Solar EUV Rocket Telescope and Spectrograph (SERTS) Observations of Fe XII Emission Lines

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Theoretical electron density sensitive emission line ratios involving transitions in the 186–383 Å wavelength range are compared with observational data for a solar active region and a subflare, obtained by the *Solar EUV Rocket Telescope and Spectrograph* (*SERTS*). Electron densities derived from the majority of the ratios are consistent with one another, and are also in good agreement with the values of density estimated from diagnostic lines in other species formed at similar temperatures to Fe XII. These results provide observational support for the general accuracy of the diagnostic calculations. In addition, our analysis indicates that a line at 283.70 Å in the active region spectrum is the $3s^2 3p^3\ ^2D_{3/2}$– $3s3p^4\ ^2P_{1/2}$ transition in Fe XII, the first time (to the best of our knowledge) that this line has been identified in the solar spectrum. Several of the line ratios considered are predicted to be relatively insensitive to the adopted electron temperature and density, and the generally good agreement found between theory and observation for these provides evidence for the reliability of the *SERTS* instrument calibration. The application of the Fe XII diagnostics to *EUVE* observations of the F5 subgiant Procyon is briefly discussed.

1. Introduction

Emission lines due to $3s^2 3p^3$–$3s3p^4$ and $3s^2 3p^3$–$3s^2 3p^2 3d$ transitions in Fe XII have been frequently observed in solar spectra (see, for example, Kastner & Mason 1978). Dere et al. (1979) noted that the ratios of these lines are very sensitive to electron density, and hence are potentially very useful N_e–diagnostics for the emitting plasma. These authors plotted several theoretical Fe XII line ratios as a function of density, but restricted their results to diagnostics involving either $3s^2 3p^3$–$3s3p^4$ or $3s^2 3p^3$–$3s^2 3p^2 3d$ transitions only. This was primarily because the S082A spectrograph on board *Skylab*, from which Dere et al. obtained their observational data, detected solar spectra in two wavelength settings, making the measurement of ratios involving lines in both wavelength regions difficult to determine. More recently however, the *Solar EUV Rocket Telescope and Spectrograph* (*SERTS*) has obtained solar spectra over the full wavelength range of 170–450 Å in a single exposure (Thomas & Neupert 1994), thereby allowing the development and testing of Fe XII diagnostics involving both $3s^2 3p^3$–$3s3p^4$ and $3s^2 3p^3$–$3s^2 3p^2 3d$ transitions. This is potentially very important, as both the *Extreme Ultraviolet Explorer* satellite (*EUVE*) and the *Coronal Diagnostic Spectrometer* on board the *Solar and Heliospheric Observatory* (*SOHO*) mission, should detect many of the Fe XII EUV lines, which fall within the 186– 383 Å wavelength range. In this paper we therefore compare theoretical Fe XII line ratios with the *SERTS* observations, and hence investigate their usefulness as electron density diagnostics.

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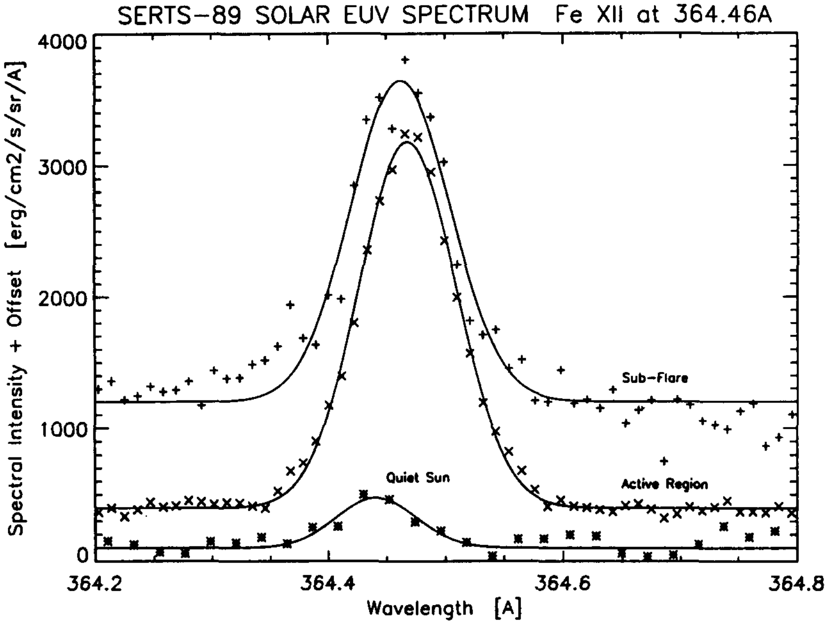

