SOFT X-RAY EMISSION LINES OF Fe xv IN SOLAR FLARE OBSERVATIONS AND THE CHANDRA SPECTRUM OF CAPELLA

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ABSTRACT

Recent calculations of atomic data for Fe xv have been used to generate theoretical line ratios involving \( n = 3\)–4 transitions in the soft X-ray spectral region (\( \sim 52\)–83 Å), for a wide range of electron temperatures and densities applicable to solar and stellar coronal plasmas. A comparison of these with solar flare observations from a rocket-borne spectograph (X-Ray Spectrometer/Spectrograph Telescope [XSST]) reveals generally good agreement between theory and experiment. In particular, the 82.76 Å emission line in the XSST spectrum is identified, for the first time to our knowledge in an astrophysical source, as the 3s 3d \( ^3D_2 \sim 3s\) 4p \( ^3P_2 \) transition of Fe xv. Most of the Fe xv transitions that are blended have had the species responsible clearly identified, although there remain a few instances in which this has not been possible. The line ratio calculations are also compared with a co-added spectrum of Capella obtained with the Chandra satellite, which is probably the highest signal-to-noise ratio observation achieved for a stellar source in the \( \sim 25\)–175 Å soft X-ray region. Good agreement is found between theory and experiment, indicating that the Fe xv lines are reliably detected in Chandra spectra and hence may be employed as diagnostics to determine the temperature and/or density of the emitting plasma. However, the line blending in the Chandra data is such that individual emission lines are difficult to measure accurately, and fluxes may only be reliably determined via detailed profile fitting of the observations. The co-added Capella spectrum is made available to hopefully encourage further exploration of the soft X-ray region in astrophysical sources.

Subject headings: atomic data — stars: individual (Capella) — stars: late-type — Sun: flares — Sun: X-rays, gamma rays

Online material: color figure

1. INTRODUCTION

Emission lines arising from \( n = 3\)–3 transitions in Fe xv are widely detected in solar extreme ultraviolet (EUV) spectra covering the \( \sim 200\)–400 Å wavelength interval (Dere 1978; Thomas & Neupert 1994). The \( 3s^2 \ 1S \sim 3s\) \( ^3P \) resonance line at 284 Å is one of the most intense emission features in the solar EUV spectrum, and has been also widely observed in stellar coronal sources by the Extreme Ultraviolet Explorer (EUV) satellite (Laming & Drake 1999). Bely & Blaha (1968) first noted the potential of EUV lines of Fe xv as diagnostics for the emitting plasma, and since then many authors have calculated emission line intensities for this ion and compared these with solar observations (see, e.g., Kastner & Bhatia 2001 and references therein).

However, Fe xv also shows a rich emission line spectrum in the soft X-ray region, \( \sim 50\)–80 Å, arising from \( n = 3\)–4 transitions. In contrast to the EUV lines, there has been little work on the soft X-ray transitions in the astrophysical literature, probably as a result of the limited availability of high-quality solar spectra for this wavelength region. There were several rocket-borne flights in the 1960’s that covered the soft X-ray region, but these detected few or no Fe xv transitions (see, e.g., Austin et al. 1966; Widing & Sandlin 1968; Behring et al. 1972; Malinovsky & Heroux 1973). The most detailed measurements of the \( n = 3\)–4 lines in Fe xv to date were made by the X-Ray Spectrometer/Spectrograph Telescope (XSST) spectrograph during a rocket flight in 1982 (Acton et al. 1985). However, even these observations have only been subject to a brief analysis by Bhatia et al. (1997), as part of their work to produce a large atomic data set for this ion. Finally, Campbell & Brickhouse (2001) presented preliminary results from an investigation of Fe xv and Fe xvi lines in Chandra X-ray spectra of the late-type, coronally active stars Capella (G1 III+ G8 III) and Procyon (F5 IV).

In this paper we use the most recent atomic physics calculations for Fe xv to generate soft X-ray line ratios for a wide range of electron temperatures and densities applicable to coronal plasmas. We compare these in detail with the XSST observations of Acton et al. (1985) to assess the usefulness of the Fe xv transitions as plasma diagnostics. However, in addition we analyze a Chandra spectrum of Capella constructed from multiple observations. This co-added X-ray spectrum has one of the highest signal-to-noise ratios ever achieved for an astrophysical coronal plasma in the \( \sim 25\)–175 Å soft X-ray region, thus allowing us to perform an investigation of the Fe xv \( n = 3\)–4 lines in an astronomical source other than the Sun.

The Capella spectrum is also made freely available to encourage further research on the soft X-ray spectral region. For example, in conjunction with the published XSST solar line list, the Capella data should be useful for reliably identifying new emission features. In addition, there are potentially many useful diagnostic lines in the soft X-ray wavelength range, especially for solar flare–type plasmas (see, e.g., Brown et al. 1986; Feldman et al. 1992), and hence further exploration and assessment of these is warranted.

