TESTING EUV/X-RAY ATOMIC DATA FOR THE SOLAR DYNAMICS OBSERVATORY

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ABSTRACT

The Atmospheric Imaging Assembly (AIA) and the Extreme-ultraviolet Variability Experiment (EVE) on board the Solar Dynamics Observatory (SDO) include spectral windows in the X-ray/EUV band. Accuracy and completeness of the atomic data in this wavelength range is essential for interpretation of the spectrum and irradiance of the solar corona, and of SDO observations made with the AIA and EVE instruments. Here, we test the X-ray/EUV data in the CHIANTI database to assess their completeness and accuracy in the SDO bands, with particular focus on the 94 Å and 131 Å AIA passbands. Given the paucity of solar observations adequate for this purpose, we use high-resolution X-ray spectra of the low-activity solar-like corona of Procyon obtained with the Chandra Low Energy Transmission Grating Spectrometer (LETGS). We find that while spectral models overall can reproduce quite well the observed spectra in the soft X-ray range \( \lambda \leq 50 \AA \), and at the EUV wavelengths \( \lambda \geq 130 \AA \), they significantly underestimate the observed flux in the 50–130 Å wavelength range. The model underestimates the observed flux by a variable factor ranging from \( \approx 1.5 \), at short wavelengths below \( \approx 50 \AA \), up to \( \approx 5-7 \) in the \( 70-125 \AA \) range. In the AIA bands covered by LETGS, i.e., 94 Å and 131 Å, we find that the observed flux can be underestimated by large factors (\( \sim 3 \) and \( \sim 1.9 \), respectively, for the case of Procyon presented here). We discuss the consequences for analysis of AIA data and possible empirical corrections to the AIA responses to model more realistically the coronal emission in these passbands.

Key words: stars: coronae – stars: individual (Procyon) – stars: late-type – Sun: corona – Sun: X-rays, gamma rays – X-rays: stars

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1. INTRODUCTION

The solar EUV and X-ray radiation plays a double role in the physics of the solar upper atmosphere: by representing an important term in the energy equation, and by bearing the signatures of the most important physical phenomena that occur during solar activity, namely, flares and coronal mass ejections (CMEs). It is also one of the primary energy inputs to Earth’s upper atmosphere: it heats the thermosphere, creates the ionosphere, and drives a number of dynamical motions and photochemical reactions at different heights. By its own nature, the EUV and X-ray emission of the Sun is highly variable on all time scales, from a factor two to several orders of magnitude (Woods et al. 2004). The largest variations occur at the shortest wavelengths.

The 10–170 Å region includes a large number of spectral lines emitted by highly ionized species formed at temperatures at, or above, 1 MK. These lines dominate the solar irradiance, and are of crucial importance for investigating the interaction between the solar radiative output and Earth’s upper atmosphere. For example, Pawlowski & Ridley (2008) showed that flare radiation, dominated by highly ionized Fe transitions in the 90–140 Å range, can increase the density of Earth’s thermosphere by as much as \( \approx 15\% \) in less than 2 hr. These lines also provide excellent diagnostic tools for measuring the physical properties of the emitting plasmas under quiescent, active, and flaring conditions. Furthermore, key ions routinely detected by in situ measurements of the solar wind (O vii, viii, C vi, vi) emit very strong lines between 18 Å and 40 Å.

