NEW EUV Fe\textsc{x} EMISSION LINE IDENTIFICATIONS FROM HINODE/EIS

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ABSTRACT

Four Fe\textsc{x} transitions in the wavelength range 188–198 Å are identified for the first time in spectra from the EUV Imaging Spectrometer on board the Hinode satellite. In particular the emission line at 197.86 Å is unblended and close to the peak of the EIS sensitivity curve, making it a valuable diagnostic of plasma at around 800,000 K—a critical temperature for studying the interface between the corona and transition region. Theoretical ratios among the four lines predicted from the CHIANTI database reveal weak sensitivity to density and temperature with observed values consistent with theory. The ratio of $\lambda 197.86$ relative to the $\lambda 171.07$ resonance line of Fe\textsc{x} is found to be an excellent temperature diagnostic, independent of density, and the derived temperature in the analyzed data set is $\log T = 5.95$, close to the predicted temperature of maximum ionization of Fe\textsc{x}.

Key words: atomic data – line: identification – Sun: corona – Sun: UV radiation

1. INTRODUCTION

Although the solar vacuum ultraviolet (VUV; 100–2000 Å) spectrum has been studied for many years and most of the strong lines identified, there remain a large number of unidentified lines. Classifying these lines is important for several reasons: they may yield new diagnostics for the Sun or other astrophysical bodies; they may contribute to the passbands of solar imaging instruments, distorting results if not accounted for; they add to models of the total irradiance from the Sun; and they improve our knowledge of atomic structure. While line identifications can be performed in the laboratory, a high-resolution solar spectrometer with imaging capability is a particularly powerful tool for line identification studies as the morphology of images formed in a given emission line will be highly characteristic of the temperature the line is formed at, making the parent ion much easier to establish.

Recently the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) was launched on board the Hinode satellite (Kosugi et al. 2007) and it is the first space-borne spectrometer to routinely observe the Sun in the wavelength ranges 170–212 and 246–292 Å with a high resolving power (3000–4000). The majority of strong emission lines and their diagnostic properties are known (Young et al. 2007b; Brown et al. 2008), but 45% of the lines listed were classified as unidentified by Brown et al. (2008). The majority of these unidentified lines likely belong to the iron ions Fe\textsc{vii}–\textsc{xiv} for which there are many levels that do not have experimental energy levels, thus making the wavelengths from these emission lines very uncertain.

This work presents new identifications for four emission lines of Fe\textsc{x} based on comparisons with the atomic model of the ion in version 5.2 of the CHIANTI atomic database (Landi et al. 2006; Dere et al. 1997). Although the strong $\lambda 171.07$ resonance line of Fe\textsc{x} is found in the EIS short wavelength band, the effective area is so low (around 1000 times less than the peak effective area of the instrument) that it is not scientifically useful in most circumstances. The newly identified lines are much stronger in terms of counts at the detector and bring new capability to the instrument, giving access to strong unblended lines from the complete sequence of iron ions from Fe\textsc{viii} to Fe\textsc{xvii}. In addition, the newly identified line at 197.86 Å is found to contribute to one of the best coronal temperature diagnostics at ultraviolet wavelengths.

2. OBSERVATIONS

Active region AR 10942 was observed by the EIS on 2007 February 21 with the study HPW008\_FULL\_CCD\_RAST which covers an area $128'' \times 128''$ with the 1'' slit. Full CCD spectra are obtained with an exposure time of 25 s, and the raster duration is 57 mins. Images from the data set in a variety of emission lines are shown in Figure 1. The raster was pointed at the footpoint regions on the east side of the active region. A number of spiky structures are seen in the cool lines, which can be identified with the footpoints of loops visible in Fe\textsc{x} and Fe\textsc{xi}. A key feature of this observation is a spatial area (indicated by an arrow in Figure 1(c)) that is bright at temperatures $\log T = 5.7$–6.0, but has relatively little emission from plasma at $\log T > 6.0$. The spectrum in this region is not dissimilar to a coronal hole spectrum, but because the observed features are bright coronal loop footpoints the signal-to-noise is high allowing weak lines to be observed.

