CLUES TO THE MODE OF EXCITATION OF Fe x IONS IN THE SOLAR CORONA FROM THE 1980 ECLIPSE OBSERVATIONS

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(Received 5 July; in revised form 7 November, 1984)

Abstract. The line and continuum intensities deduced from the multislit spectra of the (Fe X) coronal emission line taken at the 1980 eclipse are used to discuss the relative roles of radiative and collisional excitation mechanisms. It is shown that for $R/R_\odot < 1.2$, collisional excitation is the predominant mode. Collisional as well as radiative excitation is equally important for $1.2 < R/R_\odot < 1.4$, whereas beyond 1.4 $R_\odot$ radiative excitation becomes dominant. The line width measurements indicate that a large number of locations have half-widths around 1.3 Å. The maximum half-width is reached at $\sim 1.4\, R_\odot$ with an average value of 1.6 Å.

1. Introduction

Multislit spectra of (Fe X) 6374 Å line were obtained at the eclipse of 1980 February 16 (Singh *et al.*, 1982; Singh, 1984). The spectrograph was designed to give a dispersion of 2.5 Å mm^{-1} in the fourth order red. The spectra have a wavelength resolution of 0.05 Å limited by the grain size of the photographic emulsion (Kodak 103-aD). The use of an image intensifier and sufficiently long exposure ensured that the continuum was well exposed out to large distances in the corona and made available data over a wide range in distance, namely, $1.1 < R/R_\odot < 1.7$. The line width measurements, line-of-sight velocities, continuum and line intensities and comparison of line widths with white-light corona have already been published (Singh *et al.*, 1982).

In this paper we make use of these intensity measurements to study the variation of line and continuum intensities with radial distance. We discuss the clues this variation provides towards understanding the relative roles and radial dependence of collisional and radiative excitations in producing the Fe X ions.

2. Results

We have measured the widths and relative intensities of the red coronal line at 236 locations all around the solar limb. A histogram of the line widths shown in Figure 1 indicates a predominance of values of FWHM around 1.3 Å and an extended tail towards higher values. The value of 1.3 Å for line widths implies random motions of the order of 30 km s^{-1} assuming that the temperature of the solar corona is 1.3×10^6 K for Fe X ion (Jordan, 1969). The smallest value of about 0.7 Å of line widths corresponding to a kinetic temperature of 1.3×10^6 K seems to be representative of the state of ionization (Singh *et al.*, 1982) and larger FWHM are due to contribution to it by Doppler motions. The nonthermal velocity of about 30 km s^{-1}, derived in this

Solar Physics **95** (1985) 253–262. 0038–0938/85.15

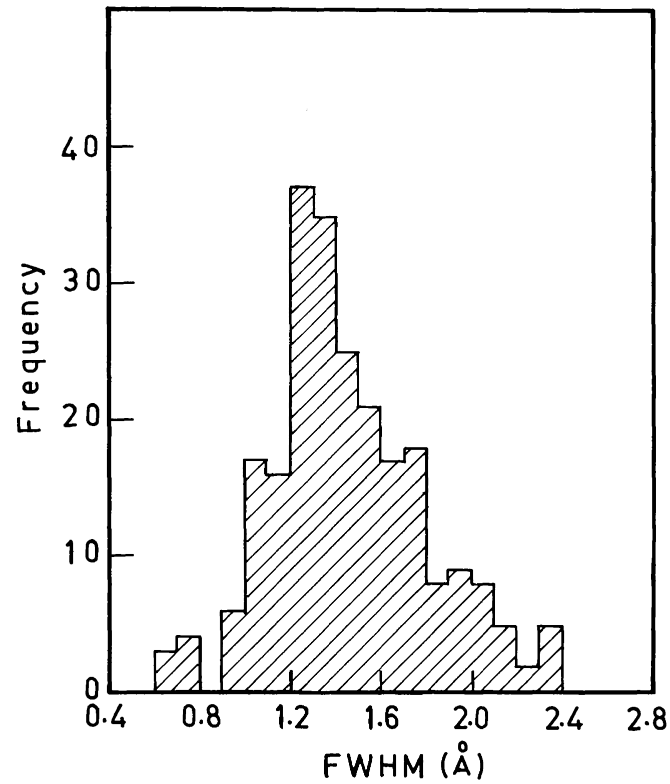

Fig. 1. Frequency distribution of the true line widths of the 6374 Å line.

manner, agrees well with the findings of Delone and Makarova (1975), Mariska *et al.* (1978), and Cheng *et al.* (1979).