In recent years, the 10–170 Å range has attracted considerable attention because of several instruments, both already launched and being developed, that can observe astrophysical objects in this spectral interval. EUVE, Chandra, and XMM-Newton obtained high-resolution spectra from all kinds of astrophysical objects, while the Thermosphere Ionosphere Mesosphere Energetics and Dynamics and Solar EUV Experiment (SEE) and the recently launched Solar Dynamics Observatory (SDO) include instrumentation aimed at studying the solar corona, the solar irradiance, and their variability using this range. In particular, the Extreme-Ultraviolet Variability Experiment (EVE; Woods et al. 2010) and the Atmospheric Imaging Assembly (AIA; Lemen et al. 2011; Boerner et al. 2011) on board SDO include spectral windows in the 10–170 Å range aimed at studying the energy input, storage, and release mechanisms that rule coronal heating and the variability of the solar spectrum. AIA is a suite of four telescopes providing high-cadence (\( \sim 12 \) s, for the standard observing mode, though higher cadence is possible) full Sun observations in seven EUV narrow passbands, at high spatial resolution (\( \sim 0.6 \) pixel\(^{-1}\)): six EUV narrowbands are centered around 94 Å, 131 Å, 171 Å, 195 Å, 211 Å, and 335 Å, respectively, which are generally dominated by emission of plasma at temperatures \( \log(T[K]) \geq 5.7 \). AIA also observes cooler plasma in the 304 Å channel (dominated by He ii emission) and in a UV channel (where three passbands can be selected at \( \lambda \) 1600, 1700, 4500). EVE measures the full disk solar irradiance in the EUV and soft X-ray energy range (from 1 to 1050 Å), with a cadence of 10 s. EVE spectral resolution is \( \sim 1 \) Å between 50 and 1050 Å (with the Multiple EUV Grating Spectrographs MECS-A and MECS-B), and 10 Å in the 1–50 Å range (with MECS-SAM). EVE also includes an EUV Spectrophotometer measuring the irradiance in broadband in the 1–390 Å range, and a MECS-Photometer (MEGS-P) measuring the hydrogen Lyα line at 1216 Å.
In order to understand the solar EUV and X-ray spectrum, as well as using it for diagnostic purposes, theoretical models of the sources in the solar atmosphere need to be combined with spectral models (such as CHIANTI: Dere et al. 1997, 2009 and APEC: Smith et al. 2001; Foster et al. 2010) that can compute it. A key issue in such modeling is the accuracy and completeness of the spectral models: inaccurate or incomplete sets of atomic data and transition rates can jeopardize the success of any modeling effort. Also, the narrowband filters in the AIA instrument can be used for quantitative scientific purposes only if the spectrum in the wavelength range they cover is known with accuracy. For this reason, available spectral models need to be benchmarked with observations. Benchmarking spectral codes by comparison with X-ray (1–20 Å; Phillips et al. 1999; Landi & Phillips 2006), EUV (170–630 Å; Young et al. 1998; Raassen et al. 2002), and UV (500–1600 Å; Landi et al. 2002b) high-resolution spectra revealed some discrepancies and led to substantial improvements in the available data. Benchmark studies focusing on the 20–170 Å range are limited, such as, for instance, the work by Del Zanna & Ishikawa (2009) who carried out a detailed benchmark of X-ray and EUV Fe xvi lines only, or Liang & Zhao (2010) who used Chandra/LETGS Procyon spectra for a comparison of their Fe xvi–Fe xvi atomic data with observed spectral lines in the 49–106 Å range.

The aim of the present series of papers is to test the CHIANTI atomic data in the 10–170 Å wavelength range, which is relevant to SDO (AIA and EVE) observations. In this paper, the first of the series, we focus on issues in the wavelength ranges of the two shortest-wavelength AIA channels, centered at 94 Å and 131 Å. We also provide a broad overview of the shortcomings of CHIANTI in reproducing observed spectra in the 10–170 Å, consequential for EVE observations. In the next two papers of the series, we will present a systematic benchmark of the CHIANTI data with the observed lines, ion by ion (J. J. Drake et al. 2011, in preparation; E. Landi et al. 2011, in preparation).