The data set was calibrated using the routine EIS\_PREP, which is described in detail by Young et al. (2008). In order to measure the intensities and wavelengths of the Fe\textsc{x} lines, a region of 38 spatial pixels indicated by the arrow in Figure 1(d) was chosen where the Fe\textsc{x} lines are particularly enhanced. The spectra from these pixels were averaged, with care taken not to include pixels flagged as “missing” by EIS\_PREP. The spatial offsets between different wavelengths highlighted by Young et al. (2008) that are due to the tilt of the EIS grating relative to the EIS CCD have been corrected for to ensure the same spatial region is used for each line. The resulting spectrum in the vicinity of the four Fe\textsc{x} lines is shown in Figure 2, where the Fe\textsc{x} lines are seen to be comparable in strength to Fe\textsc{x} $\lambda 190.04$ and Fe\textsc{xi} $\lambda\lambda 188.23, 188.30$, among the strongest transitions observed by EIS for these two ions (Young et al. 2007b).

The present work is focused on four emission lines at 188.50, 189.94, 191.22, and 197.86 Å that were seen to be strongly enhanced in the loop footpoint regions. Only one of these ($\lambda 197.86$) was classified as unidentified by Brown et al. (2008), with $\lambda 188.50$ listed as an Fe\textsc{xi} transition, $\lambda 189.94$ as an Fe\textsc{x}...
transition, and $\lambda 191.22$ as a blend of Fe $\text{XIII}$ and S $\text{XI}$. We note that emission lines at these wavelengths have been reported in solar spectra dating back to the 1970s (Behring et al. 1972, 1976) and Brosius et al. (1998) measured emission lines at 188.49 and 191.26 Å from spectra of the 1995 flight of the SERTS rocket experiment, although lines at 189.94 and 197.86 Å are not discernible. The SERTS spectrum has lower signal-to-noise than the present spectrum and also does not show the strongly enhanced emission from the upper transition region found here.

To identify the lines with Fe $\text{IX}$ we compare images formed in the lines with other, known species. Figure 1 shows images from Mg $\text{V} \lambda 276.58$, Mg $\text{VI} \lambda 268.99$, Fe $\text{VIII} \lambda 185.21$, Fe $\text{X} \lambda 184.54$, Fe $\text{XII} \lambda 195.12$, and Fe $\text{XV} \lambda 284.16$, together with images from the lines at 188.50, 189.94, and 197.86 Å. (The $\lambda 191.22$ image looks very similar, except that there is a contribution to the latter image from hotter plasma. This is due to the blending S $\text{XI}$ line, see below.) In each case the images were formed by summing seven wavelength pixels across the line profile. Although the strongest resonance line of Fe $\text{IX}$ at 171.07 Å is found in the EIS spectrum, it is a factor 40 weaker than the $\lambda 188.50$ line due to the low telescope effective area at this wavelength. The image formed in this line is thus very noisy but bright patches can be identified that correspond to the bright areas in the other lines.