FIGURE 1. Plot of the active region and subflare spectra obtained with *SERTS* in the wavelength interval 364.2 – 364.8 Å, containing the Fe XII 364.46 Å line. Also shown in the figure are the *SERTS* Quiet Sun observations in this wavelength range.

2. Observational Data

The solar spectra analysed in the present paper are those of an active region and a small subflare, recorded on Eastman Kodak 101–07 emulsion by *SERTS* during a rocket flight on 1989 May 5 at 17:50 UT (Neupert et al. 1992). The observations cover the wavelength region 235.46–448.76 Å in first order and 170–224.38 Å in second, with a spatial resolution of about 7 arc sec and a spectral resolution of better than 80 mÅ (FWHM). The active region measurements used here were spatially averaged over the central 4.6 arc min of the spectrograph slit, whereas the subflare results come from a 22 arc sec portion of the same dataset.

The Fe XII transitions identified in the *SERTS* spectra are listed in Table 1, where we note that we have detected the 196.62 and 283.70 Å lines, which were not listed by Thomas & Neupert (1994) in their summary of the 1989 May 5 observations. Our tenative measurement of the $3s^23p^3\ {}^2D_{3/2}$ $-3s3p^4\ {}^2P_{1/2}$ line at 283.70 Å is of particular importance, as to the best of our knowledge this transition has not previously been detected in solar spectra. Intensities of the Fe XII lines were determined by fitting gaussian profiles to microdensitometer scans of the recorded spectra. The intensities of the 364.46 Å line in the two solar features are listed in Table 1; the observed intensities of the other Fe XII transitions may be inferred from these using the line ratios given in the table.

The quality of the observational data are illustrated in Figure 1, where we plot the active region and subflare spectra between 364.2–364.8 Å. Also shown for comparison in

TABLE 1. Fe XII transitions in the 1989 May 5 *SERTS* observations.

Transition	λ(Å)	R =I(λ)/I(364.46 Å)		Ratio
		Active region[a]	Subflare[b]	designation
$3s^23p^3\ ^2D_{5/2}$– $3s^23p^2(^3P)3d\ ^2F_{7/2}$	186.88	5.73+0[c]	1.04+1	R_1
$3s^23p^3\ ^4S$– $3s^23p^2(^3P)3d\ ^4P_{1/2}$	192.37	1.02+1	1.18+1	R_{11}
$3s^23p^3\ ^4S$– $3s^23p^2(^3P)3d\ ^4P_{3/2}$	193.51	5.49+0	5.35+0	R_{12}
$3s^23p^3\ ^4S$– $3s^23p^2(^3P)3d\ ^4P_{5/2}$	195.12	5.24+0	6.62+0	R_{13}
$3s^23p^3\ ^2D_{5/2}$– $3s^23p^2(^1D)3d\ ^2D_{5/2}$	196.62[d]	7.95–1	–	R_2
$3s^23p^3\ ^2P_{3/2}$– $3s^23p^2(^1D)3d\ ^2S$	200.41	1.57+0	2.93+0	R_9
$3s^23p^3\ ^2P_{3/2}$– $3s^23p^2(^1D)3d\ ^2P_{3/2}$	201.13	1.69+0	1.48+0	R_3
$3s^23p^3\ ^2D_{5/2}$– $3s^23p^2(^3P)3d\ ^2P_{3/2}$	219.43	5.83–1	7.77–1	R_4
$3s^23p^3\ ^2D_{3/2}$– $3s3p^4\ ^2P_{1/2}$	283.70[d]	7.85–2	–	R_8
$3s^23p^3\ ^2D_{5/2}$– $3s3p^4\ ^2P_{3/2}$	291.01	4.69–1	4.42–1	R_5
$3s^23p^3\ ^2D_{3/2}$– $3s3p^4\ ^2D_{3/2}$	335.04	5.59–2	7.08–2	R_6
$3s^23p^3\ ^2D_{5/2}$– $3s3p^4\ ^2D_{5/2}$	338.27	3.30–1	5.27–1	R_7
$3s^23p^3\ ^4S$– $3s3p^4\ ^4P_{1/2}$	346.86	2.88–1	2.72–1	R_{14}
$3s^23p^3\ ^4S$– $3s3p^4\ ^4P_{3/2}$	352.11	6.22–1	7.54–1	R_{15}
$3s^23p^3\ ^4S$– $3s3p^4\ ^4P_{5/2}$	364.46	1.00+0	1.00+0	–
$3s^23p^3\ ^2P_{3/2}$– $3s3p^4\ ^2D_{5/2}$	382.86	3.06–2	3.38–2	R_{10}