Despite the observational attention given to the 10–170 Å wavelength range, in the context of atomic physics it has been somewhat neglected in the recent literature. For the last two decades or so, the atomic data effort stemming from solar physics has been directed toward the wavelength ranges covered by the high-resolution spectrometers on board the Solar and Heliospheric Observatory (SOHO) and Hinode, all exceeding 170 Å. Also, few high-resolution spectra have ever been recorded from the Sun in this range, all of them 25 or more years ago, since most of the rocket- and satellite-borne instrumentation built in the past was optimized to work either below 20 Å or above 170 Å. Ironically, the best spectra in the 10–170 Å wavelength range available today have been observed from much fainter stellar sources with the Chandra Low Energy Transmission Grating Spectrometer (LETGS; Brinkman et al. 1987) and, at lower resolution, with the Extreme Ultraviolet Explorer (EUV; Bowyer & Malina 1991). In order to test CHIANTI, we chose to use X-ray/EUV spectra of the low-activity solar-like coronal emission of the subgiant Procyon, observed with Chandra/LETGS, which is characterized by spectral resolution ($\Delta \lambda \sim 0.05$ Å) significantly better than the resolution of EVE ($\Delta \lambda \sim 1$ Å). Procyon (F5 IV; α CMi, HD 61421; $d = 3.51$ pc, van Leeuwen 2007) is one of the brightest stars in the sky and also thanks to its proximity has been very well studied at optical to X-ray energies (e.g., Steffen 1985; Drake et al. 1995; Allende Prieto et al. 2002). The coronal emission of Procyon has been studied in detail in the past three decades at EUV and X-ray wavelength with several instruments (e.g., Lemen et al. 1989; Drake et al. 1995; Raassen et al. 2002), indicating that the X-ray emission is rather constant ($L_X \sim 2 \times 10^{28}$ erg s$^{-1}$, in the energy range 0.1–2.4 keV based on the ROSAT All-Sky Survey; Hünsch et al. 1999), and characterized by a relatively cool plasma thermal distribution that peaks around 1–3 MK. These temperatures are close to values typical of non-flaring solar plasmas, therefore making Procyon an excellent X-ray source to benchmark the atomic data for plasma conditions typically observed by SDO.

The observations are described in Section 2. The data analysis and results of the determination of the plasma temperature distribution are presented and discussed in Section 3. We summarize our findings and draw our conclusions in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

We analyzed Chandra spectra of Procyon obtained in four different pointings (two in 1999 November and two in 2009 December), using the LETG and High-Resolution Camera spectroscopic detector (HRC-S) in its standard instrument configuration. Observational data were obtained from the public Chandra Data Archive and reduced using the CIAO software package (v4.3). For the analysis presented in this paper, we used the Package for Interactive Analysis of Line Emission (PINTofALE; Kashyap & Drake 2000).

The details of the four Chandra observations are listed in Table 1. Light curves derived from the zeroth-order photon events, binned at an interval of 1 ks, are illustrated in Figure 1 and the spectra extracted from each epoch are shown in Figure 2. Both light curves and spectra show the X-ray emission of Procyon to be remarkably constant, both in terms of flux level and spectral characteristics, and on all observed timescales, from 1 ks to much longer timescales of over 10 years. Close inspection of the spectra does reveal some differences, especially between 49 and 69 Å, and above 160 Å. These can be ascribed to the different effective areas at those wavelengths, due to the wavelengths in the spectra at which the HRC-S plate gaps occur. These vary from epoch to epoch because of the secular aim point drift of Chandra relative to the detector coordinate system. We found no evidence for any significant differences between the spectra taken at different epochs outside of the wavelength regions affected by plate gaps. This lack of variability over timescales ranging from ~1 ks to about 10 years is remarkable for the X-ray emission of late-type stars. Although the sampling is sparse, this constancy hints at a lack of a large amplitude magnetic activity cycle analogous to that observed for the Sun and seen in X-rays in other low and moderately active

| ObsID | Start (UT) | Exposure (ks) | $F_X$ (erg cm$^{-2}$ s$^{-1}$) | $L_X$ (erg s$^{-1}$) |
|-------|------------|---------------|-------------------------------|-------------------|
| 63    | 1999-11-06 21:11:32 | 69.7 | $1.95 \times 10^{-11}$ | $3.03 \times 10^{28}$ |
| 1461  | 1999-11-07 16:59:48 | 69.8 | $1.98 \times 10^{-11}$ | $3.06 \times 10^{28}$ |
| 10994 | 2009-12-15 02:05:38 | 71.3 | $2.02 \times 10^{-11}$ | $3.15 \times 10^{28}$ |
| 12042 | 2009-12-26 01:23:39 | 65.1 | $2.01 \times 10^{-11}$ | $3.13 \times 10^{28}$ |

Notes.

$^a$ X-ray flux in the range 5–165 Å (∼0.075–2.5 keV).

$^b$ X-ray luminosity, in the range 5–165 Å, corrected for absorption (assuming $N_{H} = 1.15 \times 10^{18}$ cm$^{-2}$; Linsky et al. 1995).
stars (e.g., Hempelmann et al. 2006; Favata et al. 2008; Ayres 2009).

