Fe VII Emission Lines in the Wavelength Range 193–197 Å

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Abstract

The identifications of Fe VII emission lines in the wavelength range 193–197 Å are discussed in the light of new measurements of laboratory spectra and atomic data calculations. This region is of importance to studies of solar spectra from the EUV Imaging Spectrometer (EIS) on board the Hinode spacecraft, which has its peak sensitivity at these wavelengths. Ten lines are measured, arising from seven fine structure levels in the 3p5d3 configuration. Two lines have not previously been reported and lead to new experimental energies for the (a2D)p3F3,3 levels. Updated experimental energies are obtained for the remaining levels. The new atomic model is used to compute theoretical values for the two density diagnostic ratios λ196.21/λ195.39 and λ196.21/λ196.06, and densities are derived from EIS spectra of coronal loop footpoints.

Unified Astronomy Thesaurus concepts: Atomic spectroscopy (2099); Spectroscopy (1558); Line intensities (2084); Solar extreme ultraviolet emission (1493); Solar transition region (1532)

1. Introduction

Fe VII is formed at temperatures 0.2–0.5 MK in the solar atmosphere and produces many emission lines through the extreme ultraviolet (EUV) spectrum from 160 to 300 Å. These offer a number of temperature and density diagnostic ratios (Del Zanna 2009; Young & Landi 2009), and the ion can be used for element abundance diagnostics. For example, the ion is formed at similar temperatures to O V and O VI, which also have lines in the EUV, thus allowing the Fe/O abundance ratio to be measured. This is an important ratio for understanding abundance anomalies in the solar corona (Del Zanna & Mason 2014) and solar wind (Ko et al. 2014). The Fe VII lines also make contributions to the bandpasses of EUV spectroscopic imaging instruments such as the EUV Imaging Telescope (EIT; Delaboudinière et al. 1995), the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999), the EUV Imager (EUVI; Howard et al. 2008), and the Atmospheric Imaging Assembly (AlA; Lemen et al. 2012). Young & Landi (2009) demonstrated that Fe VII enhanced the 171 and 195 Å channel response functions for TRACE by around 50% at the temperature of formation of the ion, and studies of prominence eruptions have suggested EUV channels can be dominated by ion species formed at 0.2 MK (Ciaravella et al. 2000; Landi et al. 2010).

Fe VII is of particular interest for studies of active region fan loops (Schrijver et al. 1999) and sunspot plumes (Foukal et al. 1974). The lower sections of these structures have a large emission measure at temperatures of 0.2–0.8 MK (Landi & Young 2009), strongly enhancing emission lines in this region. The ion is thus valuable for measuring the temperature gradient in the loops, thus constraining the conductive energy flux.

The EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on the Hinode spacecraft (Kosugi et al. 2007) has observed the Sun’s EUV spectrum in the bandpasses 170–212 and 246–291 Å for more than 14 yr. Landi & Young (2009), Young & Landi (2009) and Del Zanna (2009) presented examples of spectra from fan loops and sunspot plumes, respectively, and compared the Fe VII emission with atomic models formed from the data of Witthoeft & Badnell (2008). However, the two groups of authors came to different conclusions on line identifications in their spectra. In the present work we present analysis of high-resolution laboratory spectra, and create a new atomic model using data from Tayal & Zatsarinny (2014) and Li et al. (2018). Our focus is on Fe VII lines in the region 193–197 Å as this contains some of the strongest Fe VII transitions and is also the region where the EIS effective area is highest.

Section 2 presents the new atomic model of Fe VII. Section 3 describes the laboratory spectra, and the line identifications are discussed in Section 4. Section 5 discusses the results, particularly in relation to the Del Zanna (2009) analysis, and Section 6 gives a summary.

2. Atomic Data and Models

A new atomic model was constructed using the data set published by Tayal & Zatsarinny (2014), which provided Maxwellian-averaged collision strengths (“upsilons”) and radiative decay rates for 189 levels belonging to the 3p5d5 configuration. Although Tayal & Zatsarinny (2014) stated their data should be more accurate than earlier works of Zeng et al. (2005) and Witthoeft & Badnell (2008), they also commented that computational limitations meant that configuration interaction effects could not be fully modeled in the scattering calculation. This particularly affects the complex 3p5d3 configuration that produces most of the EUV lines.

Only radiative decay rates for allowed transitions were provided by Tayal & Zatsarinny (2014), so forbidden transition rates were taken from Li et al. (2018) and, where necessary, from Witthoeft & Badnell (2008). Appendix C compares radiative decay rates and upsilons between the different atomic calculations, with agreement found within 25% and 30%, respectively, except for one transition.