Line widths are plotted as a function of radial distance in Figure 2, which shows that the line widths are randomly distributed and do not have maximum at any particular radial distance. The mean curve of all these plots is shown in Figure 3. This does indicate a line width maximum around a radial distance of 1.4 $R_\odot$. The line width maximum has a value of about 1.6 Å. We discuss it further in the next section.

We have plotted the ratio of line intensity, I_l/I_c, versus radial distance for all those directions for which the data are available. These plots are distributed in the two Figures 4 and 5. Figure 4 shows that I_l/I_c is almost constant with radial distance between 1.2 $R_\odot$ and 1.4 $R_\odot$ whereas Figure 5 indicates that I_l/I_c falls steeply till 1.2 $R_\odot$ and rises subsequently with a maximum around 1.4 $R_\odot$. The ratio I_l/I_c^2 as a function of radial distance for all the above mentioned directions is plotted in Figures 6 and 7. Only four directions, out of 16 directions, have data points between 1.1 and 1.2 $R_\odot$. These four plots indicate that the ratio l_l/I_c^2 remains almost constant upto 1.2 $R_\odot$. But all the 16 plots show that this ratio increases with radial distance beyond 1.2 $R_\odot$.

3. Discussion

The contribution of the background K corona to the visible portion of the electromagnetic spectrum is mainly due to the scattering of photospheric radiation into the line

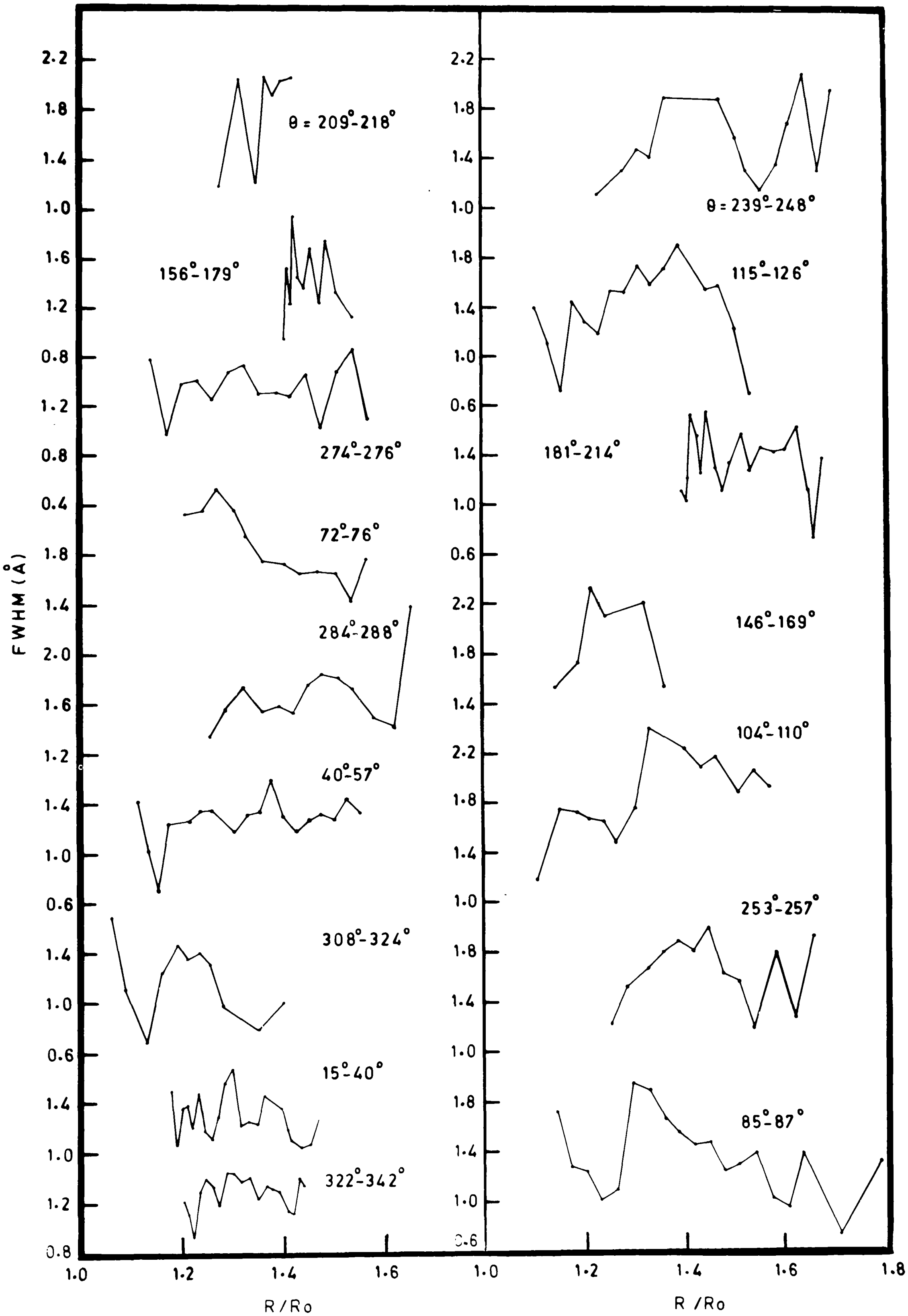

Fig. 2. Variation of the true line widths with radial distance. Position angle for each direction is also indicated.