3. ANALYSIS METHODS AND RESULTS

In order to assess completeness and accuracy of the CHIANTI atomic database we proceeded as follows: (1) we selected a set of lines formed over a wide temperature range, unblended, and with reliable atomic data; (2) we reconstructed the emission measure distribution, EM(T), of the emitting coronal plasma using the measured fluxes, and finally (3) we synthesized the model spectrum using CHIANTI and the EM(T) derived from the data and compared it with the observed spectrum at all wavelengths.

The line fluxes used for determining the thermal distribution of the plasma are listed in Table 2. The selected lines are formed over a broad temperature range, as indicated by their temperature of maximum formation, covering roughly the interval from log(T[K]) ~ 5.7 to log(T[K]) ~ 6.9 (see Table 2).

We determined the emission measure distribution by using an iterative method based on a Markov Chain Monte Carlo algorithm (see Kashyap & Drake 1998 for details on assumptions and approximations, and also Testa et al. 2011 for further description of the characteristics of the method). The emission measure distribution is reconstructed using the line emissivities from CHIANTI version 6.0.1 (Dere et al. 1997, 2009) and assuming the ionization balance of Bryans et al. (2009).

Previous analyses of X-ray and EUV spectra of Procyon have indicated that the element abundances of its coronal plasma are close to its photospheric abundances (e.g., Drake et al. 1995; Raassen et al. 2002; Sanz-Forcada et al. 2004), which in turn are similar to solar photospheric abundances (e.g., Steffen 1985; Drake & Laming 1995; Bruntt et al. 2010). By using an abundance diagnostic technique based on temperature insensitive line ratios (Drake & Testa 2005; Huenemoerder et al. 2009) we derive an estimate of the Ne/O abundance ratio of 1.3 × the solar photospheric value of Grevesse & Sauval (1998). This diagnostic technique uses the measured fluxes of the strong H-like and He-like transitions, lying at the short wavelength range of the Chandra spectra. Procyon is characterized by a rather inactive and cool corona, compared with the more active stellar coronae usually observed with Chandra. Therefore, even with the long accumulated exposure time of the spectra analyzed here (~275 ks) the H-like and He-like lines of the higher Z elements (mainly Mg, Si, S, Fe), which are formed at temperatures higher than the corresponding transitions of Ne and O, are not detected.

We ran the procedure to derive the emission measure distribution several times and “manually” adjusted the abundances of those elements if the agreement with the model was unsatisfactory and the predicted line fluxes for a given element were consistently lower or higher than the observed fluxes. The model we deemed to be best is characterized by photospheric abundances (Grevesse & Sauval 1998), except for N and Ne which are enhanced by 30% and Mg, Ca, and Fe which are enhanced by 50%. While perhaps slightly higher than current assessments of solar-like photospheric abundances in Procyon, our values are not significantly different considering the combined systematic and random errors of photospheric and coronal analyses. We express our derived abundances relative to the reference set of abundances of Grevesse & Sauval (1998), but the choice of reference is arbitrary. We adopted the set of Grevesse & Sauval (1998) for easier comparison with other works in the literature.

The emission measure distribution derived from the measured fluxes is illustrated in Figure 4. It is a rather smooth and broad function of temperature, with most material found around log(T[K]) ~ 6.1–6.3, i.e., at temperatures typical of non-flaring solar coronal plasmas. This emission measure distribution we derive from the long Chandra-LETGS exposure compares well with those derived for the same source by Drake et al. (1995) from EUVE observations, and by Raassen et al. (2002) from the first two LETGS observations and XMM-Newton spectra, having a similar peak temperature (~1.5 MK), emission measure value (~10^50 cm^-3), and width of the distribution. Some small differences are present either sides of the EM distribution peak at temperatures of log T = 6.0–6.4. Such differences might be expected based on the different global model fitting approach adopted by Raassen et al., in addition to the more up-to-date ionization balance and collisional excitation data used in the current study. In order to evaluate how well the EM(T) of Figure 4 reproduces the observed emission, the measured fluxes are compared with the fluxes predicted by the model EM(T) in Table 2. Agreement is satisfactory and typically within ~30%, which is in accordance with the assessment by Drake et al. (1995) of typical atomic data uncertainties.

