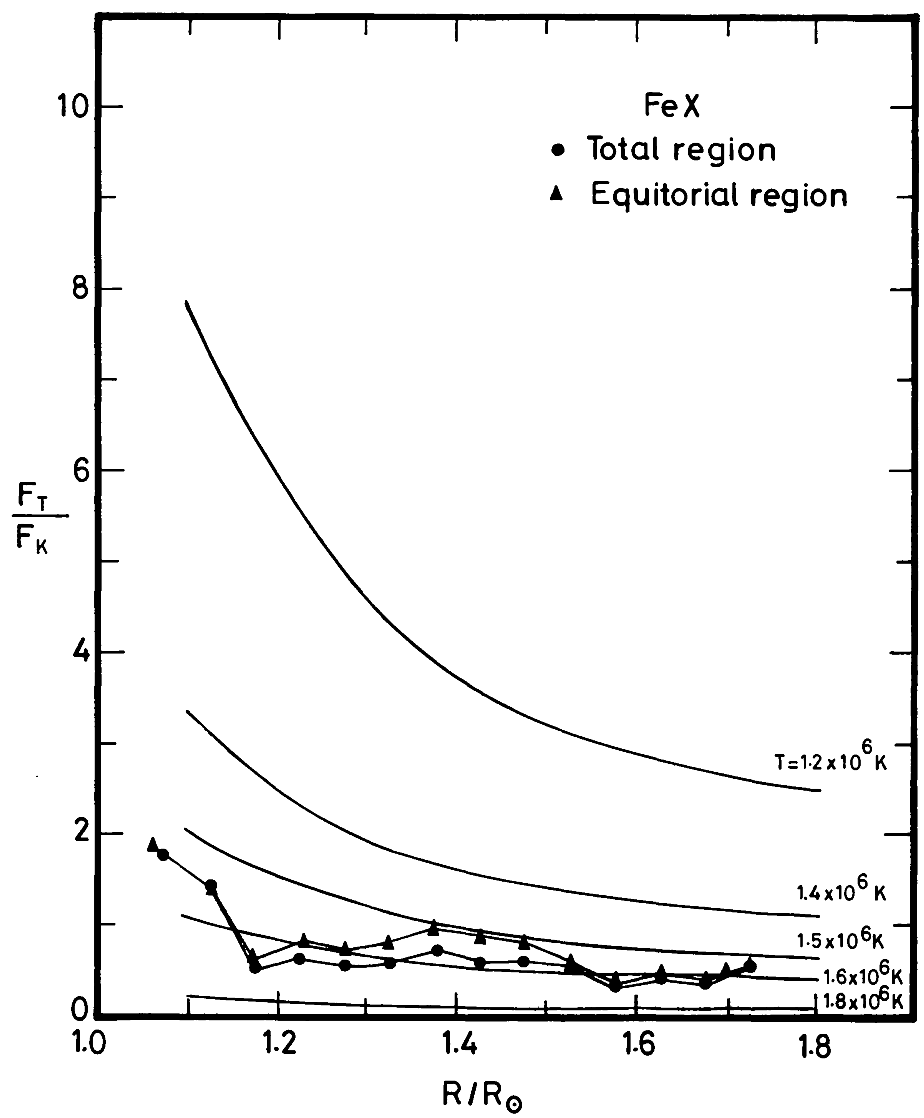

Fig. 2. Continuous curves represent the computed ratios of line to continuum flux for Fe X (6374 Å) as a function of radial distance for various coronal temperatures. Filled circles represent observed ratios averaged over the whole coronal region. Filled triangles represent the observed ratios averaged over the equatorial region.

the other slit, making it difficult to derive the reliable continuum intensity as a function of solar radius. Singh *et al.* (1982) have used interference filter of 10 Å pass-bandwidth and thus recorded spectra due to each slit without any superimposition. The derived line and continuum intensities at various locations between 1.1 and 1.7 solar radii from these spectra are best suited for the present study.