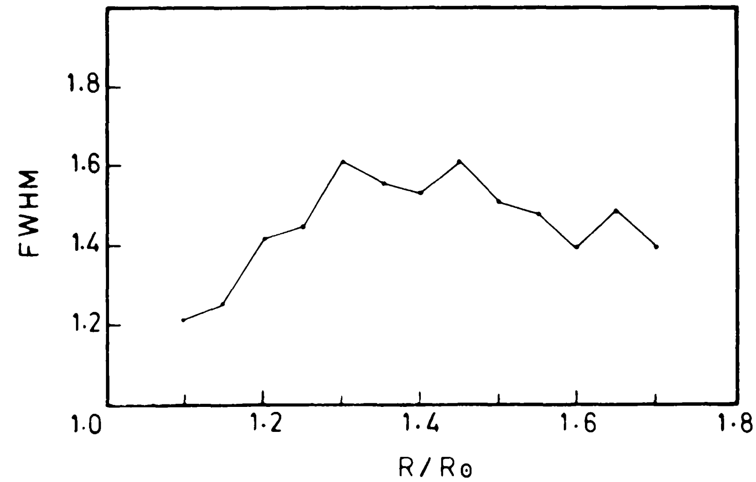

Fig. 3. Mean variation of the line width with radial distance.

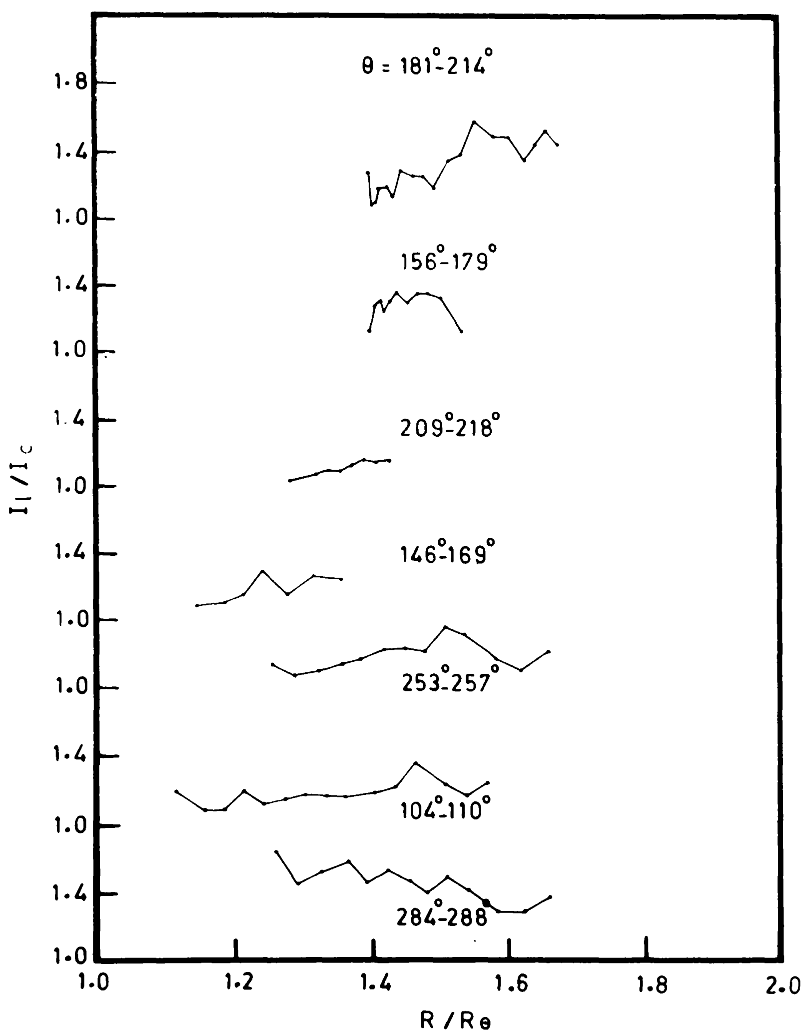

Fig. 4. I_l/I_c versus radial distance. Position angle is indicated for each curve.