Comparisons of calculated 3p5d4f and 3p5d3 energies with the experimental levels from Ekberg (1981) showed
deviations of $-4200$ to $+22600$ cm$^{-1}$ for Tayal & Zatsarinny (2014), and $-210$ to $9570$ cm$^{-1}$ for Li et al. (2018). Therefore the Li et al. (2018) energies were used for levels with no experimental energies.

Experimental energies are taken from Ekberg (1981), except where these were updated by Young & Landi (2009). Updated energies for five levels are given in the present work, and new energies are provided for two levels (Section 4).

The atomic data were converted to the CHIANTI$^5$ database format. In particular, an assessment procedure was applied to the upshifts such that they were scaled and extrapolated using a modification of the Burgess & Tully (1992) method, as described in CHIANTI Technical Report No. 4.$^6$ The procedure identified a number of transitions for which the allowed transition upshifts did not tend toward the high-temperature limit points. This was likely due to the fact that Tayal & Zatsarinny (2014) used a more elaborate model for the structure calculation compared to the scattering calculation.

With the data in the CHIANTI format, the CHIANTI IDL software was run to compute emissivities and assess the strengths of the transitions in the 193–197 Å region. Although there are uncertainties in the line identifications in this region, it is clear from the atomic models that the only transitions that are relevant belong to four multiplets. In each case the transitions are decays from the $3p^33d^1$ configuration to the ground $3p^33d^2$ configuration and henceforward we will not refer to the configurations when specifying the transitions. (Thus $3F_a-(^2H)^3G_g$ is shorthand for $3p^33d^2$ $3F_a-3p^33d^1$ $(^2H)^3G_g$.) The $3p^33d^3$ levels are assigned parent terms due to the many duplicate terms in this configuration. The parent term assignments come from the AUTOSTRUCTURE model mentioned in Young & Landi (2009). The multiplets are (in order of importance) $3F-(^2H)^3G$ (5 lines), $1G-(^2H)^1H$ (1 line), $3F$–,$(a^2D)^3F$ (3 lines) and $3P$–,$(a^2F)^3F$ (1 line). Figure 1(a) shows the Fe VII spectrum computed from the current atomic model for a temperature, $T$, of $10^{5.5}$ K and electron number density, $N_e$, of $10^9$ cm$^{-3}$. The lines belonging to the four multiplets are indicated. The wavelengths of these lines are discussed in the following sections. Figure 1(b) shows the EIS spectrum from Landi & Young (2009) with the model Fe VII intensities from panel (a) over-plotted.

Table 1 gives the emissivities for the eleven transitions considered in this work, computed at log $T = 5.5$ and log $N_e = 8, 9, 10$, which are values typical of the solar atmosphere. Additional values are given for log $N_e = 18$, which is the approximate density of the laboratory plasma. Level indices correspond to those given in Table 2 of Tayal & Zatsarinny (2014). The quantity shown is:

$$\epsilon_{ij} = \frac{E_{ij}n_iA_{ji}}{N_e} \quad \text{(erg cm}^{-3}\text{s}^{-1})$$

where $E_{ij}$ is the energy of the $i$–$j$ transition, $n_i$ is the population of the upper level (normalized such that $\sum n_j = 1$), and $A_{ji}$ is the radiative decay rate. We note that the contribution function (in the format returned by the CHIANTI IDL routine gofnt) is obtained by multiplying $\epsilon$ by the ionization fraction and the element abundance, and dividing by $4\pi$.

Comparisons with emissivities constructed from two other atomic models—one of which is that used by Young & Landi (2009)—are given in Appendix B. Agreement is found to within 26%, except for one transition that shows differences of up to 43%.