2. THEORETICAL LINE RATIOS

The model ion for Fe xv consisted of the energetically lowest 53 fine-structure levels belonging to the \( 3s^2, 3s\ 3p, 3p^2, 3s\ 3d, \)
Fig. 1.—Theoretical Fe xv emission line intensity ratios $R_1 = I(52.91 \text{ Å})/I(59.40 \text{ Å})$, $R_2 = I(63.97 \text{ Å})/I(59.40 \text{ Å})$, and $R_3 = I(69.65 \text{ Å})/I(59.40 \text{ Å})$, where $I$ is in photon units and plotted as a function of logarithmic electron temperature ($T_e$ in K) at an electron density of $N_e = 10^{10} \text{ cm}^{-3}$. However, we note that the line ratios are insensitive to the adopted electron density for $N_e = 10^{8}–10^{13} \text{ cm}^{-3}$.

3p 3d, 3d$^2$, 3s 4s, 3s 4p, 3s 4d, 3p 4s, and 3s 4f configurations. Energies of these levels were obtained from Churilov et al. (1985, 1989), Litzen & Redfors (1987), Sugar & Corliss (1985), and Aggarwal et al. (2003).

Electron impact excitation rates for transitions among all the levels discussed above were taken from Aggarwal et al. (2003). For Einstein $A$-coefficients, the calculations of Deb et al. (1999) were employed for allowed and intercombination lines. Radiative rates for forbidden transitions have also been taken from the work of Deb et al., although the data were not included in the published paper for conciseness. Other $A$-value results for the forbidden transitions are in general very similar to those calculated by others, such as Bhatia et al. (1997). Proton impact excitation is only important for transitions among the 3s 3p $^3P$ levels of Fe xv, and in the present analysis we have employed the calculations of Landman & Brown (1979).

Fig. 2.—Theoretical Fe xv emission line intensity ratios $R_2 = I(53.11 \text{ Å})/I(59.40 \text{ Å})$ and $R_3 = I(55.78 \text{ Å})/I(59.40 \text{ Å})$, where $I$ is in photon units, plotted as a function of logarithmic electron temperature ($T_e$ in K) at logarithmic electron densities of $\log N_e = 9.0$, 10.0, and 11.0 ($N_e$ in cm$^{-3}$).

Using the atomic data discussed above in conjunction with a recently updated version of the statistical equilibrium code of Dufton (1977), relative Fe xv level populations and hence emission line strengths were calculated for a wide range of electron temperatures ($T_e$) and densities ($N_e$). Details of the procedures involved and approximations made may be found in Dufton (1977) and Dufton et al. (1978).

In Figures 1–7 we plot the theoretical emission line intensity ratios $R_1$ through $R_{11}$, which are defined in Table 1. These ratios are shown as a function of $T_e$ and/or $N_e$ for a range of temperatures ($T_e = 10^6–10^{10} \text{ K}$) over which Fe xv has a fractional abundance in ionization equilibrium of $N(\text{Fe xv})/(\text{Fe}) > 10^{-3}$ (Mazzotta et al. 1998), and for values of $N_e (=10^8–10^{13} \text{ cm}^{-3})$ appropriate to solar and stellar coronal plasmas. In some instances the ratios are predicted to be insensitive to electron density over the $N_e$ interval considered (for example, $R_1$), in which case values are plotted only as a function of electron temperature at a single density. Others, such as $R_5$, are weakly dependent on density and are therefore shown for a limited range of $N_e$ values. However, those ratios that vary significantly with $T_e$ and $N_e$, such as $R_4$, are plotted over the full range of plasma parameters. We note that the $R_{12}$ ratio is not shown in the figures, as it has the same temperature.
and density dependence as $R_3$, owing to common upper levels, but with

$$R_{12} = 2.95R_3.$$ 

Given errors in the adopted atomic data of typically ±10% (Aggarwal et al. 2003; Deb et al. 1999; Landman & Brown 1979), we would expect the theoretical ratios to be accurate to better than ±20%.

The ratios in Figures 1–7 are given relative to the 59.40 Å transition, as this feature is the cleanest and most reliably detected Fe xv emission line in the soft X-ray spectral region. This has been checked by a search of line lists and also by generating synthetic spectra with the latest version (4.2) of the CHIANTI database (Dere et al. 1997; Young et al. 2003), which confirm that no blending species is present that has a line intensity greater than 2% of that of the Fe xv 59.40 Å feature.\(^5\)

An inspection of Figures 1–7 reveals that several of the ratios are sensitive to variations in the electron temperature and/or density. For example, $R_7$ varies by a factor of about 2.0 between $T_e = 10^8$ and $10^6$ \(\text{K}\) while being insensitive to the adopted electron density. Similarly, $R_{11}$ changes by a factor of 3.4 over the (relatively narrow) density interval of $N_e = 10^9$–$10^{11}$ \(\text{cm}^{-3}\) at $T_e = 10^6$ \(\text{K}\). Hence the ratios should, in principle, provide useful $T_e$- and/or $N_e$-diagnostics for the Fe xv emitting region of a plasma.