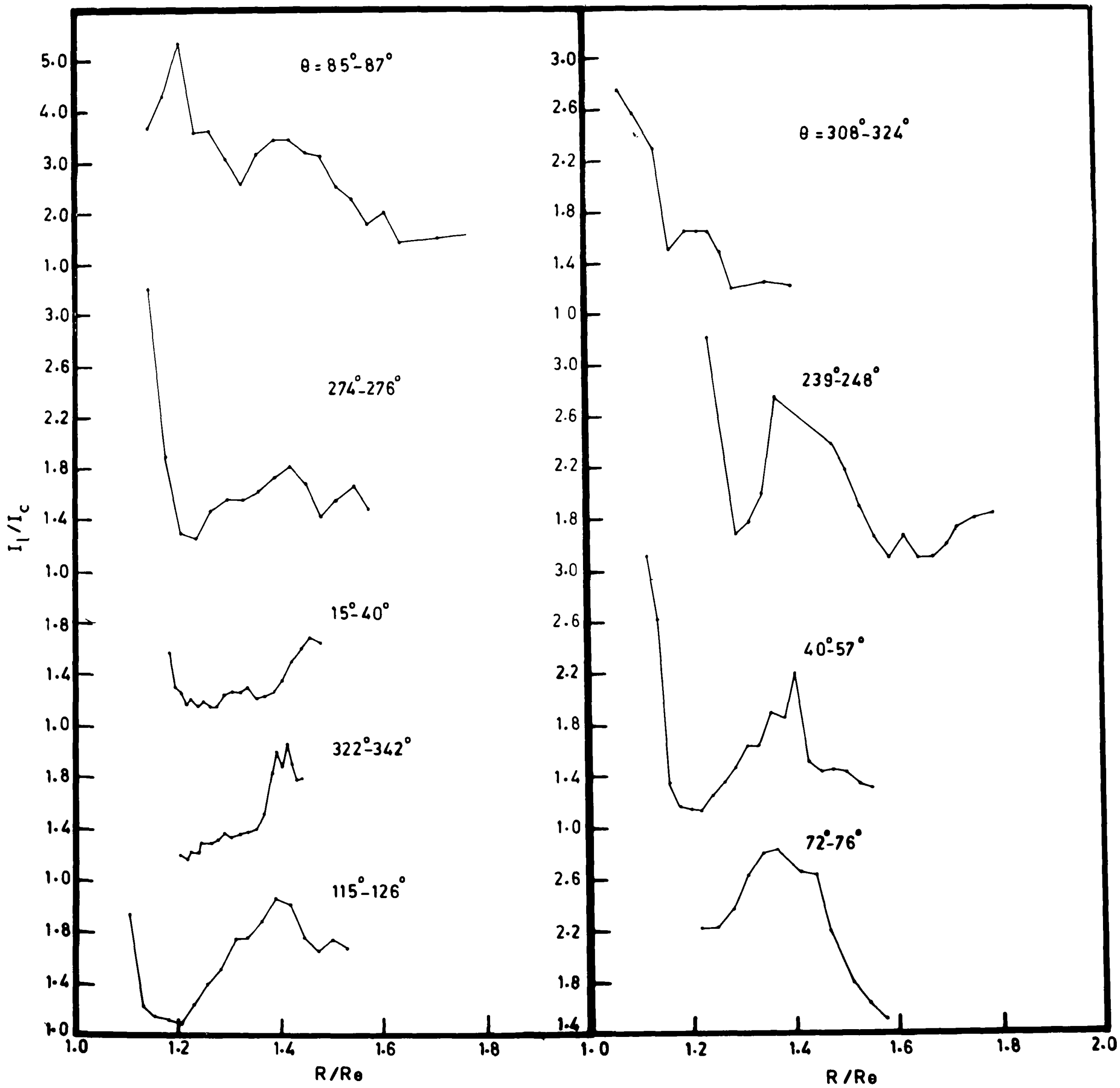

Fig. 5. I_l/I_c versus radial distance. Position angle is indicated for each curve.

of sight. The mechanism of scattering is usually assumed to be Thompson scattering by free electrons. Thus the amount of scattered radiation in the optical continuum depends directly on the electron density. Line radiation arising from forbidden transitions depends solely on the number of ions in the excited level. This in turn depends onthe mode of excitation to the level. The rate of radiative excitation per unit volume for (Fe X) line is given by (de Boer *et al.*, 1972)

$$R_{lu} = [n(\text{Fe X})/n(\text{Fe})]A(\text{Fe})0.8\,N_e A_{ul} D(g_u/g_l)(e^{h\nu/kT} - 1)^{-1},$$

where P and u refer to lower and upper levels, n(Fe X) and n(Fe) are the number of Fe X ions and Fe atoms per unit volume respectively. A(Fe) is the abundance of Fe relative to hydrogen, N_e is the electron density, A_{ul} is the spontaneous transition probability,