[a] I(364.46 Å) = 288.0 erg $cm^{-2}\,s^{-1}\,sr^{-1}$.
[b] I(364.46 Å) = 260.0 erg $cm^{-2}\,s^{-1}\,sr^{-1}$.
[c] A±B implies A × $10^{\pm B}$.
[d] Line not listed by Thomas & Neupert (1994).

the figure are the *SERTS* Quiet Sun data in this wavelength range, which we note are of too low a quality for reliable Fe XII line ratios to be derived.

3. Theoretical Ratios

The model ion adopted for Fe XII has been discussed by Keenan et al. (1995), where details of the line ratio calculations may be found. In Table 1 we list the electron density sensitive emission line ratios R_1 through R_{10}; plots of these ratios as a function of electron density may be found in Keenan et al. (1995).

4. Results and Discussion

In Table 2 the electron densities derived from the observed values of R_1 through R_{10} in Table 1 are summarised. An inspection of the table reveals that the logarithmic electron densities deduced from R_1, R_3 and R_9 in the active region are all $\geq$11.0, which are much higher than those previously estimated for active regions at electron temperatures where the Fe XII lines are formed in ionisation equilibrium, T_{max} = 1.4 × 10^6 K (Arnaud & Raymond 1992). For example, Brickhouse, Raymond & Smith (1995) derived log $N_e \simeq$ 9.5 for the *SERTS* active region from line ratios in Fe XIII, which is formed at a similar electron temperature to Fe XII (T_{max}(Fe XIII) = 1.6 × 10^6 K; Arnaud & Raymond 1992). The very large Fe XII densities deduced here probably arise from overestimates

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TABLE 2. Fe XII logarithmic electron densities.

Ratio	Log N_e(R) Active region	Subflare
R_1	11.0	H[a]
R_2	9.6	–
R_3	11.2	11.0
R_4	9.6	9.8
R_5	10.1	10.1
R_6	9.2	9.3
R_7	10.1	10.3
R_8	9.7	–
R_9	11.5	H
R_{10}	9.5	9.5
Mean density[b]	9.7±0.3	9.8±0.4

[a]Indicates that the observed ratio is larger than the theoretical high density limit.
[b]Average density excluding results from the R_1, R_3 and R_9 ratios.

TABLE 3. Fe XII density insensitive ratios.

Ratio	Observed Active region	Observed Subflare	Theoretical[a]
R_{11}	1.02+1[b]	1.18+1	2.55+0
R_{12}	5.49+0	5.35+0	6.78+0
R_{13}	5.24+0	6.62+0	1.12+1
R_{14}	2.88–1	2.72–1	3.67–1
R_{15}	6.22–1	7.54–1	6.99–1

[a]Ratios calculated for $N_e = 10^{10}$ cm^{-3}; $T_e = T_{max} = 1.4 \times 10^6$ K (Arnaud & Raymond 1992).
[b]A±B implies A $\times$ $10^{\pm B}$.

of the relevant line ratios due to blending, a conclusion which is also supported by the fact that R_1 and R_9 in the subflare are larger than the theoretical high density limits.