We note that the present theoretical line ratios are generally not excessively different from other recent calculations. For example, at $T_e = 10^6.3$ \(\text{K}\) and $N_e = 10^8$ \(\text{cm}^{-3}\), we calculate $R_3$ = 0.58 compared to $R_3$ = 0.68 from CHIANTI and $R_1$ = 0.38 from Bhatia et al. (1997). Similarly, at these plasma parameters we find $R_2 = 3.6$, compared to $R_2 = 3.5$ (CHIANTI) and $R_7 = 3.3$ (Bhatia et al. 1997). However, a notable exception is the $R_2$ ratio, for which we estimate $R_2 = 0.17$ at $T_e = 10^6.3$ \(\text{K}\) and $N_e = 10^8$ \(\text{cm}^{-3}\), and Bhatia et al. calculate $R_2 = 0.11$. By contrast, CHIANTI indicates that $R_3$ = 0.019, a factor of 6–9 lower than the other results. This discrepancy arises due to the adopted $A$-value for the $3s^2 1S - 3s 4p^3 P_1$ transition. In our calculations, we use $A = 8.1 \times 10^{10}$ \(\text{s}^{-1}\) from Deb et al. (1999), and Bhatia et al. employ their own value of $A = 8.4 \times 10^{10}$ \(\text{s}^{-1}\). However the CHIANTI database uses $A = 1.5 \times 10^{10}$ \(\text{s}^{-1}\) from Griffin et al. (1999), which is significantly smaller than the other two calculations. Furthermore, Deb et al. undertook two independent calculations of radiative rates for Fe xv, using the CLI3 atomic structure code of Hibbert (1975) and the GRASP code of Dyall et al. (1989). Their $A$-values for the $3s^2 1S - 3s 4p^3 P_1$ transition from the two codes differ by only 11%, and as a consequence

\[ R = \frac{I(\lambda)}{I(59.40 \text{ Å})} \]

### TABLE 1

**Fe xv Transitions in the X-St Solar Flare Spectrum and Line Ratio Designations**

| Wavelength (Å) | Transition | $R = \frac{I(\lambda)}{I(59.40 \text{ Å})}$ |
|----------------|------------|---------------------------------|
| 52.91          | $3s^2 1S - 3s 4p^3 P_1$ | $R_1$ |
| 53.11          | $3s^2 1S - 3s 4p^3 P_1$ | $R_1$ |
| 55.78          | $3s 3p^3 P_1 - 3s 4d^3 D_{3/2}$ | $R_9$ |
| 56.17          | $3s 3p^3 P_1 - 3s 4d^3 D_{3/2}$ | $R_9$ |
| 59.40          | $3s 3p^3 P_1 - 3s 4d^3 D_{3/2}$ | $\cdots$ |
| 63.97          | $3p^2 1D_{5/2} - 3s 4f^3 F_{1/2}$ | $R_5$ |
| 66.25          | $3s 3p^3 P_1 - 3s 4d^3 D_{5/2}$ | $R_9$ |
| 69.65          | $3s 3p^3 P_1 - 3s 4d^3 D_{3/2}$ | $R_7$ |
| 69.93          | $3s 3d^3 D_{5/2} - 3s 4f^3 F_{5/2}$ | $R_8$ |
| 69.98          | $3s 3d^3 D_{5/2} - 3s 4f^3 F_{5/2}$ | $R_9$ |
| 70.05          | $3s 3d^3 D_{5/2} - 3s 4f^3 F_{3/2}$ | $R_{10}$ |
| 73.47          | $3s 3d^3 D_{5/2} - 3s 4f^3 F_{1/2}$ | $R_{12}$ |
| 82.76          | $3s 3d^3 D_{5/2} - 3s 4f^3 F_{1/2}$ | $R_{11}$ |
they assess that their calculations should be accurate to better than 20%. Given this and the excellent agreement with the result of Bhatia et al., who also performed an independent calculation with the SUPERSTRUCTURE code of Eissner et al. (1974), we therefore believe that the Griffin et al. $A$-value is in error and should be reevaluated.

3. OBSERVATIONAL DATA

We compare our Fe XV line ratio calculations with two data sets, namely that for a solar flare obtained with a rocket-borne spectrograph and a composite spectrum for Capella observed with the Chandra satellite. These data sets are discussed separately below.

3.1. Solar Flare Observations

The solar spectrum analyzed in the present paper is that of an M class flare, recorded on Kodak 101-07 emulsion by an X-ray spectrograph (XSST) during a rocket flight on 1982 July 13. These observations spanned the wavelength range 11–97 Å, at a spectral resolution of 0.02 Å, and covered a solid angle of approximately 625 arcsec$^2$, centered on or near the brightest source of X-rays. The XSST made two exposures, one of 54 s beginning at 16:33:50 UT and the other of 145 s commencing at 16:35:35 UT. Unfortunately, a failure of the mechanism to move the film more than 1 mm between the two exposures resulted in their being nearly superimposed on the same plate. However, a careful analysis allowed the two spectra to be separated so that analysis of the data could be performed, and the observations presented here are for the 145 s exposure. Further details of the XSST instrument can be found in Brown et al. (1979) and Bruner et al. (1980), while the observations are discussed in Acton et al. (1985).