In Figure 3 (bottom panel), we show the model spectrum synthesized from the EM(T) of Figure 4 using the CHIANTI database (v.6.0.1) and the element abundances and ionization equilibrium described above. In order to allow a more detailed comparison of the model with the observed spectrum, in Figure 5 we show the two spectra superimposed (observed spectrum in black and model in red).

Figures 3 and 5 demonstrate quite a favorable comparison at the shorter wavelengths. At longer wavelengths, especially in the ~80–110 Å range, it is apparent that the observed spectrum contains a large number of lines, strong and weak, missing in the CHIANTI spectral model. This missing flux was first noted in earlier work on EUVE stellar spectra, including that of Procyon.
Figure 2. Comparison of Chandra LETGS spectra of Procyon obtained in four different observations (a different color is used for each observation, as labeled in the bottom plot). For easier comparison each spectrum is shifted by +0.1 Å with respect to the preceding one.

(A color version of this figure is available in the online journal.)
Figure 3. Top: Chandra LETGS spectrum of Procyon, obtained with a total exposure time of approximately 275 ks (ObsID: 63, 1461, 10994, 12042). Bottom: model spectrum synthesized using CHIANTI 6.0.1 and the emission measure distribution derived from the measured line fluxes listed in Table 2 and plotted in Figure 4. An expanded version of the model and observed spectra, allowing a more detailed comparison, is presented in Figure 5.

Figure 4. Emission measure distribution, EM(T), derived applying a Markov Chain Monte Carlo (MCMC) iterative method to the measured fluxes of the lines listed in Table 2.

(see, e.g., discussions by Drake 1996; Drake & Kashyap 2001) and was also touched upon by Raassen et al. (2002) in their analysis of the first two LETGS Procyon observations. We also note that analyses of SDO-EVE spectra appear to show the same effect: spectral models are in good agreement with the observed spectra at EUV wavelengths (\( \gtrsim 150 \) Å), whereas they represent a poor match to the observed emission in the \( \sim 50–150 \) Å range (H. Warren 2011, private communication). These findings strongly suggest that the missing flux is not due to inadequate modeling of transitions included in current databases but to incompleteness atomic databases at those wavelengths. In order to estimate the effect of the flux apparently lacking in the model spectrum on the analysis of EVE spectra, we degraded both the model and the observed spectrum to EVE spectral resolution and plot their ratio in Figure 6. This plot shows that the model underestimates the observed flux by a variable factor ranging from \( \approx 1.5 \), at short wavelengths below \( \sim 50 \) Å, up to \( \approx 5–7 \) in the \( \sim 70–125 \) Å range. We defer a more detailed discussion to J. J. Drake et al. (2011, in preparation).

Figure 7 shows the comparison of the spectral model and observations in the wavelength ranges of the AIA passbands centered on 94 Å and 131 Å (171 Å is at the edge of the sensitivity of Chandra-LETGS). These plots demonstrate that the model lacks a significant portion of the observed flux, especially in the 94 Å range. In particular, in the 94 Å band, not only is the strongest feature, Fe xviii 93.93 Å+ Fe x 94.01 Å,
Figure 5. Comparison of Chandra LETGS observations (black) and CHIANTI 6 model (red; including orders ±1, 2, 3) synthesized using the EM(T) shown in Figure 4, derived using the line fluxes of Table 2. (A color version of this figure is available in the online journal.)
the 131 Å band, the disagreement is less severe: the predicted fluxes of the strong Fe viii lines are close to the measured values, though the flux contribution of weaker lines is underpredicted (or completely lacking) in the model. We note that neither the uncertainties on the background subtraction nor the possible contamination from the overlapping higher spectral orders can explain the observed discrepancies (in Figure 7 we also show separately the modeled high-order contribution, as a blue dotted curve).

In order to estimate what the effect of the missing flux would be on an AIA observation of coronal plasma with Procyon-like X-ray–EUV emission, we convolved the observed and modeled spectrum with the responses of the AIA 94 Å and 131 Å narrow passbands as a function of wavelength. We find that the AIA flux for a Procyon-like source would be underestimated by the spectral model by a factor of roughly three in the 94 Å passband and 1.9 in the 131 Å passband. The plots of the observed and model spectra folded with the AIA responses in the 94 Å and 131 Å channels (bottom panels of Figure 7), clearly show which spectral features are more relevant, contributing more significantly to the AIA intensity.

