Fe XVI LINE RATIOS IN THE SUN

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Received 1993 December 8; accepted 1994 March 18

ABSTRACT

Recent R-matrix calculations of electron impact excitation rates in Fe XVI are used to derive the emission-line ratios $R_1 = I(251.07 \text{ Å})/I(335.40 \text{ Å})$, $R_2 = I(262.98 \text{ Å})/I(335.40 \text{ Å})$, and $R_3 = I(265.00 \text{ Å})/I(335.40 \text{ Å})$. A comparison of these with solar observational data obtained by the Naval Research Laboratory's S082A slitless spectrograph on board Skylab reveals generally good agreement between theory and observation, which provides experimental support for the accuracy of the atomic data adopted in the analysis. However, several of the measured ratios are much larger than theory predicts, which is probably due to saturation of the strong 335.40 Å line on the photographic film used to record the S082A data. The potential usefulness of $R_1$, $R_2$, and $R_3$ as electron temperature diagnostics for the solar corona is briefly discussed.

Subject headings: atomic data — atomic processes — Sun: flares — Sun: UV radiation

1. INTRODUCTION

Emission lines arising from transitions in Na-like ions have been frequently observed in the spectra of both laboratory and astrophysical plasmas (Sandlin et al. 1986; Wang et al. 1988). Flower & Nussbaumer (1975) pointed out that these transitions may be used to determine the electron temperature of the solar transition region/corona through diagnostic line ratios, although to calculate these reliably accurate atomic data must be employed, especially for electron impact excitation rates. In addition, Feldman & Doschek (1977) have shown that the Na-like emission-line ratios are also sensitive to variation in the electron density when $N_e \geq 10^{13} \text{ cm}^{-3}$, so that they may be used as $N_e$-diagnostics in laboratory plasmas such as tokamaks, where $N_e$ is greater than this limit (see, for example, Keenan et al. 1991).

Recently, Tayal (1994) has calculated electron impact excitation rates for transitions in Na-like Fe XVI with the R-matrix code of Burke & Robb (1975). In this paper we use the Tayal rates to derive emission line ratios for Fe XVI applicable to the solar atmosphere, and compare these with flare and active region observations from the S082A instrument on board Skylab.

2. ATOMIC DATA AND THEORETICAL RATIOS

The model ion adopted for Fe XVI consisted of the six energetically lowest LS states, namely, $3s^2S$, $3p^2P$, $3d^2D$, $4s^2S$, $4p^2P$, and $4d^2D$, making a total of 10 levels when the fine structure splitting was included. Energies of all these levels were taken from Corliss & Sugar (1982).

Electron impact excitation rates for transitions among the six lowest LS states in Fe XVI have been calculated by Tayal (1994) using the R-matrix code (Burke & Robb 1975). These data, which include the effects of resonance structure in the collision strengths, are probably the most accurate currently available, and have therefore been adopted in the present analysis.

Einstein A-coefficients for allowed transitions in Fe XVI were obtained from the extensive compilation of Fuhr et al. (1981). Radiative rates for the forbidden $3s^2S$ -- $3d^2D$ transitions from Godefroid et al. (1985) were also included in the model ion, although we note that inclusion of these data do not have a significant effect on the derived emission-line ratios.

As has been discussed by, for example, Seaton (1964), proton excitation may be important for transitions with small excitation energies, i.e., fine-structure transitions such as in the $2s^22p^2^2P$ ground term of fluorine-like Fe XVIII (Foster, Keenan, & Reid 1994). However, test calculations for Fe XVI setting the proton rates for $^2P_{1/2} - ^2P_{3/2}$ and $^2D_{3/2} - ^2D_{5/2}$ equal to the electron rates, or 100 times these values, had a negligible effect on the level populations, showing this atomic process to be unimportant, as found by Keenan, Dufton, & Kingston (1986) and Keenan (1988) for the Na-like ions Al XII, Si IV, and S VI.

Using the atomic data discussed above in conjunction with the statistical equilibrium code of Dufton (1977), relative Fe XVI level populations and hence emission-line strengths were calculated for a range of electron temperatures about that of maximum Fe XVI fractional abundance in ionization equilibrium, log $T_e = \log T_{\text{max}} = 6.4$ (Arnaud & Raymond 1992). The following assumptions were made in the calculations: (1) that ionization to and recombination from other ionic levels is slow compared with bound-bound rates, (2) that photoexcitation and induced de-excitation rates are negligible in comparison with the corresponding collision rates, (3) that all transitions are optically thin. Further details of the procedures involved may be found in Dufton (1977) and Dufton et al. (1978).