Electron densities deduced from the remaining Fe XII line ratios in Table 2 are consistent, with discrepancies of typically $\leq$0.3 dex with the mean values, $\overline{log\ N_e} = 9.7\pm0.3$ and 9.8±0.4 for the active region and subflare, respectively. These mean densities are in excellent agreement with the values determined from diagnostic ratios in species formed at similar temperatures to Fe XII. For example, as noted above, Brickhouse et al. (1995) found log $N_e \simeq 9.5$ for the active region from Fe XIII, while for the subflare we derive log $N_e \simeq 9.5$ from the I(219.12 Å)/I(211.32 Å) ratio in Fe XIV (Keenan et al. 1991), which has $T_{max} = 1.9 \times 10^6$ K (Arnaud & Raymond 1992). In addition, the fact that the R_8 ratio leads to an electron density in good agreement with those inferred from the other Fe XII diagnostics confirms our tentative identification of the 283.70 Å feature as the $3s^23p^3\ ^2D_{3/2}$ $-3s3p^4\ ^2P_{1/2}$ line. These results provide experimental support for the theoretical Fe XII line ratios (and hence the atomic data used in their derivation), and implies that they may be applied in the future to high resolution observations from the *Coronal Diagnostic Spectrometer* on the *SOHO* mission (Harrison 1993).

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We note that the line ratios R_{11} through R_{15} in Table 1 are predicted to be relatively insensitive to the adopted plasma parameters (temperature and density), and hence may be useful in investigating either blending or the reliability of the instrument calibration (Neupert & Kastner 1983). The observed values of R_{11} through R_{15} are therefore summarised in Table 3, along with the calculated ratios. An inspection of the table reveals excellent agreement between theory and observation for R_{12}, R_{14} and R_{15}, with discrepancies of $\leq$25% in all cases, once again providing support for the theoretical ratios. Additionally, as R_{12} contains the 364.46 and 193.51 Å transitions, measured in first and second order, respectively, the good agreement also provides verification of the *SERTS* instrument calibration between the two orders. However agreement between theory and observation for R_{11} and R_{13} is very poor, which is probably due to a combination of blending in the observational data and errors in the theoretical line ratios (see Keenan et al. 1995 for more details). More theoretical work on the Fe XII spectrum is clearly needed.

Several of the Fe XII lines discussed in this paper have been observed in *EUVE* spectra of the F5 subgiant Procyon (Drake, Laming & Widing 1995). Unfortunately, these authors do not list an intensity for the 364.46 Å line (probably due to blending with nearby strong features, such as Mg IX 367.34 Å), and only give data for the 186.88, 192.37, 193.51 and 195.12 Å transitions. However the ratio I(186.88 Å)/I(192.37 Å) is predicted to be N_e-sensitive, and the Drake et al. value of ~0.6 implies log $N_e \simeq 9.5$. This is in excellent agreement with the densities estimated for Procyon from species formed at similar temperatures to Fe XII, including Fe XIII and Fe XIV, which give log $N_e \simeq 9.5$–9.7 (Drake et al.). We note that although the 192.37 Å line, observed in second order by *SERTS*, is blended with the first order Mn XV 384.75 Å transition in this dataset (Thomas & Neupert 1994), this problem does not of course apply to the *EUVE* observations. In addition, although 186.88 Å is blended with S XI in *SERTS*, it appears to be resolved by *EUVE* (Drake *et el.*).

Both the I(193.51 Å)/I(192.37 Å) and I(195.12 Å)/I(192.37 Å) ratios are predicted to be insensitive to N_e and T_e, with theoretical values of 2.6 and 4.3, respectively. The *EUVE* measurement of the former, I(193.51 Å)/I(192.37 Å) $\simeq$ 1.7, is in reasonable agreement with theory, but the observed value of I(195.12 Å)/I(192.37 Å) $\simeq$ 2.1 is smaller than theory predicts. This problem is also found in the *SERTS* observations (see Table 3), and is probably due to errors in the adopted atomic data (see Keenan et al. 1995).

Clearly, more work on the Fe XII emission lines in *EUVE* observations is required, especially regarding their usefulness as N_e-diagnostics. We plan to undertake this research in the near future (Drake & Keenan 1995).

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