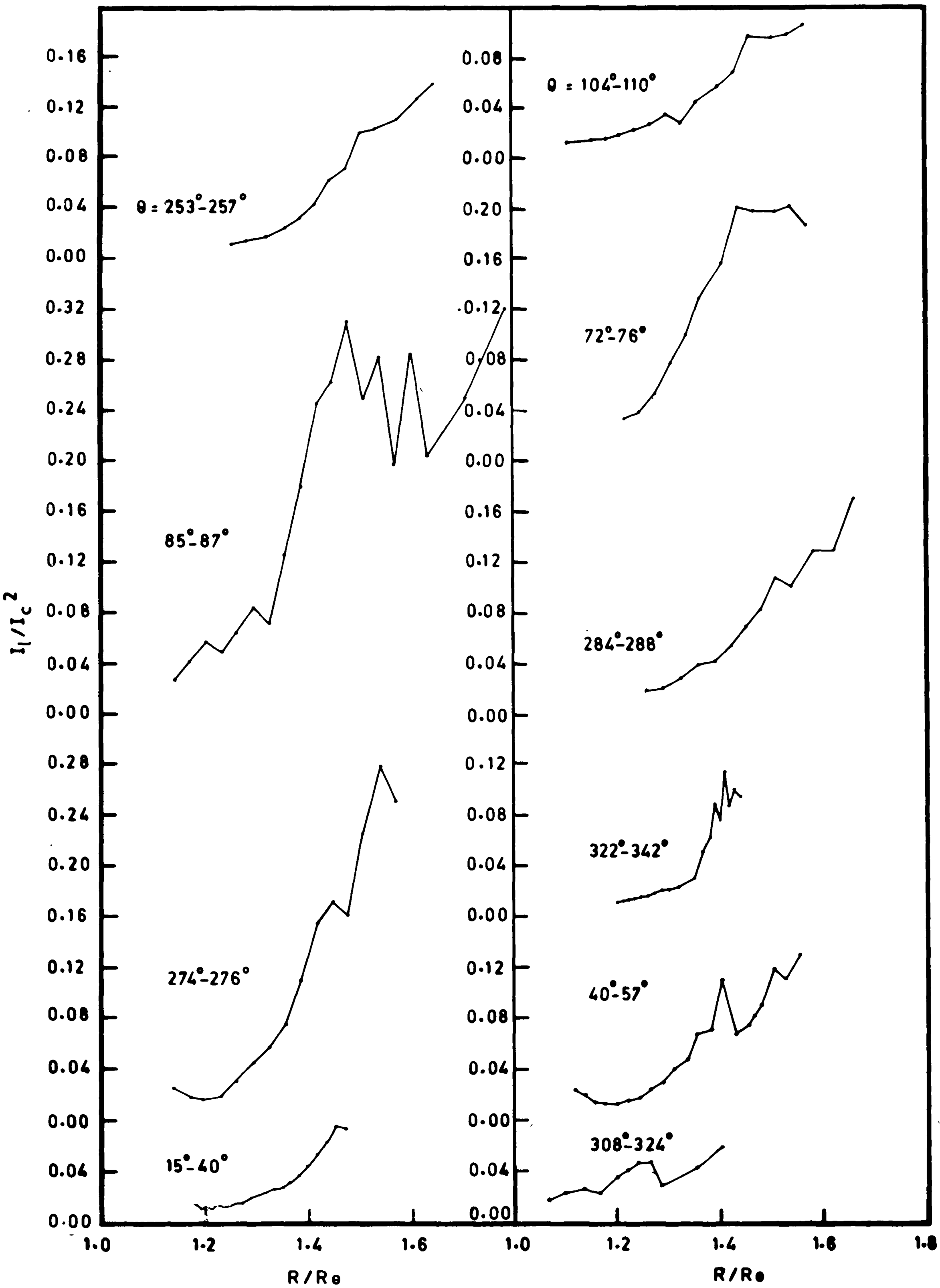

Fig. 6. I_l/I_c^2 versus radial distance. Position angle is indicated for each curve.