In Figure 1 the theoretical emission-line ratios

$$R_1 = I(3p^2P_{1/2} - 3d^2D_{5/2})/I(3s^2S - 3p^2P_{3/2}),$$

$$R_2 = I(3p^2P_{3/2} - 3d^2D_{5/2})/I(3s^2S - 3p^2P_{3/2}),$$

are plotted as a function of electron temperature at an electron density of $N_e = 10^{11} \text{ cm}^{-3}$, although we note that the results
are insensitive to variations in the density for $N_e \leq 10^{16}$ cm$^{-3}$ (Feldman & Doschek 1977). The ratio

$$R_3 = l(3p^2 2P_{3/2} - 3d^2 D_{3/2})/l(3s^2 S - 3p^2 P_{3/2})$$

has the same temperature dependence as $R_1$ due to common upper levels, except that

$$R_3 = 0.161 \times R_1.$$  

3. RESULTS AND DISCUSSION

The $3p^2 2P_{3/2} - 3d^2 D_{3/2}$ and $3p^2 3P_{3/2} - 3d^2 D_{5/2}$, $3p^2 3P_{3/2} - 3d^2 D_{3/2}$ and $3s^2 S - 3p^2 P_{3/2}$ emission lines in Fe xvi have been observed at wavelengths of 251.07, 262.98, 265.00 Å, and 335.40 Å, respectively, in solar spectra obtained with the Naval Research Laboratory’s XUV slitless spectrograph (SO82A) on board Skylab (Dere 1978). This instrument operated in the 171–630 Å wavelength range in two sections (171–350 Å and 300–630 Å), and produced dispersed images of the Sun on photographic film with a spatial resolution of 2″ and a maximum spectral resolution of $\sim 0.1$ Å. It is discussed in detail by Tousey et al. (1977) and Dere (1978).

In Table 1 we summarize measurements of the line ratios

$$R_1 = l(251.07 \text{ Å})/l(335.40 \text{ Å}) ,$$

$$R_2 = l(262.98 \text{ Å})/l(335.40 \text{ Å}) ,$$

$$R_3 = l(265.00 \text{ Å})/l(335.40 \text{ Å}) ,$$

for several active regions observed between 1973 January and June (discussed in detail by Dere 1982), and the solar flares of 1973 August 9 at 1553 and 1557 UT (Dere & Cook 1979; Dere et al. 1979), 1973 December 17 at 0044 UT (Widing & Spencer 1980; Widing & Cook 1987), and 1973 December 22 at 0222 UT (Widing 1982).

Also listed in Table 1 are the theoretical values of $R_1$, $R_2$, and $R_3$ at the temperature of maximum Fe xvi fractional abundance in ionization equilibrium, log $T_{\text{max}} = 6.4$ (Arnaud & Raymond 1992). An inspection of the table reveals that there is good agreement between theory and observation for the McMath 12686 active region, and also the August 9, 1553 UT and December 22 flares, with average discrepancies of only 18%, 21%, and 11% for $R_1$, $R_2$, and $R_3$, respectively. However, for the other solar features the observed line ratios are consistently larger than theory predicts, by up to a factor of 3.3 in one instance ($R_1$ in active region McMath 12390). These disagreements could be due to (1) blending of the 251.07, 262.98, and 265.00 Å lines (which would lead to their intensities being overestimated), (2) the strong 335.40 Å resonance transition being optically thick, or (3) saturation of this line on the photographic film, both of which would lead to an underestimation of the line intensity. To investigate the first of these possibilities, we summarize in Table 1 the observed values of $R_1/R_2$ and $R_4/R_3$, along with the theoretical estimates. An inspection of the table reveals generally very good agreement between observation and theory for these ratios, with typical discrepancies of only 10% for $R_1/R_2$ and 25% for $R_4/R_3$. Hence it is highly unlikely that blends contribute a significant amount to the 251.07, 262.98, and 265.00 Å line intensities, especially as inspection of line lists reveals no probable blending candidates (Kelly & Palumbo 1973). Optical thickness of the 335.40 Å transition may also be discounted, as this should affect all the solar features, and in addition the resonance lines in other Na-like ions have been found to be optically thin under solar plasma conditions (Keenan, Dufon, & Kingston 1986; Keenan 1988). We therefore conclude that saturation of the 335.40 Å line on the photographic film is probably the cause of the observed discrepancies between theory and observation.

As all of the emission lines in $R_1$, $R_2$, and $R_3$ have large A-values, they are in the coronal approximation (Elwert 1952), so that the theoretical values of the ratios depend principally

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on the ratio of the $3s^2S-3d^2D$ and $3s^2S-3p^2P$ electron excitation rates. The good agreement found between theory and observation for $R_1$, $R_2$, and $R_3$ in several solar features therefore provides experimental support for the accuracy of the adopted atomic data.

Finally, we note that the ratios in Figure 1 are quite sensitive to changes in the electron temperature, and hence in principle may be useful as $T_e$-diagnostics for the solar corona. For example, $R_1$ varies by $\sim 40\%$ between $\log T_e = 5.9$ and 6.8, while $R_2$ changes by $\sim 45\%$ over the same temperature interval. These variations are significantly larger than the estimated uncertainties in the theoretical line ratios, which are less than $15\%$ given that the relevant excitation rates should be in error by less than $10\%$ (Tayal 1994). However, for reliable temperatures to be derived, the observed ratios would need to be determined to a much higher degree of accuracy than is possible with the S082A instrument ($\sim 30\%$; Keenan et al. 1984; Widing, Feldman, & Bhatia 1986). In the future accurate measurements for Fe xvi should be possible using the Coronal Diagnostic Spectrometer on board SOHO (Harrison 1993).

E. S. C. is grateful to the SERC for financial support, while V. J. F. acknowledges the award of a studentship from the Department of Education of Northern Ireland. This work was supported by NATO travel grant CRG.930722 and the Nuffield Foundation.

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