ELECTRON DENSITY DIAGNOSTIC FOR HOT PLASMAS IN THE CORONAL REGIME BY USING B-LIKE IONS

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ABSTRACT

A line ratio of 3d–2p transition lines in boron-like spectra of Si x, S xii, Ar xiv, and Fe xxii has been investigated. Collisional-radiative model calculations reveal that the line ratio is sensitive to the electron density in ranges of \( n_e = 4.0 \times 10^7–3.0 \times 10^{10} \text{ cm}^{-3} \), \( 4.0 \times 10^6–3.0 \times 10^{11} \text{ cm}^{-3} \), \( 3.0 \times 10^9–4.0 \times 10^{12} \text{ cm}^{-3} \), and \( 2.0 \times 10^{12}–3.0 \times 10^{15} \text{ cm}^{-3} \), respectively. This complement the K-shell diagnostics of helium-like ions. By a comparison between the predicted and the measured values, effective electron densities in the electron beam ion trap (EBIT) plasmas, performed by Lepson and collaborators at the Lawrence Livermore EBIT, are estimated to be \( n_e = 3.4^{+0.8}_{-0.6} \times 10^{10} \text{ cm}^{-3} \) and \( 5.6^{+1.6}_{-1.1} \times 10^{10} \text{ cm}^{-3} \) for sulfur and argon plasmas, respectively. In the case of argon, a good agreement is shown with the actual electron density derived from an N vi K-shell spectrum. We further explore the 3d–2p transition lines of Si x and S xii in the stellar coronal spectra measured with the low energy transmission grating spectrometer combined with a high resolution camera on board the Chandra X-Ray Observatory. The constrained electron densities show a good agreement with those determined from C vii and O vi K-shell spectra.

Key words: atomic data – stars: coronae – stars: late-type – techniques: spectroscopic – X-rays: general

Online-only material: color figures

1. INTRODUCTION

Electron density (\( n_e \)) plays an important role in the fields of stellar corona, galaxies, interstellar medium of galaxies, clusters of galaxies, as well as the ground tokamak, laser-produced, electron beam ion trap hot plasmas. K-shell spectra (generally helium-like) show a powerful diagnostic potential for electron density. Since the work of Gabriel & Jordan (1969), which defines a ratio of the forbidden f line (1s 2s 1S 1–1s 2 1S 0) to the intercombination lines i line (1s 2p 3P 1–1s 2 1S 0), much of the literature reported the ratio by considering the effects of the radiation field (Ness et al. 2001), dielectronic and radiative recombinations (Porquet et al. 2001). Porter & Ferland (2007) re-investigated the ratio by using updated atomic data on dielectronic and radiative recombinations. Since spectra with high resolution have been available, especially after the launch of Chandra and XMM-Newton missions, the ratio of helium-like spectra has been extensively adopted to derive the electron density and further estimations of the stellar structure and the heating mechanism in X-ray emitting regions (Audard et al. 2001; Ness et al. 2002a, 2002b, 2003, 2004; Schmitt et al. 2005). Moreover, spatial information of coronae could be assessed indirectly using the correlation \( EM = n_e^2 Y \) (\( EM \) refers to an emission measure) between the electron density and the emission measure.

Besides the K-shell emission lines, many L-shell emission lines from highly charged oxygen, neon, silicon, sulfur, calcium, iron, and nickel ions have been detected in stellar coronal spectra. For inactive stars, M-shell transition lines were also identified (Raassen et al. 2002). The diagnostic potential of the L-shell emission lines has been investigated by many authors, such as the ratio \( I(50.524)/I(50.691) \) of Si x, \( I(52.306)/I(43.743) \), \( I(52.306)/I(46.391) \) of Si xii addressed in our previous works (Liang & Zhao 2006a; Liang et al. 2006b). Similar characteristics were explored for Si viii, S x, Ar xiv, and Ca xvi (Keenan et al. 1993, 2000, 2001, 2003; Liang et al. 2006c).