It would clearly have been preferable to model the XSST observations in detail using profile fitting methods, as for the Chandra data (see § 3.2). This was unfortunately not possible, as the original XSST spectra are no longer available, following the retirement of several key staff involved in the mission. Consequently, only the published line list and intensities for XSST are now accessible. We have searched for Fe XV emission lines in the XSST spectrum using the identifications of Acton et al. (1985), the NIST database,$^6$ and other line lists, such as the Atomic Line List of P. van Hoof.$^7$ In Table 1 we list the Fe XV transitions found in the spectrum, along with their measured wavelengths.

The intensity of the 59.40 Å line of Fe XV measured by Acton et al. (1985) in the XSST spectrum is given in Table 2; observed intensities of the other Fe XV transitions may be inferred from this using the line ratios given in the table (see § 2). Acton et al. (1985) note that a strong second-order spectrum falling between 25–50 Å is evident in the XSST observations and that the effects of scattered light and double exposure made the reduction of the data difficult. However although it was difficult, Acton et al. did succeed in producing a well-calibrated spectrum and hence reliable measurements of emission line intensities. Evidence for this comes from, for example, our previous analysis of Ni XVIII emission lines in the XSST spectrum (Keenan et al. 1999). We found that for 6 out of 7 line ratios involving Ni XVIII transitions in the 41–53 Å wavelength region, agreement between theory and observation is excellent, with differences that average only 11%. For the sole Ni XVIII line ratio that shows a large discrepancy between theory and observation, this is explained by a known blend with a Fe XIX transition. The Fe XV lines in the XSST spectrum should in fact be more reliably measured than those for Ni XVIII, as the former lie outside the 25–50 Å range affected by the second-order spectrum. Brown et al. (1986) and Keenan et al. note that the relative intensities of lines in the XSST spectrum similar in strength to the Fe XV transitions discussed here should be accurate to about ±20%, and hence line ratios to ±30%. The observed Fe XV line ratios in Table 2 have therefore been assigned a uniform ±30% uncertainty.

3.2. Capella Spectrum

3.2.1. Observations and Reduction

Capella is the mainstay target for calibrating and monitoring the Chandra transmission grating spectrometer dispersion relation. As such, it is currently observed approximately every 12 months using the LETG+HRC-S combination. The Capella observations analyzed here were obtained by the Chandra Low-Energy Transmission Grating Spectrograph (LETGS), employing the High-Resolution Camera spectroscopic detector (HRC-S) in its standard configuration, yielding spectra with a resolution of approximately 0.06 Å. (See Weisskopf et al. 2003 for a recent overview of the Chandra instrumentation and its in-flight performance.) We have taken advantage of the multiple observations of Capella accrued to date to construct a composite spectrum with the highest signal-to-noise ratio possible. The different observations used, together with their dates of acquisition and exposure times, are listed in Table 3. Observations from 2002 were obtained at significantly different off-axis angles and were not included in this analysis.

Data were uniformly processed and spectra extracted using the Chandra Interactive Analysis of Observations (CIAO) software Version 3.1. Photon event lists were also filtered in detector pulse height in order to remove particle-induced background events.$^8$ The final extracted co-added spectrum is shown in Figure 8.$^9$ In Figure 9 we plot the 50–75 Å portion of the spectrum, as this contains all of the Fe XV soft X-ray lines identified in Capella. Unfortunately, the spectrum is too noisy at longer wavelengths for other (weak) Fe XV features to be detected.

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* See http://physics.nist.gov/PhysRefData/.
7 See http://star.pst.qub.ac.uk/~pvh/.

| Table 2 |
|---|---|---|
| **Fe XV Line Ratios in the XSST Solar Flare Spectrum** |
| Line Ratio | Observed | Theoretical$^b$ |
| $R_1$ | $0.78 ± 0.23$ | $0.58 ± 0.12$ |
| $R_2$ | $0.36 ± 0.11$ | $0.18 ± 0.04$ |
| $R_3$ | $0.33 ± 0.10$ | $0.13 ± 0.03$ |
| $R_4$ | $0.54 ± 0.16$ | $0.23 ± 0.05$ |
| $R_5$ | $0.35 ± 0.08$ | $0.40 ± 0.08$ |
| $R_6$ | $2.6 ± 0.8$ | $0.23 ± 0.05$ |
| $R_7$ | $3.0 ± 0.9$ | $3.6 ± 0.7$ |
| $R_8$ | $0.28 ± 0.08$ | $0.16 ± 0.03$ |
| $R_9$ | $0.33 ± 0.10$ | $0.25 ± 0.05$ |
| $R_{10}$ | $0.73 ± 0.22$ | $0.46 ± 0.09$ |
| $R_{11}$ | $0.75 ± 0.23$ | $0.50 ± 0.10$ |
| $R_{12}$ | $1.4 ± 0.4$ | $1.2 ± 0.2$ |