Laboratory experiments with the Lawrence Livermore electron beam ion trap, EBIT, (Beiersdorfer et al. 1999; Lepson et al. 2002) focusing on the wavelength range ∼60–140 Å investigated the presence of Fe lines (Fe vii–x) possibly not included in current atomic databases and potentially important for the interpretation and modeling of solar and stellar soft X-ray–EUV spectra. We reviewed their findings to explore whether any of their detected emission lines that are still absent from atomic databases might affect significantly the 94 Å and 131 Å AIA wavelength ranges. In their list of emission lines, we find that there are two transitions with potentially significant impact for the 94 Å AIA passband. These are two Fe ix lines—$3p^5 5f \rightarrow 3p^5 3d$ transitions—with measured wavelengths of 93.59 and 94.07, respectively (Lepson et al. 2002), and intensities of roughly 0.25 and 0.3× the intensity of the Fe ix emission at 103.55 Å. We note that the intensities reported in these laboratory experiments cannot be directly translated into relative intensity expected for the emission of coronal plasma, as in EBIT experiments the plasma conditions can significantly deviate from the conditions generally assumed for coronal thermal plasma (for instance the electrons have non-Maxwellian distribution). Foster & Testa (2011) used the flexible atomic code to carry out calculations for these Fe ix transitions, and we explore
the possible relevance of these lines to explain the missing flux, by recomputing the model adding these additional Fe\textit{x} contributions in the 94 Å range to the synthetic CHIANTI model spectrum. This new spectral model including the Fe\textit{x} transitions, shown in Figure 8 (blue line), is in much better agreement with the observed spectrum in that narrow wavelength range and reduces the flux discrepancy from the factor \( \sim 3 \) for the pure CHIANTI 6 spectrum to roughly 80%.

If we include the contribution functions of these Fe\textit{x} lines, we can estimate the impact on the temperature response of the AIA 94 Å passband. The “corrected” AIA temperature response is shown in Figure 9, compared to the default response computed using CHIANTI 6. Addition of the Fe\textit{x} contribution increases the response of the AIA 94 Å channel by roughly a factor two in the cool temperature range (see also Foster & Testa 2011, where APED is used; Smith et al. 2001).

In the 131 Å wavelength region, none of the lines identified in Lepson et al. (2002) appear to have significant impact for AIA observations. However, some might be relevant to the analysis of EVE spectra, such as for instance two Fe\textit{x} \( 3p^54f \rightarrow 3p^53d \) transitions with measured wavelengths of \( \lambda_{\text{134.08}} \) and \( \lambda_{\text{136.70}} \) (see discussion in Foster & Testa 2011, where a synthetic spectrum including these transitions is compared with an EVE quiet-Sun spectrum). Besides these lines around \( \sim 94 \) Å and \( \sim 135 \) Å, the new calculations presented in Foster & Testa (2011) indicate that the added Fe\textit{x} transitions provide only limited additional flux in the 10–170 Å band, compared to current versions of atomic databases. This modest additional emission is expected around 82 Å, in the 110–115 Å range, and around \( \sim 164 \) Å where the model predicts a strong \( 4p–3d \) transition.

The study by Liang & Zhao (2010) is also potentially helpful for identifying lines missing in the atomic databases. They compare their Fe\textit{vii}–Fe\textit{xvi} atomic data with Chandra/LETGS observations of Procyon. As they note, CHIANTI 6 only includes data from \( n = 3 \) levels for Fe\textit{x}, Fe\textit{xii}, Fe\textit{xiii}, Fe\textit{xiv}, and the missing lines from these ions might contribute non-negligible flux in the 10–170 Å wavelength range. Although we use a set of spectral observations partially overlapping with
correction to the CHIANTI model including Fe, those used by Liang & Zhao (2010), their aim and methods were different with respect to ours. They carry out a detailed comparison of their theoretical models with existing alternative atomic data focusing exclusively on Fe\textsuperscript{vii}–Fe\textsuperscript{x} lines, and they did not analyze the spectra longward of 106 Å. Also, they used a simplified three temperature model from Raassen et al. (2002) which is expected to be a less accurate representation of the temperature distribution of the coronal plasma compared to the emission measure distribution we use here and therefore lead to a less accurate reproduction of the line fluxes in the whole wavelength range (see also above comparison of our finding for the EM(T) with the results of Raassen et al. 2002). Finally, the total exposure time of the observations we analyze here is almost twice as long as the one used by Liang & Zhao (2010), improving the signal-to-noise ratio of the spectrum.

