Fe XIII Emission Lines Observed by *EUVE* and the S082A Instrument On-Board *Skylab*

F. P. KEENAN,[1] J. J. DRAKE,[2] V. J. FOSTER,[1] C. J. GREER,[1] S. S. TAYAL,[3] AND K. G. WIDING[4]

[1]Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN, N. Ireland

[2]Center for EUV Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720-5030, USA

[3]Department of Physics and Center for Theoretical Studies of Physical Systems, Clark Atlanta University, Atlanta, GA 30314, USA

[4]Code 4174W, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington DC 20375, USA

Recent R-matrix calculations of electron impact excitation rates for Fe XIII are used to derive the theoretical electron density sensitive emission line ratios R_1 = I(318.12 Å)/I(320.80 Å) and R_2 = I(256.42 Å)/I(251.95 Å), which are found to be up to 50% different from earlier diagnostics. A comparison of the current line ratios with both solar flare and active region observations, obtained by the Naval Research Laboratory's S082A spectrograph on board *Skylab*, reveals generally good agreement between densities deduced from Fe XIII and those estimated from diagnostic line ratios in species formed at similar temperatures. This provides experimental support for the accuracy of the line ratio calculations, and hence the atomic data adopted in their derivation. In *Extreme Ultraviolet Explorer* satellite (*EUVE*) spectra the Fe XIII emission lines are found to be severely blended. However, an analysis of these lines measured in the spectra of Procyon and α Cen demonstrates that they still allow very approximate values of the electron density to be inferred. Moreover, it should be possible to increase the accuracy of the measured line fluxes, and hence of the inferred densities, if longer exposures of the stars concerned can be obtained.

1. Introduction

Emission lines arising from $3s^23p^2$– $3s3p^3$ transitions in Fe XIII have been frequently detected in solar EUV spectra (Dere 1982), while more recently they have been measured in *Extreme Ultraviolet Explorer* (*EUVE*) satellite observations of late-type stars, such as Procyon (Drake, Laming & Widing 1995). The diagnostic potential of these lines was first noted by Flower & Nussbaumer (1974), and since then several authors have produced theoretical Fe XIII line ratios, the most recent being those of Brickhouse, Raymond & Smith (1995), which employ the electron excitation rates of Fawcett & Mason (1989). However very recently, Tayal (1995) has used the R-matrix code to calculate electron rates for transitions in Fe XIII, which include the effects of resonances converging to the $3s^23p^2$, $3s3p^3$ and $3s^23p3d$ states.

In this paper we use the Tayal (1995) atomic data to derive diagnostic line ratios for Fe XIII, and compare them both with previous calculations, and with solar and stellar observations from *Skylab* and *EUVE.*

2. Theoretical Ratios

The model ion for Fe XIII has been discussed by Keenan et al. (1995), where details of the line ratio calculations may be found. In Figure 1 we plot the ratio R_1 = I($3s^23p^2$

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 525–529.

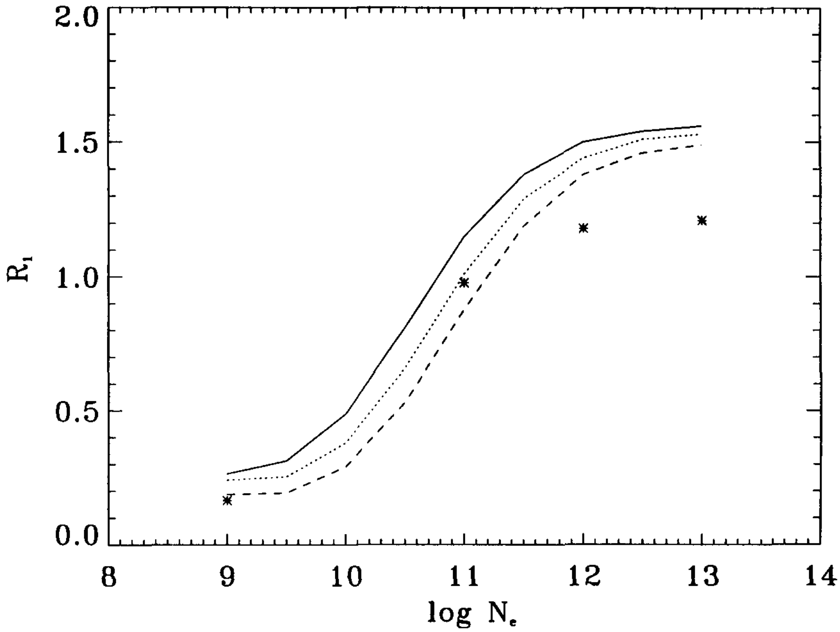

FIGURE 1. The theoretical Fe XIII emission line ratio R_1 = I(318.12 Å)/I(320.80 Å), plotted as a function of electron density at electron temperatures of log T_e = 5.9 (*solid line*); 6.2 (*dotted line*); 6.5 (*dashed line*). The calculations of Brickhouse et al. (1995) at log T_e = 6.2 are shown as stars.