$^a$ If(59.40 Å) = 85 photons cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$.
$^b$ Determined from Figs. 1–7 at $T_e = 10^6 K$ and $N_e = 10^{10.4}$ cm$^{-3}$.
The Capella spectrum was analyzed using the PINTofALE\textsuperscript{10} IDL\textsuperscript{11} software suite (Kashyap & Drake 2000). Line fluxes were measured by fitting “modified Lorentzian,” or Moffat, functions of the form $F(\lambda) = a/[1 + (\lambda - \lambda_0)/\Gamma]^p$, where $a$ is the amplitude, and $\Gamma$ is a characteristic line width. For a value of $\beta = 2.4$, it has been found that $F(\lambda)$ reproduces the line response function of the LETG+HRC-S instrument to the photometric accuracy of lines with a few thousand counts or less (Drake 2004). Uncertainties were estimated using a Monte Carlo sampling of the free parameters in the line fits.

Free parameters are, in general, the line width, position, and amplitude, although for some of the fitting of poorer quality spectral features we constrained the line width to the value 0.065 Å/c. Position uncertainties were estimated using a Monte Carlo sampling of the free parameters in the line fits.

### 3.2.2. Analysis

The Capella spectrum was analyzed using the PINTofALE\textsuperscript{10} IDL\textsuperscript{11} software suite (Kashyap & Drake 2000). Line fluxes were measured by fitting “modified Lorentzian,” or Moffat, functions of the form $F(\lambda) = a/[1 + (\lambda - \lambda_0)/\Gamma]^p$, where $a$ is the amplitude, and $\Gamma$ is a characteristic line width. For a value of $\beta = 2.4$, it has been found that $F(\lambda)$ reproduces the line response function of the LETG+HRC-S instrument to the photometric accuracy of lines with a few thousand counts or less (Drake 2004). Uncertainties were estimated using a Monte Carlo sampling of the free parameters in the line fits.

Free parameters are, in general, the line width, position, and amplitude, although for some of the fitting of poorer quality spectral features we constrained the line width to the value 0.065 Å/c, which was found for nearby clean lines. Continua were estimated locally by eye for each fit. Line positions were allowed to vary from their reference positions by $\leq 0.05$ Å/c, this being dictated by the imaging characteristics of the HRC-S detector. As discussed by Chung et al. (2004), the HRC-S exhibits small-scale imaging nonlinearities that vary over the detector, and which can displace a spectral line from its true position by up to 0.05 Å/c. While this effect can be calibrated to some extent using bright, well-known spectral lines, the wavelength range of interest to this $\text{Fe}^{xv}$ study is devoid of such transitions, and the characteristics of the imaging nonlinearities have not been well defined in the relevant regions of the detector. For lines closely spaced in wavelength, the relative separations of the lines were kept fixed to their reference values, while the position of the group was allowed to vary. In the case of the group of lines in the 69.4–70.2 Å range (Fig. 10), the wavelengths of the 69.93, 69.98, and 70.05 Å transitions were decoupled from the stronger 69.65 Å feature. We found the best-fit location of the former group to be displaced by 0.04 Å from the reference position, while the latter line lies very close to its expected location.

The relatively unexplored and complex nature of the crowded soft X-ray spectrum in the 50–75 Å wavelength range poses particular challenges for estimating line fluxes. In addition to the lines from the $n = 3$ shells of abundant elements such as Mg, Si, S, and Ar and the $n = 3$ shell of Fe, lines from shorter wavelengths arising from higher spectral orders are also present in this range. Unlike the Chandra ACIS CCD detector, the HRC-S microchannel plate detector possesses no energy resolution of its own, and overlapping spectral orders cannot be separated. Prior to performing line fits we therefore looked for the presence of significant blends from known strong lines in higher orders.

The LETGS is designed with a grating bar-to-space ratio of 1 : 1, which results in some suppression of even orders. The most important order for line blends in the 50–75 Å range is the third, which has an efficiency of about 10% that of first order.\textsuperscript{12} Two of the $\text{Fe}^{xv}$ lines in our list coincided reasonably closely with notable third-order lines, $\lambda$66.25, which lies slightly less than one line width away from third-order $\lambda$22.098, and $\lambda$52.91, $\lambda$22.098, and $\lambda$52.91.

\textsuperscript{10} Freely available from http://hea-www.harvard.edu/PINTofALE/.

\textsuperscript{11} Interactive Data Language, Research Systems Inc.

\textsuperscript{12} See http://cxc.harvard.edu/cal/letg/HO2004/.