For the 94 Å wavelength range, they noted problems in their model for Fe\text{x}, which is predicting the 94.02 Å flux to be much lower than the CHIANTI 6 expected flux (and much lower than the observed flux). They did not include the Fe\text{x} lines around \(\sim\)94 Å observed in the EBIT experiments (Lepson et al. 2002). Aschwanden & Boerner (2011) also attempted an estimate of the correction factor for the response of the 94 Å AIA channel to the cool (1 MK) plasma, by analyzing a sample of loops for which emission in the other AIA bands is compatible with a near isothermal emission measure distribution. They derive a factor of 6.7 ± 1.7, which is significantly larger than the contribution of Fe\text{x} estimated by Foster & Testa (2011) and in this work, suggesting that other ions also provide non-negligible contributions.\(^3\)

\[^3\] P. Boerner et al. (2011, in preparation) by looking at the morphology of quiet Sun in deep exposures in the AIA passbands suggest possible additional contribution of emission from log \(T[K]\) = 6.0–6.3.

In the 131 Å range the EBIT experiments suggest the presence of several Fe\textsuperscript{vii} lines, in the 127–134 Å range, which are not included in CHIANTI 6.0.1 (or APED) and might provide significant contribution. Also an Fe\text{x} line (134.08 Å) and an Fe\text{x} line (134.09 Å) are observed in the EBIT spectra, though their contribution might be rather limited given that the AIA response at those wavelengths is already roughly 2 orders of magnitude lower than at its peak. Additional contribution can also come from ions other than the Fe\textsuperscript{vii}–Fe\text{x} studied in the EBIT laboratory experiments. In particular, L-shell transitions of Mg and Ne are expected to fall around 94 Å and 132 Å. At the time of writing, the new version of the CHIANTI database (ver. 7) is still under testing, though based on the changes in the ions relevant to the AIA bandpasses under consideration no significant differences are expected.

4. CONCLUSIONS

High-resolution X-ray spectra of the low-activity solar-like corona of Procyon obtained with the LETGS have been used for testing the X-ray/EUV data in the CHIANTI database. A systematic benchmark ion by ion will be presented in two future papers (Drake et al. 2011, in preparation; E. Landi et al. 2011, in preparation). Model and observed spectra are in reasonably good agreement in the soft X-ray range (\(\lambda \lesssim 50\) Å) and at the longer LETGS wavelengths \(\lambda \gtrsim 130\) Å. However, the model flux lies significantly below the observed flux in the 50–130 Å wavelength range. In particular, in the 94 Å and 131 Å AIA bands the observed flux exceeds the model flux by factors of \(\sim 3\) and \(\sim 1.9\), respectively. By including two relatively strong Fe\text{x} lines at \(\lambda 93.59\) and 94.07 observed in the laboratory by Lepson et al. (2002), the discrepancy in the 94 Å band is reduced to \(\sim 80\%\). The AIA temperature response corrected in this way is increased by roughly a factor of two at 10\(^6\) K. In the 131 Å band, Fe\textsuperscript{vii} transitions, not included in CHIANTI but observed in laboratory experiments, as well as L-shell Ne transitions, might explain part of the missing flux.