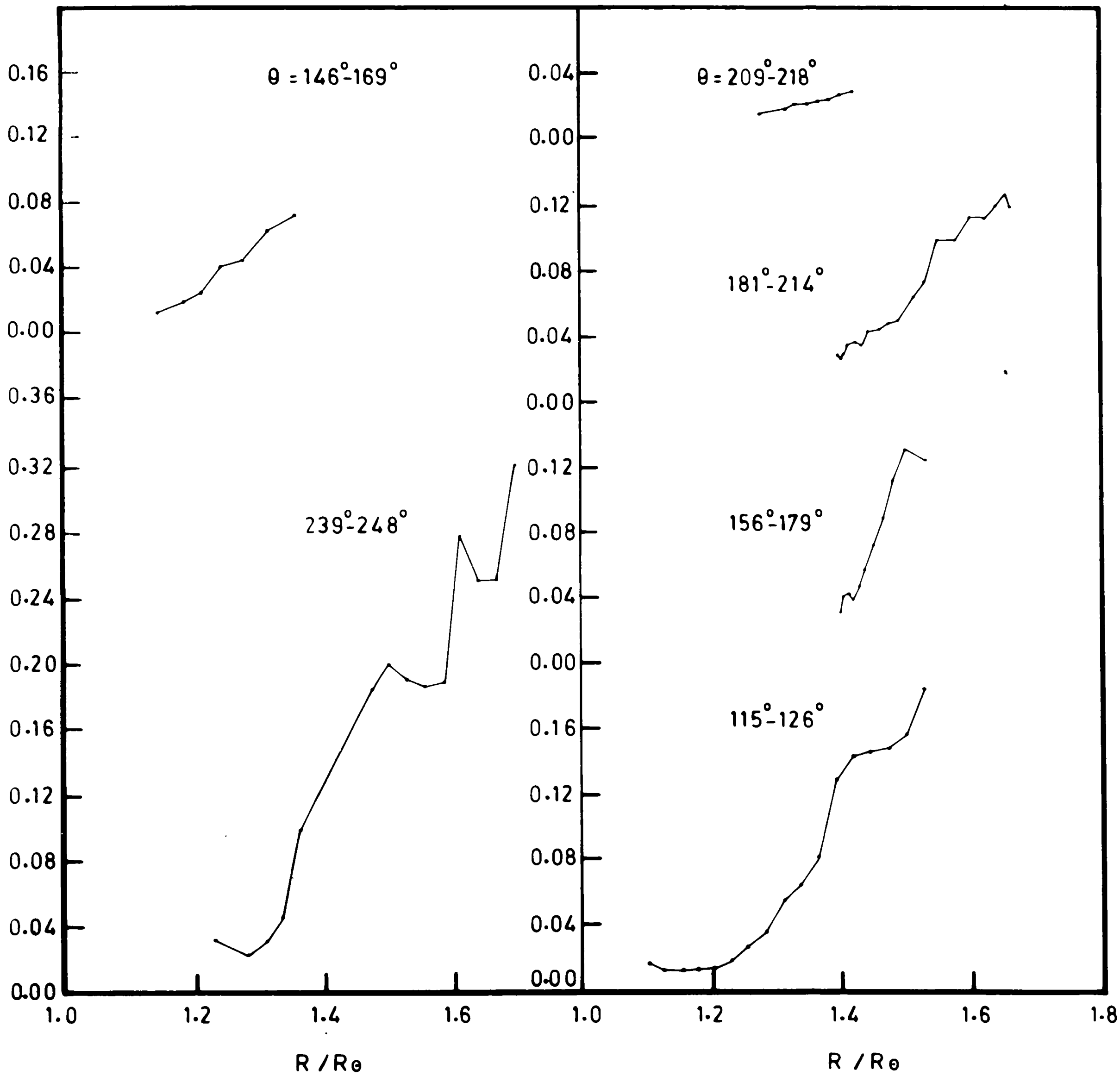

Fig. 7. I_l/I_c^2 versus radial distance. Position angle is indicated for each curve.

D is the dilution factor, g_u and g_l are statistical weights for upper and lower levels and T_r is radiation temperature.

Similarly the rate of collisional excitation by electrons per unit volume is (de Boer *et al.*, 1972)

$$C_{lu} = 8.63 \times 10^{-6}\, T_e^{-1/2}\, (\Omega(l, u)/g_l)\, (n(\text{Fe x})/n(\text{Fe}))A(\text{Fe})\, 0.8\, N_e^2\, e^{-h\nu/kT_e},$$

where T_e is the electron temperature and $\Omega(l, u)$ is the collision strength. Thus for isothermal corona R_{lu} is directly proportional to N_e whereas C_{lu} is proportional to the N_e^2.

Therefore if excitation is mainly collisional then the number of ions in the excited state is proportional to the square of the electron density. On the other hand, if radiative excitation is dominant, then the number of ions in the excited state would simply be proportional to the electron density. In other words, for radiative excitation I_l/I_c will be constant and I_l/I_c^2 will increase with distance. In the case of collisional excitation, I_l/I_c^2 will be a constant and I_l/I_c will decrease with distance. Thus, the behaviour of the ratios I_l/I_c and I_l/I_c^2 as a function of distance can tell us which of the two modes is the dominant one (Billings, 1966).