Young & Landi (2009) identified the $\lambda 196.21$/$\lambda 195.39$ ratio as a good density diagnostic, with sensitivity over the range log $[N_e$/cm$^{-3}] = 6.5$ to 9.5. From the EIS spectra they derived a density of log $N_e = 8.68 \pm 0.08$. However, the 195.39 Å line contains a weak Fe X blend (noted in Young & Landi 2009) that was not corrected for. Adjusting for this yields a value of $9.05^{+0.24}$.$^7$ The ratio curve from the new atomic model is shown in Figure 2(a) and compared with the earlier model. It is seen that the ratio is shifted slightly to lower densities, yielding an

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\begin{tabular}{llll}
5 & https://chiantidatabase.org & \\
6 & https://chiantidatabase.org/tech_reports/04_write_scups/chianti_report_04.pdf & \\
7 & https://chiantidatabase.org/tech_reports/04_write_scups/energy_tables.html
\end{tabular}
updated density of \( N_e = 8.72 \pm 0.09 \). We also show the \( \lambda 196.21/\lambda 196.05 \) ratio in Figure 2(b) as the lines are adjacent in the spectrum. The curve is about 10% lower than that from the previous model at high densities, and the measured EIS ratio is close to the high density limit giving a lower limit of \( N_e = 8.99 \). This value is consistent with the density of 9.02 \pm 0.06 obtained from the Mg VII \( \lambda 280.72/\lambda 278.39 \), which we consider the most accurate diagnostic in this temperature range.

### 3. Laboratory Spectra

Spectra in the wavelength range 90–350 Å were obtained from a high-resolution grazing incidence spectrograph with a 3 m (3600 lines mm\(^{-1}\)) grating. Previous spectra used for the analysis of Fe VIII (Ramonas & Ryabtsev 1980) were recorded on photographic plates, whereas Fuji Imaging Plates were used for the new spectra (Ryabtsev 2017). The FWHM values of the lines in the 200 Å region are 0.017 Å and 0.024 Å for the photoplates and imaging plates, respectively, corresponding to spectral resolutions \((\lambda/\Delta\lambda)\) of 12,000 and 8000. (These compare with a resolution of 3000 for the Hinode/EIS instrument at 195 Å.) Although having worse resolution, the imaging plate spectra possess a high linearity of the line intensities. The wavelengths were measured from the photoplate spectra, whereas the line intensity data were obtained from the imaging plate spectra. The estimated uncertainty of the wavelengths is from 0.004 to 0.006 Å. The intensities are given on a relative scale without taking into account possible wavelength variation of the setup sensitivity. The spectra were excited in a vacuum spark run from a capacitor with \( C = 10 \) or 150 F, charged from 1 to 5 kV. The observation of the changes of the line intensities with a variation of the discharge conditions served for a separation of the lines belonging to different iron ions. Further experimental details can be found in the earlier references.

Figure 3 shows spectra from the photoplate data, which have a higher spectral resolution. Appendix A discusses the imaging

### Table 1

| Terms          | \( J-J' \) | \( i-j' \) | Wavelength /Å | \( \epsilon_i \times 10^{15} \) erg cm\(^{-3} \) s\(^{-1} \) | \( T \) | Intensity |
|----------------|------------|------------|---------------|---------------------------------|--------|-----------|
| \( ^3S-(^3D)\)^F | 2–2        | 1–100      | 193.744(4)    | 0.31                            | 0.004  |
| 3–3            | 2–106      | 194.770(4) | 2.01          | 1.87                            | 1.86   |
| 4–4            | 3–105      | 196.426(6) | 1.27          | 1.23                            | 1.27   |
| 5–5            | 4–109      | 196.920(6) | 0.43          | 0.42                            | 0.44   |
| \( ^1G-(^3H)\)^H | 4–5        | 8–114      | 196.216(5)    | 6.68                            | 9.20   |
| \( ^3P-(^3F)\)^F | 2–3        | 7–111      | 194.961      | 0.46                            | 0.53   |

Notes.

- Level indices of Tayal & Zatsarinny (2014).
- Uncertainties on the last digit of the present wavelengths are given in parentheses.
- Computed at \( T = 5.5 \) and densities \( N_e = 8, 9, 10, 18 \).
- Blended with Fe VIII.
- Laboratory intensities are normalized to this line.
- Theoretical wavelength from Li et al. (2018).
plate spectra, which were used for intensity measurements due to the high signal linearity. Three sections of the iron spark spectra are shown in Figure 3: the strong lines between 194.5 and 195.97 Å are clearly seen. Fe VI identifications are from Azarov et al. (1996) and the lines are generally weaker in the hot spectrum. Fe VII lines have comparable intensities in the two spectra and, by comparing with the model spectrum shown in Figure 1, one can see there is a good match in terms of relative intensities. There are a number of unidentified lines, with the most significant being that at 195.53 Å, and they are likely due to Fe V or Fe VI. The strong Fe IX λ197.86 line is not present, implying an absence of species hotter than Fe VIII.