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| ObsID  | Exposure (ks) | Start Date (UT) | Start Time (UT) | End Date (UT) | End Time (UT) |
|-------|---------------|-----------------|-----------------|---------------|---------------|
| 58    | 34.11         | 2000 Mar 08     | 06:30:50        | 2000 Mar 08   | 16:25:31      |
| 62435 | 32.71         | 1999 Sep 06     | 00:27:21        | 1999 Sep 06   | 09:49:59      |
| 1009  | 26.97         | 2001 Feb 14     | 11:41:47        | 2001 Feb 14   | 19:27:44      |
| 1248  | 85.23         | 1999 Nov 09     | 13:28:25        | 1999 Nov 10   | 13:28:55      |
| 1420  | 30.19         | 1999 Oct 29     | 22:31:27        | 1999 Oct 30   | 07:29:02      |
| 3675  | 27.16         | 2003 Aug 28     | 04:23:10        | 2003 Sep 28   | 12:21:25      |

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**Fig. 8.—** Co-added LETG HRC-S spectrum of Capella in the 5–175 Å range. The top panel shows the full dynamic range of the spectrum, while the bottom panel is an expanded spectrum to more clearly show the emission features in the 25–175 Å soft X-ray wavelength region.

**Fig. 9.—** Portion of the co-added LETG HRC-S spectrum of Capella in the 50–75 Å range. Lines of $\text{Fe}^{xv}$ analyzed in the present paper are identified, together with some other prominent transitions of $\text{Fe}$, $\text{Mg}$, $\text{Si}$, and $\text{S}$. The pseudocontinuum comprises a superposition of weak lines from the $n = 2$ levels of abundant elements, mostly Mg, Si, S, and Ar, but also including contributions from the less abundant elements Na and Al.
which lies a line width away from third-order Fe xviii λ17.62. The O vii forbidden line is quite strong in the spectrum of Capella, and Fe xv λ66.25 was therefore discarded. However, Fe xviii λ17.62 is a much weaker line, of which there is no obvious sign in third order. It arises between the levels 2s2 2p4 3p2 P21/2 and 2s2 2p6 2S1/2 and occurs because of configuration mixing (Drake et al. 1999).

Spectral orders 4 and 5 have similar efficiencies of 2%–3% of first order. The O viii + Fe xviii λ16.00 blend coincides in fourth order with Fe xv λ63.97, and was included in the spectral fit with the relative wavelengths of the two components kept fixed. While there are no other strong lines blended with our Fe xv features in fourth and fifth orders, there is a slew of weaker lines from Δn > 0 transitions in the n = 2 shells of Fe and Ni that fall in the 50–75 Å range. These transitions give rise to an additional pseudocontinuum, which we treated empirically through the estimation of a local continuum for each line or line group. Such empirical local continua were also guided by the broadband “by eye” continuum, which can be seen in Figure 8.

In the fitting of some lines, neighboring features blend in with the line wings. In most cases, these blending features are not clean lines that could be unambiguously identified with particular transitions of accurately known wavelengths, but are often complex blends with some unidentified contributions. To account for these unidentified transitions in the measured fluxes of our lines of interest, we added line components in an ad hoc fashion until the profiles of blended features could be empirically matched. Examples are shown in Figure 10, while the observed Fe xv line ratios are listed in Table 4, along with their associated errors. In Table 5 we list the wavelengths of the additional ad hoc line components.

As with the XSST observations (see § 3.1), the measured intensity of the 59.40 Å line is given in Table 4, and those of the

| Table 4 | Fe xv line ratios in the Chandra observations of Capella |
|---------|--------------------------------------------------------|
| Line Ratio | Observed | Theoretical |
| R1       | 0.55 ± 0.06 | 0.58 ± 0.12 |
| R2       | 0.16 ± 0.03 | 0.18 ± 0.04 |
| R4       | 0.26 ± 0.06 | 0.21 ± 0.04 |
| R5       | 0.39 ± 0.06 | 0.40 ± 0.08 |
| R7       | 2.9 ± 0.2   | 3.6 ± 0.7  |
| R8       | 0.28 ± 0.06 | 0.15 ± 0.03 |
| R9       | 0.35 ± 0.07 | 0.24 ± 0.05 |
| R10      | 0.49 ± 0.06 | 0.44 ± 0.09 |
| R12      | 1.3 ± 0.1   | 1.2 ± 0.2  |

a (59.40 Å) = (9.7 ± 0.7) × 10^-5 photons cm^-2 s^-1.
b Determined from Figs. 1–7 at $T_e = 10^6$ K and $N_e = 10^{10.2}$ cm^-3.
other Fe xv transitions can be inferred from this table by using the line ratio values. It should be kept in mind during the interpretation of the measured fluxes that they are also prone to uncertainty caused by hidden blends of unidentified lines. For such cases, there is an expectation that the measured fluxes might be systematically too high.