^{1}D– $3s3p^3$ ^{1}D)/I($3s^23p^2$ $^3P_2$ – $3s3p^3$ $^3P_2$) = I(318.12 Å)/I(320.80 Å) as function of electron density at the temperature of maximum Fe XIII fractional abundance in ionisation equilibrium, log T_{max} = 6.2 (Arnaud & Raymond 1992), plus ±0.3 dex about this value. Also shown in the figure are the calculations of Brickhouse et al. (1995) at log T_{max}. Our line ratios are up to 50% different from those of Brickhouse et al. , which is principally due to the adoption of improved electron excitation rate data in the present paper. We note that a similar figure for the ratio R_2 = I($3s^23p^2$ ^{1}D– $3s3p^3$ ^{1}P)/I($3s^22p^2$ $^3P_2$ – $3s3p^3$ ^{3}S) = I(256.42 Å)/I(251.95 Å) may be found in Keenan et al. (1995).

3. Observational Data

The Fe XIII 251.95, 256.42, 318.12 and 320.80 Å emission lines discussed in § 2 have been extensively observed in the solar spectrum by the Naval Research Laboratory's S082A spectrograph on board *Skylab*. 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 ~0.1 Å. It is discussed in detail by Dere (1978). In Table 1 we summarize measurements of R_1 and R_2 for two active regions and two flares. Unfortunately, R_2 could not be determined in most of the features due to blending of the 256.42 Å line with the very strong He II transition at 256.32 Å. As the R_1 and R_2 ratios involve lines which

https://doi.org/10.1017/S0252921100036496 Published online by Cambridge University Press

TABLE 1. Fe XIII emission line ratios and derived logarithmic electron densities.

Feature	R_1	R_2	log N_e (R_1)	log N_e (R_2)	log N_e (other)
(i) Skylab S082A observations[a]					
Active region McMath 12390	0.31	...	9.7	...	9.5[b]
Active region McMath 12375	0.25	...	9.5	...	9.4[b]
1973 Dec 17 flare, 0044 UT	0.50	0.62	10.3	10.5	10.4[b]
1973 Dec 17 flare, 0045 UT	0.82	...	10.8	...	10.6[b]
1974 Jan 21 flare, 2346 UT	1.03	...	11.0	...	10.8[c]
(ii) EUVE observations					
Procyon[d]	0.70±0.50	...	≤11.3	...	9.5[b]
α Cen[e]	0.78±0.41	...	10.6±0.8	...	9.2[b]

NOTES:
[a]These line ratio data should be accurate to ±20%, and hence the derived values of log N_e to ±0.2 dex.
[b]Determined from the I(219.12 Å)/I(211.32 Å) line ratio in Fe XIV.
[c]Determined from the I(215.97 Å)/I(191.29 Å) line ratio in S XI.
[d]Observed between 1993 Jan 11, 2219 UT and 1993 Jan 15, 0028 UT (100,000 sec total exposure time).
[e]Observed between 1993 May 29, 1355 UT and 1993 May 31, 0836 UT (45,000 sec total exposure time).

are close together in wavelength and are approximately equal in intensity, we estimate that the data listed in Table 1 should be accurate to approximately ±20%.

The *EUVE* instrumentation has been described in detail elsewhere. In summary, the spectrograph covers the wavelength range 70–760 Å in three bandpasses, commonly referred to as "Short", "Medium" and "Long", or SW, MW and LW, where the bandpasses are as follows: SW 70–190 Å; MW 140–380 Å; LW 280–760 Å, and the resolution in each bandpass varies from $\lambda/\Delta\lambda = 190$ (blue end) to 290 (red end). The best stellar candidates for studying EUV emission lines due to Fe XIII are Procyon (F5 IV) and α Cen (G2 V + K0 V). However as the resolution of the MW spectrometer near 256 Å is about 0.8 Å; we did not therefore expect to be able to extract fluxes for Fe XIII 256.42 Å, since it is blended with the much stronger He II line at 256.32 Å. Hence we have concentrated on the Fe XIII lines around ~318–320 Å. The intensities of the Fe XIII lines were estimated for each star by fitting Gaussian profiles using a least squares technique (see Keenan et al. 1995), the profile fit for α Cen being shown in Figure 2. The resultant R_1 ratios are summarised in Table 1, where uncertainties have been calculated from the error matrix in the least squares fitting procedure.