The wavelengths measured from the laboratory spectrum are given in the third column of Table 1, alongside the measured values of Ekberg (1981). The final column of Table 1 gives the line intensities measured from the imaging plate spectrum, with the values normalized to the theoretical emissivity of the line at 196.216 Å at log $N_e = 18$. We note that the intensities are not corrected for the spectrograph efficiency as a function of wavelength, but this effect should be small given the narrow spectral range considered here. The line at 195.971 Å is blended with a Fe VIII transition that is significantly stronger, and the line at 196.922 Å is blended with Fe VI, although in this case the Fe VII line is dominant.

**Figure 3.** Two laboratory spectra obtained with the photplates. The red and blue lines correspond to the “hot” and “cold” spectra, respectively. Lines due to the three iron species are indicated and distinguished by their relative intensities in the two spectra.

| Terms | $J$--$K$ | E81 | YL09 | DZ09 | Present | Li18 |
|-------|----------|------|------|------|---------|------|
| $^3F$--$^2H$ $^3G$ | 2–3 | 196.046 | 196.045 | 197.358 | 196.049 | 195.737 |
| | 3–3 | 196.453 | 196.450 | 197.769 | 196.453 | 196.229 |
| | 3–4 | 196.423 | 195.480 | 196.210 | 195.480 | 194.691 |
| | 4–4 | 196.917 | 195.970 | 196.704 | 195.971 | 195.177 |
| | 5–4 | 195.391 | 195.388 | 196.046 | 195.392 | 194.450 |
| $^3F$--($^2\Delta$) $^2F$ | 2–2 | ... | 193.788 | ... | 193.744 | 193.498 |
| | 2–3 | ... | 194.728 | ... | 194.770 | 194.453 |
| | 3–4 | ... | 196.423 | ... | 196.426 | 196.150 |
| | 4–4 | ... | 196.918 | ... | 196.920 | 196.643 |
| $^1G$--$^2H$ $^1H$ | 4–5 | ... | 196.212 | 196.209 | 196.216 | 195.073 |

Note.

$^a$ Estimated wavelengths (see main text).

### 4. Line Identifications

Table 2 summarizes the experimental wavelengths in the 193–197 Å range that were reported by Ekberg (1981, E81), Young & Landi (2009, YL09) and Del Zanna (2009, DZ09). Also shown are the wavelengths obtained from the theoretical energy values of Li et al. (2018, Li18). Table 3 compares the experimental energies with the theoretical energies of Witthoeft & Badnell (2008, WB08), Tayal & Zatsarinny (2014, TZ14) and Li et al. (2018). For levels within a multiplet, the lowest energy level is listed with the energy splitting relative to this level given for the remaining levels.

Ekberg (1981) was the first to perform a detailed study of the Fe VII EUV spectrum using laboratory spectra, and this was the starting point of the Young & Landi (2009) analysis. A key discrepancy was found for the $^2H$ $^3G_4$ level, which Ekberg (1981) identified with emission lines at 196.42 and 196.92 Å (Table 2) leading to an energy only 72 cm$^{-1}$ greater than that of $^2H$ $^3G_3$ (Table 3). The three theoretical works consistently yield a much larger separation of 2700–3100 cm$^{-1}$. This led to Young & Landi (2009) identifying the $^2H$ $^3G_4$ level with the strong line at 195.48 Å, which gives better agreement with the theoretical energy splittings. We note here an error in Table 3 of Young & Landi (2009) whereby the energy of 512.601 cm$^{-1}$ for $^2H$ $^3G_4$ should have been given as 512.613 ± 8 cm$^{-1}$, which is derived from the 195.48 Å line measured in the EIS spectrum. It is the latter value that is given in Table 3. The laboratory spectra presented here clearly demonstrate that the 195.48 Å line is due to Fe VII. A comparison of the model...
emissivities with the laboratory intensities (Table 1) also clearly shows that the strength of the 195.48 Å line is much more consistent with the \((2H)\)\(G_4\) level than the weak line at 196.42 Å.

With the lines measured by Ekberg (1981) at 196.42 and 196.92 Å no longer associated with \((2H)\)\(G_4\), Young & Landi (2009) identified them with \((a^2D)\)\(F_2\). Table 1 shows that the model emissivity for the 196.92 Å line is in good agreement with the laboratory intensity, but the 196.42 Å measured intensity is much stronger than expected. However, no other \(J=4\) level identification is suitable and so we believe these identifications are correct. Young & Landi (2009) did not identify the 196.92 Å line in their spectrum, but they did measure a line at 196.964 Å. Correcting this wavelength for the plasma Doppler shift gives 196.937 Å. The intensity ratio relative to the 196.42 Å line is 0.77, significantly larger than the theoretical ratio of 0.34 (Table 1). Thus the solar line at 196.4 Å appears to be blended.