Comparing the images it is clear, first, that $\lambda 188.50$, $\lambda 189.94$, and $\lambda 197.86$ are formed at the same temperature since the images are very similar to each other and, second, that the temperature of formation is somewhere between that of Fe $\text{VIII}$ and that of Fe $\text{X}$. As the lines in question are strong (within a factor 2 in intensity of the strongest Fe $\text{VIII}$ lines observed by EIS) they must belong to an ion with a high solar abundance. Since line identifications for simple ions are well known at EUV wavelengths, the most likely ion is Fe $\text{IX}$. The fact that the $\lambda 188.50$ and $\lambda 189.94$ images look almost identical to
\(\lambda 197.86\) (an apparently unblended line) suggests that Fe\textsc{xii} and Fe\textsc{xiii} make very little contribution to \(\lambda 188.50\) and \(\lambda 189.94\), respectively. To confirm this, we note that the Fe\textsc{xii} line has an experimental wavelength of 188.45 Å (Bromage et al. 1978), and shares an upper level with the much stronger line at 186.86 Å. This latter line is itself blended with another Fe\textsc{xii} line at 186.88 Å, and the CHIANTI Fe\textsc{xii} atomic model predicts that the \(\lambda 188.45/(\lambda 186.86+\lambda 186.88)\) ratio is around 0.01–0.02. In the present spectrum the line measured at 188.50 Å is stronger than the \(\lambda 186.86+\lambda 186.88\) blend, and thus Fe\textsc{xii} contributes <1% to the Fe\textsc{xii} feature. The Fe\textsc{xii} line transition listed by Brown et al. (2008) at 189.94 Å was first identified by Bromage et al. (1977); however the CHIANTI database has this transition at 188.30 Å (Dere et al. 1997), based on the strength of the emission line predicted from the CHIANTI model, which better matches the observed line here. There is some uncertainty over the identification of the \(J = 1\) levels in the Fe\textsc{xii} atomic model due to strong level mixing, and so the CHIANTI identification cannot be considered definitive; however it is clear from the EIS images that Fe\textsc{xii} contributes very little, if at all, to the line at 189.94 Å.

The proposed Fe\textsc{ix} \(\lambda 191.22\) line is partly blended with S\textsc{i} \(\lambda 191.26\) and in fact the S\textsc{i} component dominates in the cores of active regions. Note that the Fe\textsc{ix} component compromises the use of S\textsc{i} \(\lambda 191.26\) in deblending the Fe\textsc{xii} \(\lambda 186.88\) density diagnostic line (Young et al. 2007b). The Fe\textsc{xiii} component listed by Brown et al. (2008) at 191.24 Å is predicted by the CHIANTI database to be less than 0.1% of the \(\lambda 196.54\) Fe\textsc{xiii} transition, which is measured to be <15% of the \(\lambda 191.22\) line in the present spectrum, and so the Fe\textsc{xiii} component can safely be ignored.

The measured wavelengths and line intensities of the four Fe\textsc{ix} transitions are given in Table 1, together with the newly suggested line identifications. The details for the measured \(\lambda 171.07\) line are also given. The rest wavelengths of the Fe\textsc{ix} lines are derived by first measuring the wavelengths of Fe\textsc{x} \(\lambda 184.54\) and \(\lambda 190.04\) in the spectrum. The velocity shifts of both lines relative to the rest wavelengths given in Brown et al. (2008) are then derived and averaged. The measured wavelengths of the Fe\textsc{ix} lines are then corrected by subtracting the Fe\textsc{x} velocity shift. This process assumes that Fe\textsc{ix} and Fe\textsc{x} exhibit the same velocity in the data set which we feel is reasonable given their close temperatures of formation.

3. ATOMIC DATA AND EMISSION LINE MODELING

The CHIANTI atomic database contains models suitable for predicting emission line spectra from most astrophysically abundant ions. The Fe\textsc{ix} model consists of observed energies from version 3.0 of the NIST Atomic Database, and theoretical energies, Maxwellian-averaged electron collision strengths and radiative decay rates from Storey et al. (2002). The model has 140 levels from six configurations.

To help identify the Fe\textsc{ix} transitions a synthetic isothermal spectrum was generated using CHIANTI at a temperature \(T = 5.9\) and electron density \(N_e = 9.0\). The temperature is determined from the temperature of maximum ionization of Fe\textsc{ix}, taken from the ionization balance calculations of Bryans et al. (2008). From the EIS spectrum obtained in the Fe\textsc{ix} emitting region, we used the Mg\textsc{vii} \(\lambda 280.75/\lambda 278.39\) density diagnostic (Young et al. 2007a), formed at a slightly cooler temperature of \(\log T_{\text{max}} = 5.8\) compared to Fe\textsc{ix}, to derive a density of \(\log N_e = 9.0\), and so this value was used. The synthetic spectrum reveals a number of lines clustered around the \(\lambda 171.07\) resonance line between 155 and 185 Å, several of which have intensities comparable to the \(3s^23p^6-3s^23p^53d\) transitions \(\lambda 171.10\) and \(\lambda 224.91\), and thus would be expected to be observed if they fall in the EIS wavelength range. Each of the emission lines between 155 and 185 Å (except \(\lambda 171.07\)) only has theoretical wavelengths in the CHIANTI model, and all but two of them are \(3s^23p^53d-3s^23p^4d^2\) transitions. The theoretical wavelengths are derived from energy level values from an ab initio atomic calculation (Storey et al. 2002) expected to be accurate to a few percent. Since the transitions are between two excited levels, the wavelengths can be expected to be out by up to 10–15%, depending on the energies of the levels involved.