4. Results and Discussion

The logarithmic electron densities deduced from the observed values of R_1 and R_2 in the solar features are summarised in Table 1. In view of the observational uncertainties in the line ratios (see § 3), the derived values of log N_e should be accurate to approx-

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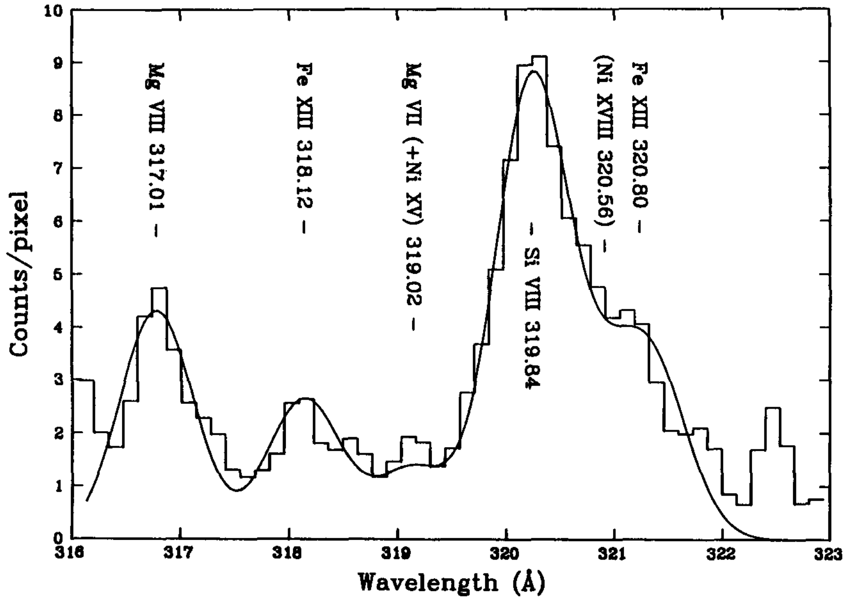

FIGURE 2. *EUVE* spectrum of α Cen in the 316–323 Å wavelength range, showing the results of a profile fitting procedure for the emission lines indicated.

imately ±0.2 dex. Also given in the table are the densities estimated from either the I(219.12 Å)/I(211.32 Å) emission line ratio in Fe XIV or the I(215.97 Å)/I(191.29 Å) ratio in S XI; as these ions are formed at electron temperatures close to that of Fe XIII, densities deduced from their line ratios should be similar to those estimated for the Fe XIII emitting region of the plasma.

An inspection of Table 1 reveals that, for the 1973 Dec 17 flare at 0044 UT, the densities derived from R_1 and R_2 are compatible, with a difference of only 0.2 dex. In addition, these values of N_e, and those estimated from R_1 in the other events, are in good agreement with densities found from line ratios in species formed at similar temperatures to Fe XIII, with discrepancies that average only ~0.1 dex. These results provide experimental support for the accuracy of the current line ratio calculations, and hence the atomic data adopted in their derivation.

The observational uncertainty of the R_1 ratio for Procyon in Table 1 implies that no firm estimate of the electron density is possible from Figure 1, with only an upper limit of log $N_e \leq 11.3$ being inferred. However in the case of α Cen, the error in the ratio is somewhat smaller, and hence the density may be constrained to log $N_e \simeq 10.6\pm0.8$. As for the solar observations, these values may be compared with the densities in Table 1 determined from line ratios in Fe XIV, namely log $N_e = 9.5$ and 9.2 for Procyon and α Cen, respectively (see Keenan et al. 1995). Although at face value these densities are not strictly compatible with the Fe XIII results, in reality the true error in disentangling the Fe XIII line fluxes from those of the blending species is larger than the simple Poisson error. It is clear therefore that these lines do not currently provide any reliable diagnostic information on the Fe XIII emitting regions of stellar atmospheres,

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due to the large observational uncertainties in the line ratios. This is caused in part by blending, but primarily by the lack of adequate signal-to-noise in the spectral data to allow detailed profile fitting to be performed, and hence the contribution of blends to be properly assessed and removed. Clearly, higher quality observations of the ~316–323 Å wavelength region in Procyon and α Cen are required in order for reliable profile fitting to be attempted, and we hope to obtain these during future allocations of observing time with *EUVE*.

We would like to thank the Principal Investigators S. Bowyer and R.F. Malina and the *EUVE* Science Team for advice and support, and N. Brickhouse for a copy of her work in advance of publication. JJD was supported by NASA contract NAS5–30180 during the course of this work, while VJF acknowledges financial support from the Particle Physics and Astronomy Research Council of the United Kingdom. This work was also supported by the Royal Society and NATO travel grant CRG.930722.

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