Young & Landi (2009) adjusted the theoretical energies of the \((a^2D)\)\(F_2\) levels based on the theoretical splittings relative to \((a^2D)\)\(F_2\) leading to improved estimates of the wavelengths of lines from these levels. It was not possible to identify these transitions in the EIS spectra, but they are apparent in the laboratory spectra close to the predicted wavelengths and are shown in Figure 3. The emissivity comparison is good for these lines (Table 1), giving confidence in the identifications. We therefore give new experimental energies for these two levels in Table 3, which we estimate to be accurate to 9 cm\(^{-1}\) (Table 4).

Ekberg (1981) was not able to identify the strong \(1G_{4,1}–(2H)\)\(G_6\) transition, perhaps because no other transitions from the \((2H)\)\(H_6\) level could be found in the spectrum. Young & Landi (2009) identified it with the 196.21 Å line as it could be clearly identified with Fe VII in the EIS spectra and the intensity was consistent with nearby Fe VII lines. This is confirmed with the laboratory spectra here.

The line at 196.45 Â was identified by Ekberg (1981), but was blended in the EIS spectra. Figure 3 clearly shows this line as a “shoulder” on the long-wavelength side of the stronger 196.42 Å line and the intensity is in reasonable agreement with the model (Table 1).

Finally we consider the \(3P_{2,1}–(2F)\)\(F_3\) transition, which is estimated at 194.96 Â using the Li et al. (2018) theoretical energy. By comparison with the \((a^2D)\)\(D_2\) and \((2H)\)\(H_6\) levels that are close to \((2F)\)\(F_3\) and have experimental energies, we can estimate that the Li et al. (2018) energy over-estimates the true energy by between 2300 and 3000 cm\(^{-1}\). This would place the \(3P_{2,1}–(2F)\)\(F_3\) transition between 195.84 and 196.11 Â, close to the strong Fe VIII and Fe VII lines in this range (Figure 3). As no candidate can be seen, then it is possible the line is blended with one of these lines.

5. Discussion

The previous section showed that the Fe VII line identifications in the 193–197 Â range are now complete except for the weak \(3P_{2,1}–(2F)\)\(F_3\) transition. In this section we discuss additional issues related to these lines.
Del Zanna (2009) presented an analysis of the EIS Fe VII spectrum using an atomic model constructed from the Witthoeft & Badnell (2008) collision strengths and the radiative decay rates from his own structure calculation. He identified the observed 196.21 Å line with the $^1G_e - (^{2}H)^{G}H_0$ transition, consistent with Young & Landi (2009). A key difference with Young & Landi (2009), however, is that he modified the line identifications of all of the $(^{2}H)^{G}G_I$ levels, giving the wavelengths listed in Table 2. In particular, the strong $^3F_{J-}(^{2}H)^{G}G_{J+1}$ transitions were matched to the observed lines at 197.36, 196.21, and 196.05 Å. The 197.36 Å line is blended with a much stronger Fe VIII line and the 196.21 Å line is a self-blend with the $^1G_e - (^{2}H)^{G}H_0$ transition. These identifications were motivated by the fact that the observed line at 195.39 Å seemed to be too strong in the EIS spectrum, and that the image formed in this line was more consistent with Fe VIII. By switching the identification to the weaker 196.05 Å line these problems could be solved.

The laboratory spectrum presented here clearly demonstrates that the 195.39 Å line is due to Fe VII. The emissivity comparison does show that the measured line is stronger than expected compared to other lines by around 30%. This may indicate a Fe VI blend (see Appendix A). The fact that the solar image formed from the EIS line appears to be hotter than Fe VII was explained by Young & Landi (2009) as due to a blend with a Fe X line.

A further problem with the Del Zanna (2009) identifications is that they require fortuitous blends with strong lines. Both lines are very narrow in the solar spectra (Landi & Young 2009), and thus the two Del Zanna (2009) identifications require very precise wavelength matches, which seems an unlikely coincidence. The Del Zanna (2009) $(^{2}H)^{G}G_I$ level splittings are in worse agreement with theory compared to our new measurements (Table 3), and the 196.45 Å line is inconsistent with the upper level being $(^{2}H)^{G}G_5$ as the $^3F_{3-} - (^{2}H)^{G}_5$ transition is forbidden.