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REFERENCES

Allende Prieto, C., Asplund, M., García López, R. J., & Lambert, D. L. 2002, ApJ, 567, 544
Aschwanden, M. J., & Boerner, P. 2011, ApJ, 732, 81
Ayres, T. R. 2009, ApJ, 696, 1931
Beiersdorfer, P., Lepson, J. K., Brown, G. V., et al. 1999, ApJ, 519, L185
Boerner, P., et al. 2011, Sol. Phys., in press
Bowyer, S., & Malina, R. F. 1991, Adv. Space Res., 11, 205
Brinkman, A. C., van Rooijen, J. J., Bleeker, J. A. M., et al. 1987, Astrophys. Lett. Commun., 26, 73
Bruntt, H., Bedding, T. R., Quirion, P.-O., et al. 2010, MNRAS, 405, 1907
Bryans, P., Landi, E., & Savin, D. W. 2009, ApJ, 691, 1540
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&A, 125, 149
Dere, K. P., Landi, E., Young, P. R., et al. 2009, A&A, 498, 915
Del Zanna, G., & Ishikawa, Y. 2009, A&A, 508, 1517
Drake, J. J. 1996, in ASP Conf. Ser. 109, Cool Stars, Stellar Systems, and the Sun, ed. R. Pallavicini & A. K. Dupree (San Francisco, CA: ASP), 203
Drake, J. J., & Kashyap, V. 2001, ApJ, 547, 428
Drake, J. J., & Laming, J. M. 1995, Observatory, 115, 118
Drake, J. J., Laming, J. M., & Widing, K. G. 1995, ApJ, 443, 393
Drake, J. J., & Testa, P. 2005, Nature, 436, 525
Favata, F., Micela, G., Orlando, S., Schnitt, J. H. M., & Sciortino, S. 2008, A&A, 490, 1121
Feldman, U. 1992, Phys. Scr., 46, 202
Foster, A., Smith, R. K., Brickhouse, N. S., & Kallman, T. R. 2010, BAAS, 42, 678
Foster, A., & Testa, P. 2011, ApJ, 740, L52
Grevesse, N., & Sauval, A. J. 1998, Space Sci. Rev., 85, 161
Hempelmann, A., Robrade, J., Schnitt, J. H. M., et al. 2006, A&A, 460, 261
Hueneemoerder, D. P., Schulz, N. S., Testa, P., Kesich, A., & Canizares, C. R. 2009, ApJ, 707, 942
Hünsch, M., Schmitt, J. H. M. M., Sterzik, M. F., & Voges, W. 1999, A&A, 353, 319
Kashyap, V., & Drake, J. J. 1998, ApJ, 503, 450
Kashyap, V., & Drake, J. J. 2000, Bull. Astron. Soc. India, 28, 475
Landi, E., Feldman, U., & Dere, K. P. 2002a, ApJ, 574, 495
Landi, E., Feldman, U., & Dere, K. P. 2002b, ApJS, 139, 281
Landi, E., & Phillips, K. J. H. 2006, ApJS, 166, 421
Lemen, J., Title, A., Akin, D., et al. 2011, Sol. Phys., in press
Lemen, J. R., Mewe, R., Schrijver, C. J., & Fludra, A. 1989, ApJ, 341, 474
Lepson, J. K., Beiersdorfer, P., Brown, G. V., et al. 2002, ApJ, 578, 648
Liang, G. Y., & Zhao, G. 2010, MNRAS, 405, 1987
Linsky, J. L., Diplas, A., Wood, B. E., et al. 1999, ApJ, 451, 335
Pawlowski, D. J., & Ridley, A. J. 2008, J. Geophys. Res., 113, 10309
Phillips, K. J. H., Mewe, R., Harra-Murnion, L. K., et al. 1999, A&A, 138, 381
Raassen, A. J. J., Mewe, R., Audard, M., et al. 2002, A&A, 389, 228
Sanz-Forcada, J., Favata, F., & Micela, G. 2004, A&A, 416, 281
Schmelz, J. T., Jenkins, B. S., Worley, B. T., et al. 2011, ApJ, 731, 49
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91
Steffen, M. 1985, A&A, 59, 403
Testa, P., Reale, F., Landi, E., DeLuca, E. E., & Kashyap, V. 2011, ApJ, 728, 30
van Leeuwen, F. 2007, A&A, 474, 653
Woods, T. N., Eparvier, F. G., Fontenla, J., et al. 2004, Geophys. Res. Lett., 31, L10802
Woods, T. N., et al. 2010, Sol. Phys., 3
Young, P. R., Landi, E., & Thomas, R. J. 1998, A&A, 329, 291