4. RESULTS AND DISCUSSION

In Tables 2 and 4 we list the observed Fe xv emission line ratios from the XSST solar flare spectrum and the Chandra Capella observations, respectively. Also shown in the tables are the theoretical results from Figures 1–7 at the temperature of maximum fractional abundance in ionization equilibrium for Fe xv, Te = 10,000 K (Mazzotta et al. 1998), and at electron densities derived for the solar and Capella observations from emission line ratios in O vi (Brown et al. 1986; Phillips et al. 2001). The temperature-sensitive G-ratio for O vi in the XSST and Capella data indicates that Te = 10,000 K in both features, similar to that of maximum fractional abundance for Fe xv. In the case of Capella, whose coronal emission measure distribution rises quite steeply to a peak at Te = 6 × 10,000 K (see, e.g., Brickhouse et al. 2000), it is possible that this G-ratio slightly underestimates the mean temperature of line formation, as was found empirically by Testa et al. (2004) for a sample of active stars. However, the ion populations of both O vii and Fe xv peak at very similar temperatures, and hence the O vii density should still accurately reflect that of the Fe xv emitting region of the plasma. We have also verified that the slightly higher temperatures of line formation that would result from the relatively steep Capella emission measure distribution do not significantly change the predicted Fe xv line ratios from those listed in Table 4. The error bars on the theoretical results are based on the estimated ±20% accuracy of the line ratio calculations (see § 2).

An inspection of Table 2 reveals very good agreement between the XSST observations and the theoretical predictions for the ratios R5 and R7. This indicates that the 63.97 and 69.65 Å lines are well detected in the XSST spectrum, and must be relatively free from blends. In particular, we confirm the identification by Bhatia et al. of the 63.97 Å feature as the 3p2 4D–3s 4f 1F transition of Fe xv, and not the Al vi 2s2 2p2 3P1/2–2s2p2 3p 1D3/2 line as originally classified by Acton et al. (1985). These authors also identify the 69.65 Å line as being partially due to Si viii and Fe xv transitions, with an unknown feature responsible for most of the line flux. However, our result for R7 clearly shows that the line is primarily the Fe xv 3s 3p 1P–3s 3s 1S transition, as suggested by Bhatia et al. We have confirmed this by generating a synthetic spectrum using CHIANTI, which indicates that the Si viii 2s2 2p2 3S–2s2p2 3s4p 3/2 line only contributes about 15% to the total 69.65 Å flux, and that no Fe xiv transitions are present.

Similarly, the observed R1, R9, R10, R11, and R12 ratios in Table 2 are only slightly larger than the theoretical values, indicating that the 52.91, 69.98, 70.05, 73.47, and 82.76 Å lines must be mostly due to Fe xv. Indeed, within the observational and theoretical errors in the line ratios, all the observed fluxes may arise from this ion. This is supported by the CHIANTI synthetic spectrum, which predicts no significant blending species for the 52.91, 69.98, and 70.05 Å features, and contributions of only about 10% from Ne vii 1s2 2p2 3P1/2–1s2 4d2 3D3/2 and 20% from Ne ix 1s2 2p2 3P–1s 3s 1S to the 73.47 and 82.76 Å lines, respectively. Our classification of the 82.76 Å feature as the Fe xv 3s 3d 3D3/2–3s 3p 3P1/2 line is, to our knowledge, the first time this transition has been identified in an astrophysical source.

The good agreement between theory and observation for the above line ratios indicates that they should provide useful diagnostics for the Fe xv emitting region of a plasma. In particular, R7, R9, R10, and R11 are all temperature and/or density sensitive, and hence with careful use should allow these parameters to be derived. For example, R7 could be employed to evaluate Te, as it does not vary with Ne (see Fig. 1), and the latter could then be determined from R10 or R11 (see Figs. 6 and 7).

The observed values of R3, R4, R5, R6, and R8 in the XSST spectrum are all significantly larger than theory, implying that the 53.11, 55.78, 56.17, 66.25, and 69.93 Å lines of Fe xv are blended to varying degrees. For the 53.11 Å feature, the blending line contributes about 50% of the measured flux, and the CHIANTI synthetic spectrum indicates that this is most likely the Si ix 2s2 2p2 3P1–2p2 3s 3P1 2 transition. This is predicted to have an intensity of approximately 10% that of the Fe xv 3p 2P–4d 2D3/2 line at 54.13 Å, i.e., about 16 photons cm−2 s−1 arcsec−2. The measured flux of the 53.11 Å feature is 31 photons cm−2 s−1 arcsec−2, so Si ix should contribute 50%, in agreement with observation. We note that Acton et al. (1985) did not classify the 53.11 Å feature, as the Fe xv identification being suggested by Bhatia et al. (1997). However, we can now confirm that the line is the 3s 2 1S–3s 3p 3P1 transition of Fe xv, although it is blended.