The main point to be noted is that we do see three regions where the behaviour of I_l/I_c and I_l/I_c^2 is distinct. For $R/R_\odot < 1.2$, I_l/I_c^2 is almost constant and I_l/I_c falls steeply indicating collisional excitation. For $1.2 < R/R_\odot < 1.4$, I_l/I_c^2 increases with $R/R_\odot$ and I_l/I_c varies slowly implying that both radiative excitation and collisional excitation are important. Beyond 1.4 $R/R_\odot$, I_l/I_c^2 increases with radial distance at a faster rate compared to that for $R/R_\odot < 1.4$. Thus collisional excitation seems to be less important for $R/R_\odot > 1.4$ than for $R/R_\odot < 1.4$. This in turn indicates that radiative excitation becomes more important at larger $R/R_\odot$ values.

Therefore, one can say that for $R/R_\odot < 1.2$ the mode of excitation is more or less collisional; collisional as well as radiative excitation is equally important for $1.2 < R/R_\odot < 1.4$; and for $R/R_\odot > 1.4$, radiative excitation becomes more dominant. At the same time one should note that these indicate only an average behaviour and are not meant to demarcate the boundaries of the excitation mode. The coronal regions $R/R_\odot > 1.2$ in all directions show an increase of I_l/I_c^2 with radial distance and only 50% of the directions indicate that I_l/I_c remains unchanged. The other half of the directions show that I_l/I_c increases between $1.2 < R/R_\odot < 1.4$ and has a maximum value around 1.4 $R_\odot$. One way of interpreting the maximum value of I_l/I_c is to accept that it represents a maximum in the degree of ionization at 1.4 $R_\odot$ along these directions.

However, without an independent knowledge of the variation of electron density with distance, it is difficult to make any statement regarding the degree of ionization and hence the variation of temperature. It is, however, interesting to note that the region close to the south pole exhibits somewhat lower values of I_l/I_c and that this region happens to contain a coronal hole. The presence of nonthermal random motions is clear, but a sensible assessment of either the variation of temperature or turbulence is not possible. However, certain broad characteristics can be inferred from our data.

One striking feature is the difference between the line width seen in contiguous 'open' field and 'closed' field regions near the south pole (Figure 8). The mean value of line widths in the open field region in the direction of 180° which contained a coronal hole, is 1.36 ± 0.26 Å (slit I(2)). The mean of the line widths in a closed field region which contained helmets, in the mean direction of 157°, is 1.76 + 0.38 Å (slit I(1)) and for another closed region at 215° (mean) it is 1.93 ± 0.33 Å (slit I(1)). The abnormally high values of the line width in the closed regions unaccompanied by any abnormalities in the ratio I_l/I_c has an important bearing on the nonthermal processes that could occur in those complex magnetic configurations seen at the neutral points of helmet and streamer structures.

Yet another characteristic that deserves comment is the general coincidence of the maxima in I_l/I_c and line width at 1.4 $R_\odot$. If this could be interpreted as a coincidence of maximum temperature and turbulence, then it brings out the usefulness of the line