Although we are confident in the line identifications given in Table 2, we highlight that the lines at 195.39 and 196.42 Å are significantly stronger than the other lines. Almost a factor three in the latter case. Blending is a possibility but we also note the conclusion of Tayal & Zatsarinny (2014) that their scattering calculation could not include all of the configuration interaction terms necessary to fully model the $3p^3d^3$ configuration. We illustrate why this is important in Table 4, which gives the mixing coefficients for the $3p^3d^3$ levels considered here, computed with the Cowan atomic code by one of us (A. Ryabtsev). (The listed theoretical energies come from this calculation.) All of the $(a^2D)^3F$ and $(^{2}H)^{G}G$ levels are highly mixed and so it is important that the scattering calculation accurately takes into account this mixing. We also highlight that the $(^{2}F)^{F}_{3-} (^{2}F)^{F}_{1-}$ (the parent term being assigned by Young & Landi 2009) level actually has a dominant contribution from $(^{2}D)^{F}_{1}$ in this calculation, illustrating how mixing can change with different calculations.

6. Summary

A new atomic model constructed from the atomic data of Tayal & Zatsarinny (2014) has been presented along with high-resolution laboratory spectra of Fe VII lines. The spectra are important for confirming Fe VII line identifications in the range 193–197 Å, which is relevant to the study of spectra from the Hinode/EIS instrument. In particular, the strong lines at 195.39 and 195.48 Å are clearly seen to be due to Fe VII. Two new line identifications have been made, leading to new experimental energies for the $(a^2D)^3F_{2,3}$ levels. The new model was recently released to the community through version 10 of the CHIANTI database (Del Zanna et al. 2020).

The intensities of the lines at 195.39 and 196.42 Å are stronger in the laboratory spectrum compared to the atomic model. This may be due to blending and/or uncertainties in the atomic data.

A detailed study of the entire Fe VII laboratory spectrum will follow, and will be used to address some of the other issues highlighted by Del Zanna (2009) and Young & Landi (2009).

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Appendix A

Laboratory Spectra Obtained with Imaging Plates

The spectra obtained with the Fuji Imaging Plates are shown in Figure 4. As with the photoplate spectra shown in Figure 3, the blue and red lines correspond to "cold" and "hot" spectra. The latter displays stronger lines from Fe VIII, while the former have stronger lines from Fe VI. The spectral resolution is a little worse in these spectra, as can be seen by comparing the feature at 196.4 Å with Figure 3, where two components are clearly seen. The imaging plate spectra have an almost linear intensity scaling and so were used to derive the intensities given in Table 1. The Fe VII lines are generally stronger in the
red spectrum, although the strongest line at 195.39 Å is a little weaker in the red spectrum. This may indicate a partial blend with an Fe VI line, although Fe VII dominates. This effect was not seen in the photoplate spectra (Figure 3).

Appendix B
Emissivity Comparison

The atomic model used in this paper was largely based on the Tayal & Zatsarinny (2014) atomic data. In Table 5 we compare the emissivities from this model with those from two other models that are indicated with “WB08” and “Li18.” The former is the same model as used by Young & Landi (2009), while the latter is the WB08 model but with the radiative decay rates replaced by those of Li et al. (2018), where available. Note that Witthoeft & Badnell (2008) and Tayal & Zatsarinny (2014) provided data for the same 189 fine structure levels, but Li et al. (2018) gave decay rates for a reduced set of 134 levels.

The WB08 and TZ14 emissivities show good agreement, with the largest difference for the 194.77 Å line, which is up to 43% larger in the WB08 model. The median difference between the two models is 7%. The effect of using the Li et al. (2018) decay rates for the WB08 model is relatively small, with a maximum difference of 19% for the weak line at 194.96 Å. The median difference for all transitions is 2.4%.

Appendix C
Comparison of Decay Rates and Upsilons

Appendix B compared emissivities computed from three atomic models. Here we compare radiative decay rates and upsilons for the strongest transitions. Table 6 gives decay rates from WB08, TZ14 and Li18, and also those from Del Zanna et al. (2020, arXiv:2011.05211) for which the TZ14 emissivity was used. For the 2–3 transition, this work we compare the WB08 and TZ14 upsilons for the dominant transitions to these levels in Table 7. As expected, the differences mirror those seen in the decay rate calculation. The largest difference is for 3F–(aD)F3, for which the TZ14 upsilon is 72% higher than the WB08 upsilon. The upsilons for other transitions are within 30%.

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