For the 55.78 Å line, CHIANTI indicates that the Si x 2s2 2p2 2S–2p 2p 3s 3P1/2, 1/2 and Si ix 2s2 2p2 3P–2s2p 3D 3D transitions should together have an intensity about 70% that of the Fe xv line. Our observation of R3 implies that the blending species may be stronger, and contribute about 150% of the Fe xv flux. However, when the uncertainties in the experimental and theoretical R3 ratios are taken into account, the data are compatible with a 70% contribution from Si x and Si ix. Similarly, a comparison of theory and observation for R4 indicates that Fe xv only contributes about 10% to the intensity of the 66.25 Å feature. This is in agreement with CHIANTI, which predicts that 90% of the observed flux is due to the Fe xv 3s 3d 3D3/2–4f 2F5/2 line.

By contrast, it is not clear from CHIANTI what the blending species are for the 56.17 and 69.93 Å lines, with no transitions predicted to have intensities more than 10% those of the relevant Fe xv features. It is, however, possible that the blending may be due to strong lines observed by XSST in second or third order, which are appearing in first order at these wavelengths. For example, in the case of the 56.17 Å line, CHIANTI indicates no strong transitions in second order (i.e., around 28.09 Å), but the intense Ca xviii 1s2 2s 2S–1s2 3p 3P1/2 transition is predicted in third order (18.73 Å). Similarly, for the 69.93 Å line there is a predicted third-order feature at 23.31 Å, namely the Ca xvii 2s2 2p2 2P3/2–2s2p 3D3/2 transition. There are unfortunately no Ca xviii lines in the XSST spectrum for comparison purposes, but there is a Ca xvi transition at 21.45 Å.

### TABLE 5

| Fe xv λ (Å) | Blend λ (Å) | Candidate Identification |
|-------------|-------------|--------------------------|
| 52.91       | 52.72       | Fe xvii, Ni xvii         |
| 55.78       | 55.87       | Si ix                    |
| 56.17       | 56.06       | Ne ix, S ix, Fe xvii     |
| 59.40       | 59.27       | Fe xvii                  |
| 63.97       | 64.00       | O vi + Fe xvii fourth order |
| 57.47       | 57.37       | Ni xv                    |
| 73.47       | 73.58       | Ne xv                    |
(2s^2 2p^2 P_{1/2} - 2s^2 3d^2 D_{3/2}), with an intensity \( I = 37 \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2} \). However, the predicted CHIANTI intensity ratio is \( I(23.31 \, \text{Å})/I(21.45 \, \text{Å}) < 10^{-3} \), indicating that the Ca \( \text{xvi} \) 23.31 \, \text{Å} transition cannot be responsible for the blend in the 69.93 \, \text{Å} line. Clearly, the identification of the blends for the 56.17 and 69.93 \, \text{Å} features will require further work.

In the case of the Chandra observations of Capella, agreement between theory and experiment in Table 4 is very good for the majority of the line ratios. Where there are discrepancies, such as for \( R_k \), these tend to mirror those found for the XSSST spectrum, with the observed value being somewhat larger than theory, indicative of some blending. However, in most instances the observed line ratios actually show smaller discrepancies with theory than do the XSSST results. To a certain extent, such agreement may be judged to be unsurprising, as in our analysis of the Capella observations we added line components in an ad hoc fashion until the profiles of blending features could be empirically matched (see § 3.2). Nevertheless, our results indicate that profile fitting of the Chandra data rather than simple measurements of emission line intensities does allow the reliable detection of Fe \( \text{xv} \) soft X-ray features in the 50–75 \, \text{Å} wavelength range. Indeed, our work represents (to our knowledge) the first time that the Fe \( \text{xv} \) new transition. In addition, the Fe \( \text{xv} \) identifications for several emission features and also detected a soft X-ray spectrum. In summary, we have performed a detailed analysis of Fe \( \text{xv} \) soft X-ray lines in the ~52–83 \, \text{Å} wavelength region, observed in the solar spectrum by the XSSST spectrograph, and confirmed identifications for several emission features and also detected a new transition. In addition, the Fe \( \text{xv} \) lines have been measured in Chandra observations of Capella and appear to provide potentially useful plasma diagnostics. We therefore hope that our work will stimulate renewed interest in this relatively unexplored spectral region, in particular through our provision of the co-added Chandra spectrum for Capella, which are probably the highest signal-to-noise data available. Many dozens of lines in the solar soft X-ray spectrum are without identifications, and the Capella spectrum (in combination with the XSSST solar line list) should provide an aid to the identification of soft X-ray transitions and the investigation of their usefulness as plasma diagnostics. This will be important for future space missions, and in particular the EEU Variability Experiment (EVE), which is part of the Solar Dynamics Observatory (SDO), due for launch in 2008. One of the EVE instruments is the Multiple EUV Grating Spectrograph (MEGS), which will observe the 50–1050 \, \text{Å} region at a spectral resolution of 1 \, \text{Å}. Clearly, the lines in this wavelength range will need to be identified and understood in advance of MEGS observations, as this instrument will not be able to resolve them individually.

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\[ ^{13} \text{See http://lasp.colorado.edu/eve/} \]