For boron-like extreme ultraviolet (EUV) spectra from transitions of \( n = 2–2 \), Keenan et al. (2000, 2003), studied density-sensitive line ratios of Si x and Ar xiv using accurate excitation data from the R-matrix method. For 3d–2p transition lines spanning in the soft X-ray region, the line intensity ratios of highly charged silicon ions were investigated in our previous work (Liang et al. 2006b), which shows an \( n_e \)-sensitivity in the range of \( n_e = 4.0 \times 10^7–3.0 \times 10^{10} \text{ cm}^{-3} \). Using laboratory measurements in the electron beam ion trap (EBIT), Chen et al. (2004) tested the density-sensitive line ratios of Ar xiv and Fe xxii in the ranges of \( n_e = 2.0 \times 10^{10}–1.0 \times 10^{12} \text{ cm}^{-3} \) and a low-density limit around \( 1.0 \times 10^{12} \text{ cm}^{-3} \). In that work, the actual electron density was constrained from the K-shell N vi spectrum. However, the diagnostic application of emission lines of S xii has not been investigated to our best knowledge, though its two lines at 36.398 and 36.564 Å have been identified for an inactive star—Procyon.

In this work, we make a systematical analysis for the 3d–2p density-sensitive transition lines of boron-like spectra including Si x, S xii, Ar xiv, and Fe xxii based on the collisional-radiative model as given in Section 2. In Section 3, we explore the 3d–2p transition lines of S xii at 36.398 and 36.564 Å in the stellar coronal spectra observed by the low energy transmission grating (LETG) spectrometer on board the Chandra X-Ray Observatory. Furthermore, the electron densities of stellar corona and laboratory plasmas produced in the EBIT are estimated as illustrated in Section 4, followed by conclusions outlined in Section 5.

2. THEORY

2.1. 3d–2p Transition Lines

The line intensity ratios of 3d \( ^2D_{3/2}–2p^2P_{3/2} \) and 3d \( ^2D_{3/2}–2p^2P_{1/2} \) transition lines are known to be sensitive to the electron
density but, on the other hand, rather insensitive to the electron temperature. This feature follows from the fact that the upper level is mainly populated by collisional excitation from the density-sensitive lower metastable level. In the following paragraph, we take Si xii to explain this property.

As shown in Figure 1, the levels of the configuration 2s2p2 are the highest excitation rate from the levels of the ground configuration, whereas the decaying lines span the EUV wavelength region. Here we pay special attention to the X-ray emission lines. The 3d 3D5/2 level has a high excitation rate from and decay rate to the metastable 2P3/2 level, which is forbidden to decay to the ground state. By increasing the electron density, a significant fraction of the 2P3/2 population can be re-excited to the 3D5/2 state, from where it relaxes to the 2P3/2 state and, therefore, the line intensity at 36.564 Å increases. On the other hand, by the depopulation of the ground state 2P1/2 due to the shelving of electrons in the metastable level, the excitation of the resonance line (3d 3D3/2→2p 2P1/2) at 36.398 Å of Si xii decreases at high densities.

It is clear that the 2s3d 3D5/2 level can also decay to the metastable 2P3/2 level with a low branching ratio. However, as this transition line (at 36.573 Å for Si xii) cannot be resolved from the 36.564 Å line due to limited spectral resolution in the present space missions, we have to take this blend effect into account. Since 3d 3D3/2 is directly populated from the ground state, the intensity of 36.573 Å has a similar dependence on ne as the 36.398 Å resonance line and its relative contribution to the blended 36.564 Å line becomes dominant at low electron density.