As found in the previous section, the four unidentified EIS lines have formation temperatures close to that of Fe\textsc{ix} so we look to identify these with the predicted CHIANTI lines. The strongest of the lines between 155 and 185 Å we identify with the strongest of the EIS lines, namely \(\lambda 188.50\). As this is a transition between levels \(3G_2\) and \(3F_4\), based on standard atomic physics properties for multiplets, we expect weaker \(3F_{2\ldots}G_2\) and \(3F_{2\ldots}G_3\) transitions whose wavelength separations will be fairly similar to the separations in CHIANTI. The wavelengths and intensities given in Table 1 demonstrate that \(\lambda 189.94\) and \(\lambda 191.22\) are an excellent match for these transitions.
energy estimates are obtained as follows: for $3s^2p^3d$ energy calculations at these energies. The error bars on the $s$ with the theoretical energies of Storey et al. (2002) are 5% and
consistent with the identification.

due there are no companion lines to serve as a check, the theoretical wavelength is $173.149 \, \text{Å}$. As this is a singlet–singlet transition there are no companion lines to serve as a check, so are less useful. Note that the different temperature diagnostics available in the VUV. The other three Fe x lines are also strongly temperature sensitive relative to $\lambda 171.07$, but these ratios show significant density sensitivity, and so are less useful. Note that the different temperature behavior of the newly identified Fe x lines means that their contribution functions peak around 0.05 dex in log $T$ higher than the $\lambda 171.07$ line and so reveal slightly hotter plasma, although the lines are still significantly cooler than Fe x lines as demonstrated by comparisons of the images in Figure 1.

4. DIAGNOSTIC POSSIBILITIES

Amid the newly identified Fe x lines, the CHIANTI model predicts some density and temperature sensitivity. Figures 3(a), (b) show the $\lambda 191.22/\lambda 188.50$, $\lambda 189.94/\lambda 188.50$, and $\lambda 197.86/\lambda 188.50$ ratios as a function of density for temperatures $\log T = 5.8, 5.9$, and 6.0. The horizontal lines in the plots indicate the measured ratios from the 2007 February 21 data set and good agreement is found with the density derived from the slightly cooler Mg vii density diagnostic.

In Figure 3(c) the CHIANTI prediction for the $\lambda 197.86/\lambda 171.07$ ratio as a function of temperature is given. The ratio is an excellent temperature diagnostic and we find a temperature of $\log T = 5.95 \pm 0.05$ from the spectrum analyzed here. This is close to the $T_{\text{max}}$ value of 5.9 discussed earlier, giving confidence in our identification of the $\lambda 197.86$ line. This Fe x diagnostic is of great interest as the lines are close in wavelength and have very little density sensitivity, making it one of the best temperature diagnostics available in the VUV. The other three Fe x lines are also strongly temperature sensitive relative to $\lambda 171.07$, but these ratios show significant density sensitivity, and so are less useful. Note that the different temperature behavior of the newly identified Fe x lines means that their contribution functions peak around 0.05 dex in log $T$ higher than the $\lambda 171.07$ line and so reveal slightly hotter plasma, although the lines are still significantly cooler than Fe x lines as demonstrated by comparisons of the images in Figure 1.