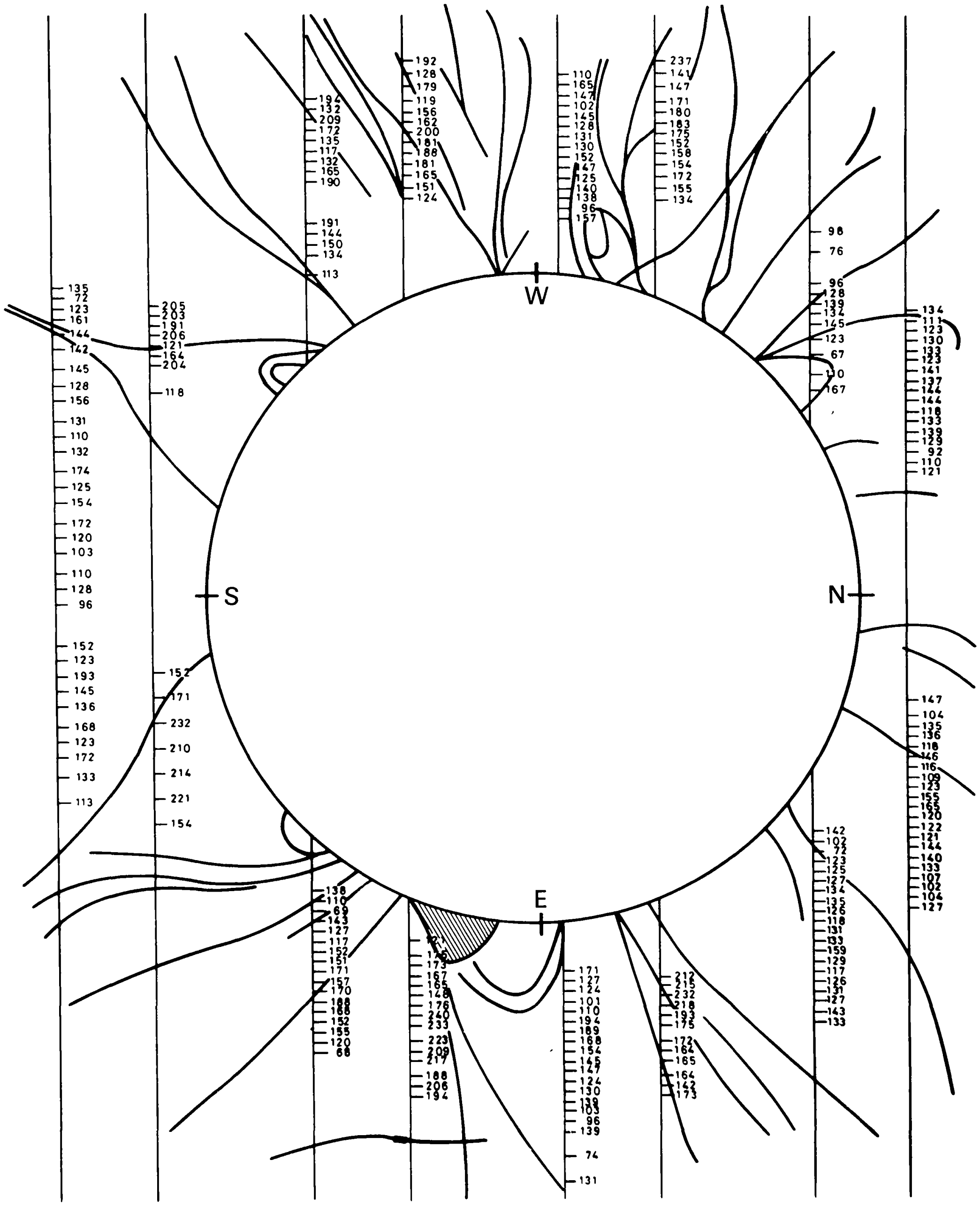

Fig. 8. True line widths of 6374 Å at various locations are indicated in units of 10^{-2} Å. Roman numerals denote the slit positions on the solar disc and the Arabic numeral in the bracket denotes the plate number. A free hand sketch of the conspicuous features of the corona as seen in the white light photograph is superposed. Shaded area on the east limb stands for an enhancement (from Singh *et al.*, 1982).

profile data in the observational study of coronal heating mechanisms, which have hitherto received mainly theoretical attention (e.g. Ionson, 1983).

4. Conclusion

We conclude that for $R/R_\odot < 1.2$, the mode of excitation of Fe X ions is predominantly collisional. Collisional as well as radiative excitation is important for $1.2 < R/R_\odot < 1.4$, whereas beyond $R/R_\odot = 1.4$ radiative excitation becomes dominant.

Acknowledgements

The experiment was planned by the late Dr M. K. Vainu Bappu. I thank Dr P. Venkatakrishnan and Drs K. R. Sivaraman, P. K. Raju, and W. C. Livingston for useful discussions.

References

Billings, D. E.: 1966, *A Guide to the Solar Corona*, Academic Press, New York.
Cheng, C. C., Doschek, G. A., and Feldman, U.: 1979, *Astrophys. J.* **227**, 1037.
de Boer, K. S., Olthof, H., and Pottasch, S. R.: 1972, *Astron. Astrophys.* **16**, 417.
Delone, A. B. and Makarova, E. A.: 1975, *Solar Phys.* **45**, 157.
Ionson, J. A.: 1983, in J. O. Stenflo (ed.), 'Solar and Stellar Magnetic Fields: Origins and Coronal Effects', *IAU Symp.* **102**, 391.
Jordan, C.: 1969, *Monthly Notices Roy. Astron. Soc.* **142**, 501.
Mariska, J. T., Feldman, U., and Doschek, G. A.: 1978, *Astrophys. J.* **226**, 698.
Singh, J.: 1984, Ph.D. Thesis, Punjabi University, Patiala.
Singh, J., Bappu, M. K. V., and Saxena, A. K.: 1982, *J. Astrophys. Astron.* **3**, 249.