2.2. Calculation of the Line Ratio

Adopting a collisional-radiative model, we calculated the line ratio \( \frac{I(3d3d/2→2p3/2)}{I(3d3d/2→2p1/2)} \) of Si xii, Ar xiv, and Fe xxi as a function of the electron density for a Maxwellian electron distribution at temperatures of peak fraction of these ions in the work of Bryans et al. (2006). The transition wavelengths are listed in Table 1. For Si x and Ar xiv, the atomic data including energy levels, radiative decay rates, and impact excitation rates are from our detailed calculations. Some excitation data within \( n = 2–2 \) transitions are replaced by more accurate calculations with the \( R \)-matrix method as explained in previous literature (Liang et al. 2006b, 2006c). For Si xii and Fe xxi, we adopt the CHIANTI package of the new version 5.2. In this code, the atomic data are updated recently as depicted by Landi et al. (2006). For Si xii, the electron impact excitation data of Zhang et al. (1994) have been adopted, in which small errors found by them have been corrected by authors in the present version of CHIANTI. Resonance effects for excitations among the lowest 15 fine-structure levels have been included by the \( R \)-matrix method. For Fe xxi, the electron excitation data between the lowest 204 levels are from the work of Badnell et al. (2001), who adopted the close-coupling \( R \)-matrix method, and are in conjunction with the intermediate-coupling frame transformation method. The electron excitation data between higher 205–513 levels adopt the calculation of Landi & Gu (2006), in which the resonance effects were considered by an isolated-resonance approximation. Above the ionization energy, the calculation of Bautista et al. (2004) with the Breit–Pauli \( R \)-matrix method was used. Additionally, proton excitations between the fine-structure states of the ground configuration and the 2s2p2 4P term were also included (Foster et al. 1997) in CHIANTI. In this work, the close-coupled impact-parameter method was used.

Figure 2 shows the prediction of the line ratio at temperatures of log \( T_e = 6.1 \) K for Si xii, 6.3 K for S xii, 6.5 K for Ar xiv, and 7.1 K for Fe xxi. This demonstrates that the ratio is sensitive to the electron density in ranges \( n_e = 4.0 \times 10^{12–3.0} \times 10^{10} \) cm\(^{-3} \), 4.0 \( \times 10^{12–3.0} \times 10^{11} \) cm\(^{-3} \), 3.0 \( \times 10^{12–4.0} \times 10^{9} \) cm\(^{-3} \), and 2.0 \( \times 10^{12–3.0} \times 10^{15} \) cm\(^{-3} \) for Si xii, S xii, Ar xiv, and Fe xxi, respectively. We further calculate the ratio in the temperature ranges \( T_e = 6.0–6.2 \) K for Si xii, 6.1–6.4 K for S xii, 6.4–6.6 K for Ar xiv, and 7.0–7.2 K for Fe xxi, as illustrated by hatched regions in Figure 2, which reveal that the ratio is insensitive to the electron temperature. This indicates that the ratio \( I(3d3d/2→2p3/2)/I(3d3d/2→2p1/2) \) is a good \( n_e \)-diagnostic method for hot plasmas and compensates the K-shell spectra.

### Table 1

| Transitions | Wavelength (Å) |
|-------------|----------------|
| Si x        | S xii          | Ar xiv | Fe xxi |
| 2s3d3D3/2→2p3/2 | 50.524        | 36.398 | 27.469 | 11.769 |
| 2s3d3D3/2→2p1/2 | 50.691        | 36.564 | 27.629 | 11.921 |
| 2s3d3D3/2→2p3/2 | 50.703        | 36.573 | 27.642 | 11.936 |

3. OBSERVATIONS

The wavelength range spanned by the 3d–2p transition lines of the present interested boron-like ions is covered by the high and medium energy grating (HEG and MEG) spectrometers, LETG spectrometer on board Chandra, as well as the reflection grating spectrometer (RGS) on board XMM-Newton with high resolution. One specific advantage of LETG observations results from its large wavelength coverage in one spectrum, that is, the 3d–2p lines (see Table 1) of the interested ions can be detected at the same time.