The computed flux (F_c) due to collisional excitation, the flux (F_R) due to radiative excitation, and the total flux (F_T) in Fe X (6374 Å) line together with the continuum flux (F_K) are plotted in Figure 1 for coronal temperatures of 1.2, 1.4, 1.5, and 1.6 × 10^6 K. The computed ratios of line to continuum flux as a function of solar radius for various

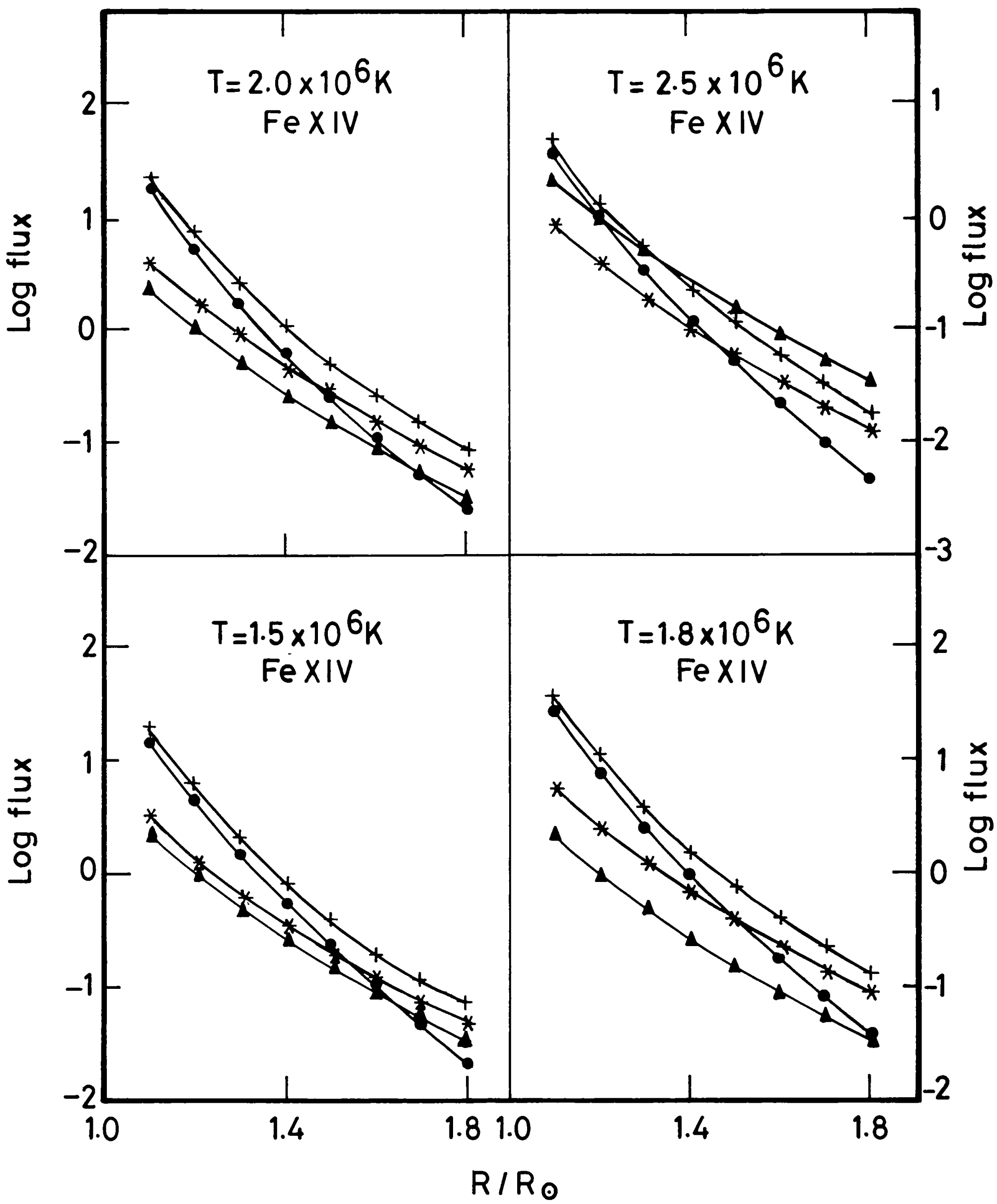

Fig. 3. Variation of flux for Fe XIV (5303 Å) line as function of radial distance, ▲, ●, *, and + represent continuum, collisional excitation part, radiative excitation part, and total flux (radiative + collisional) in the line, respectively. Temperature parameter is indicated in each sub-section.

coronal temperatures are shown in Figure 2 for Fe X (6374 Å) line. The observed intensity ratios averaged over different position angles for the equatorial corona and also the whole corona as a function of solar radius for the total solar eclipse of 16 February, 1980 (Singh, 1985) are shown in Figure 2 for comparison with the computed ratios. The observed average values of intensity ratios at different solar radii for 1980 eclipse agree well with the computed ratios for coronal temperature of about 1.55×10^6 K.