5. SUMMARY

Four new Fe x line identifications in the wavelength range 188–198 Å have been presented, based on spectra obtained by the Hinode/EIS instrument. The lines give temperature coverage for the EIS instrument at $\log T = 5.9$, a region not covered by any other ion species observed by EIS, and one of great interest as it is where the transition region gives way to the corona.

The identified $\lambda 188.50$ and $\lambda 197.86$ lines are comparable in strength in terms of counts measured on the detector, but $\lambda 197.86$ is preferred for observations as it appears to be unblended and there are no strong lines nearby. Since $\lambda 188.50$ lies close to the strong Fe xi $\lambda \lambda 188.23$, 188.30 lines many observing studies already obtained with EIS will have observed this line. For example, a wavelength window set to 32 pixels and centered on 188.23 Å will include wavelengths up to 188.60 Å. $\lambda 197.86/\lambda 171.07$ is found to be an excellent temperature diagnostic. These lines are close in wavelength and their ratio is insensitive to density. The ratio is difficult to use from EIS data as the EIS sensitivity is very low at 171 Å, but designs for a future EUV solar spectrometer should give consideration to observing both lines.

### Table 1

Fe x Transitions Observed by EIS

| Rest Wavelength (Å) | Transition | CHIANTI Wavelength (Å) | Observed Intensitya (erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$) | Predicted Intensityb (erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$) |
|---------------------|------------|------------------------|----------------------|----------------------|
| 171.071             | 3s$^2$3p$^3d$ $1_{1}P_1$ | 171.073 | 5794 ± 542 | 7328 |
| 188.491            | 3s$^2$3p$^3d$ $3_{1}F_2$–$3s^23p^3(3P)3d^{-1}G_4$ | 174.245 | 341 ± 7 | 341 |
| 189.941            | 3s$^2$3p$^3d$ $3_{1}F_2$–$3s^23p^3(3P)3d^{-1}G_4$ | 175.477 | 201 ± 4 | 206 |
| 191.216            | 3s$^2$3p$^3d$ $3_{1}F_2$–$3s^23p^3(3P)3d^{-1}G_4$ | 176.660 | 92 ± 2 | 85 |
| 197.862            | 3s$^2$3p$^3d$ $1_{1}P_1$–$3s^23p^4P_1$ $S_0$ | 173.149 | 192 ± 2 | 219 |

Note. 

- a Errors are derived from Gaussian fit errors and photon statistics. 
  - b Predicted intensities are from the CHIANTI synthetic spectrum discussed in the text, normalized relative to the observed intensity of $\lambda 188.497$.
  - c Partly blended with Fe xi $3s^23p^32D_{5/2}$–$3s^23p^32P_3(3P)3d^{-2}F_{9/2}$ (188.45 Å).
  - d Partly blended with Si xi $2s^22p^32P_2$–$2s2p^33P_3$ $S_1$ (191.26 Å).

### Table 2

New Fe x Energy Levels

| Level | Energy/cm$^{-1}$ | Indexb |
|-------|------------------|--------|
| $3s^23p^3(1P)3d^{-1}G_4$ | 955790 ± 20 | 94 |
| $3s^23p^3(1P)3d^{-2}G_4$ | 956322 ± 21 | 95 |
| $3s^23p^3(1P)3d^{-3}G_4$ | 956788 ± 20 | 96 |
| $3s^23p^4P_1S_0$ | 1089949 ± 19 | 140 |

Note. * The level index in the CHIANTI v5.2 model.
Figure 3. Panels (a) and (b) show predicted line ratio variations from CHIANTI that involve the four newly identified Fe IX transitions, relative to λ188.50. Ratios for three different temperatures—log $T = 5.8$ (dotted line), 5.9 (solid line) and 6.0 (dashed line)—are shown. The horizontal lines show the measured values of each ratio. Errors are of the order of a few percent based on fitting errors and photon statistics (Table 1). Panel (c) shows the variation of the $\lambda_{197.86}/\lambda_{171.07}$ ratio with temperature, calculated at log $N_e = 9.0$. The measured ratio value with error bars is indicated.

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