Our sample consists of six stars including two normal dwarf stars, i.e., Procyon and \( \alpha \) Cen B (Raassen et al. 2003); an active late-type dwarf star, \( \epsilon \) Eri; two active binary systems, Capella and YY Gem; and a pre-main sequence late-type star, TW Hya.
Figure 2. Line intensity ratio $I(3d_5/2–2p_3/2)+I(3d_3/2–2p_3/2)/I(3d_3/2–2p_1/2)$ of S x, S xii, Ar xiv, and Fe xxii, as a function of the electron density for a Maxwellian electron distribution at temperatures of peak fraction of these ions in the work of Bryans et al. (2006) (see the legend). The hatched areas indicate predictions for thermal plasmas in the temperature range (in log $T_e$) of 6.0–6.3 K for Si x, 6.2–6.4 K for S xii, 6.4–6.6 K for Ar xiv, and 7.0–7.2 K for Fe xxii. The black symbols with error bars are the observed line ratios of Si x in the stellar corona. The blue symbols with error bars are the observed line ratios of S xii in the stellar corona. The red-circle symbols with error bars are the laboratory measured ratios of S xii and Ar xiv in the works of Lepson et al. (2003, 2005). The red-circle symbols in the range of $n_e = 10^{11}$–$10^{12}$ cm$^{-3}$ are extracted from the work of Chen et al. (2004), which represent the measured ratios and electron densities in the EBIT experiments, whereas the dark-yellow triangle symbol denotes the ratio of Fe xxii lines extracted from the ACIS-S observation for Capella.

(A color version of this figure is available in the online journal)

Table 2

| Star      | Obs ID     | $t_{ob}$ (ks) | Spectral type | Distance (pc) | $T_{e, 2}$ (K) | log($L_{bol}$) | $R_0^2$ [R$_\odot$] | $L_X^d$ (erg s$^{-1}$) |
|-----------|------------|---------------|---------------|---------------|---------------|---------------|---------------------|-----------------------|
| Procyon   | 63+1224+1461 | 70.15+20.93+70.25 | F5.01 V-V | 3.5 | 6540 | 34.46 | 2.06 | 2.43 |
| $\alpha$ Cen B | 29 | 79.5 | K0.0 V | 1.34 | 5780 | 33.28 | 0.8 | 0.52 |
| Capella   | 1248/55 | 84.7/53.48 | G1.0III/K0.0I | 12.94 | 5850 | 35.71 | 9.2/13 | 255 |
| $\epsilon$ Eri | 1869 | 105.3 | K2.0 V | 3.22 | 4780 | 33.11 | 0.81 | 20.9 |
| YY Gem    | 28 | 57.63 | dlMo/dMle | 14.7 | ... | ... | 0.66/0.58 | 54.4 |
| TW Hya    | 6443 | 150.24 | K8 V | 56.0 | ... | ... | ... | 150.0 |

Notes.

a Exposure time of observation.

b From Ness et al. (2004).

c From Ness et al. (2002a).

d Derived from XMM-Newton observation (Stelzer & Schmitt 2004).

(Kastner et al. 2002; Ness & Schmitt 2005). The properties of our sample, along with observation ID (ObsID) and exposure time, are summarized in Table 2. All observations adopt the gratings of LETG combined with the high resolution camera (HRC) instrument on board Chandra. In the case of Capella, an additional observation (with ObsID = 55) with an Advanced CCD Imaging Spectrometer (ACIS)-S instrument is used. Because the ACIS-S instrument has significant energy resolution to separate overlapping spectral orders, LETG+ACIS-S observations are a better choice for determination of the electron density. However, only one observation is available from the Chandra Data Archival Center for our sample. Another goal of analysis for the ACIS-S spectrum of Capella is to validate whether there is significant contamination from high-order spectra around the selected lines (36.398 and 36.564 Å). If line fluxes derived from the two different observations are comparable, no contamination from high-order spectra can be concluded. Reduction of the LETG datasets uses CIAO3.3 software with the science threads for LETGS/HRC-S observations. Figure 3 shows the spectra for Procyon, $\alpha$ Cen B, Capella, $\epsilon$ Eri, YY Gem, and TW Hya in the wavelength range of 36.0–37.0 Å.

The 3d–2p transition lines of Si x have been identified and explained in detail by Liang & Zhao (2006a). Argon is an underabundant element in stellar corona, and no emission lines of Ar xiv have been identified so far. Iron is an abundant element in an astrophysical environment. However, the 3d–2p resonance line at 11.769 Å is contaminated by the Fe xxiii line at 11.738 Å for Capella (Behar et al. 2001). Here, we pay special attention to the identification of 3d–2p lines of S xii at 36.398 Å and 36.564 Å as shown in Figure 3.