Similarly, the computed fluxes, F_c, F_R, F_T, and F_K for Fe XIV (5303 Å) line are plotted in Figure 3 for coronal temperatures of 1.5, 1.8, 2.0, and 2.5×10^6 K. The variation of computed ratio of line to continuum flux as a function of solar radius for various coronal temperatures is shown in Figure 4. The average ratios for various solar radii observed

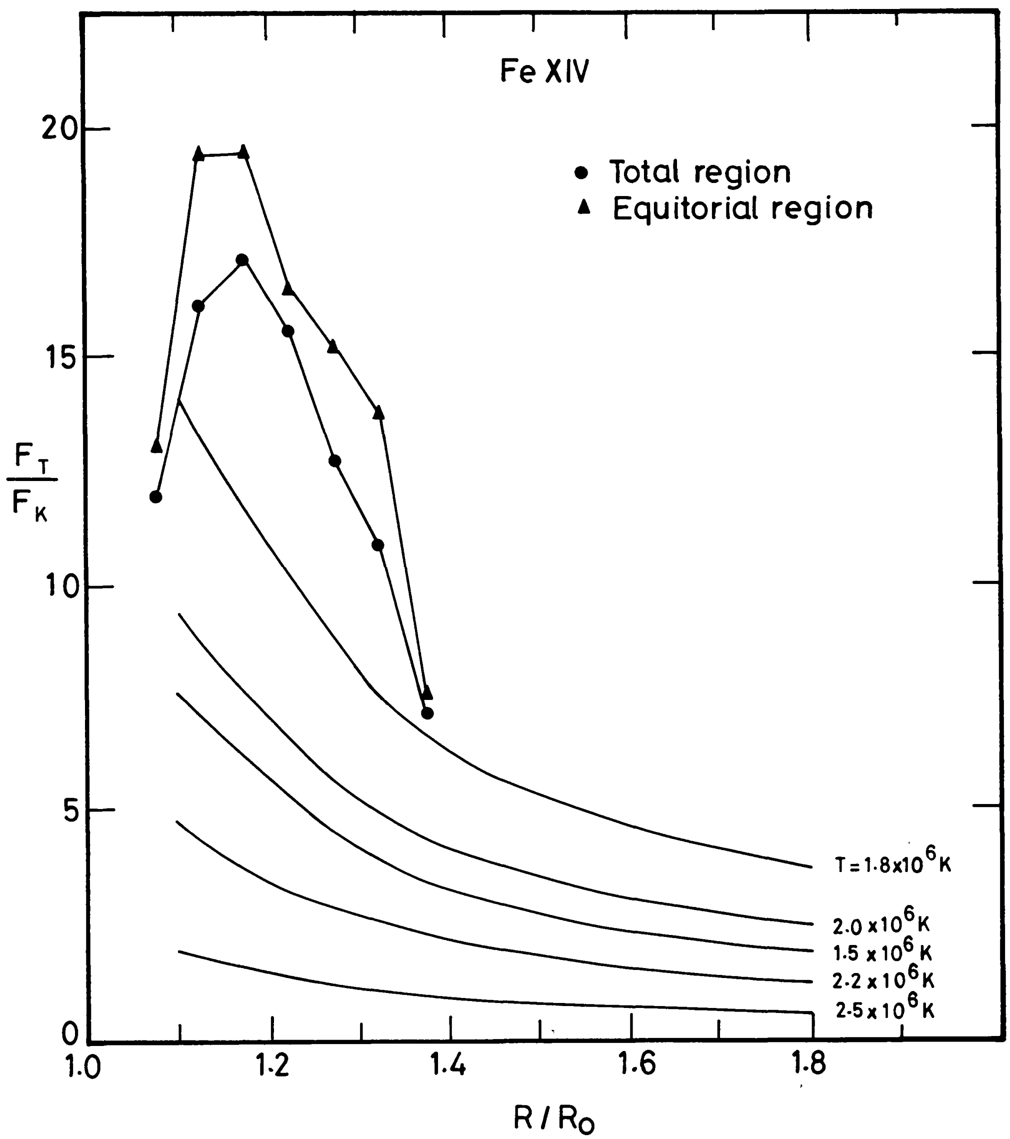

Fig. 4. Continuous curves represent the computed ratios of line to continuum flux for Fe XIV (5303 Å) as a function of radial distance for various coronal temperatures. Filled circles represent observed ratios averaged over the whole coronal region. Filled triangles represent the observed ratios averaged over the equatorial region.