4. RESULTS AND DISCUSSION

4.1. Line Fluxes of 3d–2p Transitions of S xii

Line fluxes are determined by modeling the spectra locally with narrow Gaussian profiles and constant values representing...
background and (pseudo-)continuum emissions determined in a line-free region. The observed line width is about 0.06 Å over the interested region, which is comparable with the broadening of the instrument for a point-like source. The fluxes have been obtained after correction for the effective area as listed in Table 3 for 6 stars observed with the LETG spectrometer.

For Procyon, the two transition lines have been identified by Raassen et al. (2002) in the RGS and LETG observations. Here, the line fluxes are derived separately again for the co-added LETG observations, which shows a good agreement with the results of Raassen et al. (2002) within a 1σ error as illustrated in Table 3. For other stars, no reports of the identifications for the two lines can be found to our best knowledge.

For Capella, we fit the HRC-S and ACIS-S observations separately with multi-Gaussian components as illustrated in detail in Figure 4. It is clear that the line width in the HRC-S observation is wider than the ACIS-S observation, which is due to its lower resolution. Additionally, for the line at 36.398 Å, the derived line flux from the HRC-S observation is higher than the value from the ACIS-S observation by a factor of ∼2.8 (see Table 3). This is due to the contamination from the third-order diffraction of the emission line at ∼12.136 Å with a flux of 11.04 ± 0.30 × 10⁻⁴ photons cm⁻² s⁻¹ (see the seventh column in Table 3), resulting from Ne x Lyα (12.134 Å) and Fe xvii (12.124 Å). According to the line fluxes around 36.394 Å derived from HRC and ACIS observations as well as the line flux around 12.136 Å, we conclude that the efficiency of third-order diffraction is about (17.4 ± 8.2)% at the local wavelength range. The different background levels are due to the blending from the different effective areas (6.24 and 8.43 cm², respectively). A search from APEC/APED v1.3.1 (Smith et al. 2001) indicates that another emission line from Fe xvii at 36.358 Å partially blends in the HRC-S observation. For the emission line around 36.564 Å, the fitting result in the HRC-S observation is also higher than the value derived from the ACIS-S observation by a factor of ∼1.6. This is due to the blending from the Fe xvii line at 36.692 Å as resolved in the case of the ACIS-S.

**Figure 3.** Extracted LETGS spectra of our sample in the wavelength range 36.0–37.0 Å. The HRC-S instrument was used for all observations. The prominent lines from S xii are labeled by dashed vertical lines. The dash-dotted horizontal lines refer to the continuum levels for each star.

**Table 3**

| Stars   | Instrument | $F^-$ (36.398 Å) | $F^+$ (36.398 Å) | $F^-$ (36.564 Å) | $F^+$ (36.564 Å) | $F^-$ (12.136 Å) |
|---------|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Procyon | HRC-S      | 0.38 ± 0.11     | 0.33 ± 0.13     | 0.24 ± 0.11     | 0.32 ± 0.13     | ...             |
| Procyon | HRC-S      | 0.34 ± 0.14     | ...             | 0.24 ± 0.13     | ...             | ...             |
| Procyon | RGS1       | 0.35 ± 0.10     | 0.15 ± 0.06     | ...             | ...             | ...             |
| Procyon | RGS2       | 0.28 ± 0.07     | 0.29 ± 0.09     | ...             | ...             | ...             |
| α Cen B | HRC-S      | 0.43 ± 0.11     | ...             | 0.32 ± 0.11     | ...             | ...             |
| Capella | HRC-S      | 2.61 ± 0.89     | 2.84 ± 0.87     | 0.89 ± 0.23     | 0.91 ± 0.24     | 11.04 ± 0.30    |
| Capella | ACIS       | 0.69 ± 0.14     | ...             | 0.34 ± 0.14     | ...             | ...             |
| ε Eri   | HRC-S      | 0.71 ± 0.13     | 0.78 ± 0.15     | 0.23 ± 0.11     | 0.45 ± 0.13     | 0.91 ± 0.04     |
| YY Gem  | HRC-S      | 0.29 ± 0.06     | 0.49 ± 0.09     | 0.15 ± 0.07     | 0.19 ± 0.09     | 1.03 ± 0.07     |
| TW Hya  | HRC-S      | 0.37 ± 0.10     | 0.42 ± 0.11     | 0.36 ± 0.10     | 0.13 ± 0.09     | 0.48 ± 0.03     |