by Chandrasekhar (1985) at the 1980 eclipse for equatorial and whole corona are also plotted in Figure 4 for comparison. The average observed ratios seem to have higher values than those computed for various coronal temperatures and the observed ratios have a maximum value around 1.2 solar radius. The available data on Fe XIV line covers only 13 position angles over the entire corona. Therefore, contribution of some active regions might be dominating in the average values of the ratio derived from the limited data. It is possible that a factor of 3 enhancement in the ratio F_T/F_K could occur in an active region. Hence, a maximum in the ratios F_T/F_K around 1.2 solar radius may be due to contribution from active regions. It seems that more observations covering larger solar radii are required for a fuller comparison between observed and computed ratios for Fe XIV (5303 Å) line.

A plot of computed ratios of line intensity to the square of continuum intensity as a function of solar radius is shown in Figure 5 for coronal temperature of 1.6×10^6 K for Fe X (6374 Å) line. The computed values agree with the averaged observed values plotted in Figure 5. Computed ratios of line intensity, only due to collisional excitation

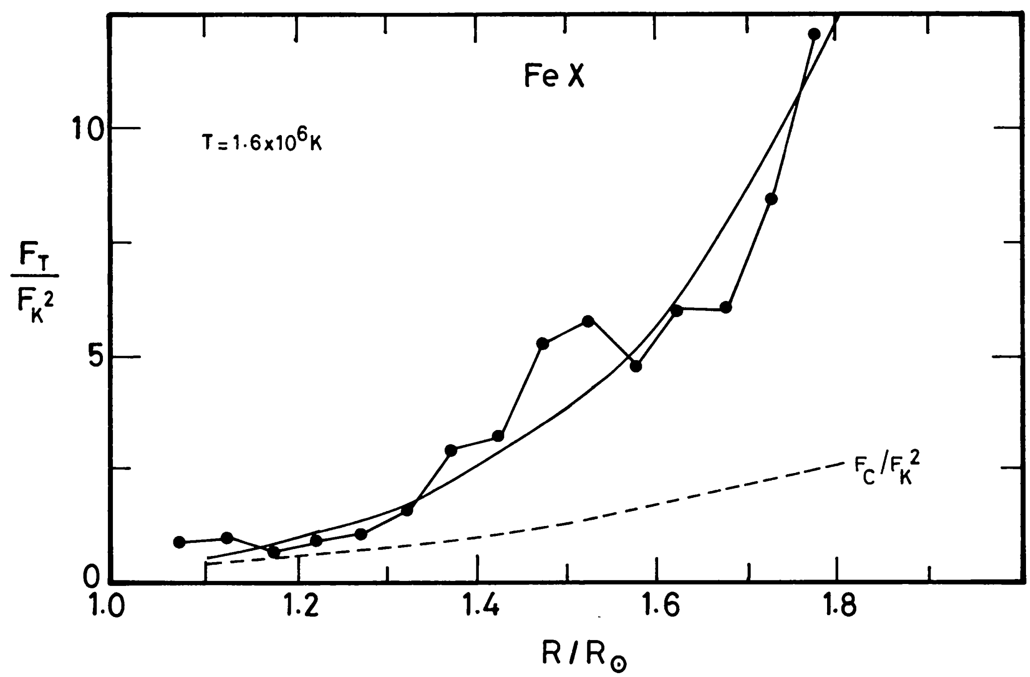

Fig. 5. Continuous curve represents computed ratios of line flux to the square of continuum flux as a function of radial distance for Fe X (6374 Å) line at coronal temperature of 1.6×10^6 K. Filled circles indicate the observed ratios for the averaged corona. Dotted curve represents computed ratios for the line flux, due to collisional excitation only, to the square of continuum flux.

to the square of continuum intensity are also indicated in this figure. The ratio increases slowly with solar radius when only collisional excitation is considered; but the value increases rapidly beyond 1.3 solar radius when radiative excitation is also taken into account and is in agreement with the observed values. These trends in ratios suggest that radiative excitation plays greater role in the solar corona beyond 1.3 solar radius.

From the above comparison of the intensity ratios it appears that the average temperature of the solar corona was about 1.6×10^6 K at the time of 1980 eclipse.

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