**Notes.**

Measured flux (in 1.0 × 10⁻⁴ photon s⁻¹ cm⁻²) of S xii lines at 36.398 Å and 36.564 Å and the line at 12.136 Å for 6 stars observed with the LETG spectrometer.

$F^-$ and $F^+$ indicate the line fluxes with 1σ error derived from negative and positive diffraction spectra, respectively.

* The line fluxes in this case are from Raassen et al. (2002).
the emission line at 36.394 Å. That is, there is no contamination from third-order diffraction at this emission line is detected at ~36.394 Å. Errors are overlaid again in Figure 2 (see black symbols). The observed ratio and the constrained electron density with 1σ uncertainty. We also notice that the electron density determined from Si xii is lower than the result from O vii, which is due to the blending effect from third-order diffraction of the emission line at 12.136 Å resulting from Fe xvii and Ne x. For a pre-main sequence star, TW Hya, Stelzer & Schmitt (2004) estimated that the electron density is from the accretion shock.

Adopting the efficiency of third-order diffraction determined in the previous subsection, and the line flux at 12.136 Å, we extract its contribution to be around 36.394 Å, and re-derive the line ratio and the corresponding electron density as illustrated by the open symbols in Figure 5. For ε Eri, the resulting electron density is still lower than the value constrained by O vii by an order of magnitude. However, the n_e determined from Si xii shows an agreement with n_e constrained by O vii for YY Gem and TW Hya within the 1σ uncertainty. We also notice that the electron density determined from Si xii (or O vii) is slightly higher than that from Si x (or C v) with a lower peak line formation temperature.

Using the line fluxes from HRC-S observations are used for other stars in our sample, that is, the blending effect has not been considered. The deduced densities are typical values for inactive stars. We compare the densities with the values derived from the spectra of helium-like ions with the same peak line formation temperatures in the ionization equilibrium (Bryans et al. 2006), as shown in Figure 5.

The density from Si x shows a good agreement with the value constrained by C v within the statistical errors. For ε Eri and α Cen B, electron densities are not available from the helium-like C v and O vii spectra, respectively. The diagnostic from boron-like Si x and S xi compensates the estimation for the X-ray emitting regions with low temperatures. For inactive stars and Capella, the density constrained by S xi is also in agreement with the results from O vii. However, for ε Eri, YY Gem, and TW Hya, it is clear that the density constrained by S xi is lower than the result from O vii, which is due to the blending effect from third-order diffraction of the emission line at 12.136 Å resulting from Fe xvii andNe x. For a pre-main sequence star, TW Hya, Stelzer & Schmitt (2004) estimated that the electron density is not less than 1.0 × 10^{12} cm^{-3}, and concluded that the X-ray emission is from the accretion shock.

Adopting the efficiency of third-order diffraction determined in the previous subsection, and the line flux at 12.136 Å, we extract its contribution to be around 36.394 Å, and re-derive the line ratio and the corresponding electron density as illustrated by the open symbols in Figure 5. For ε Eri, the resulting electron density is still lower than the value constrained by O vii by an order of magnitude. However, the n_e determined from Si xii shows an agreement with n_e constrained by O vii for YY Gem and TW Hya within the 1σ uncertainty. We also notice that the electron density determined from Si xii (or O vii) is slightly higher than that from Si x (or C v) with a lower peak line formation temperature.

Using the line ratio of S xii to Ar xiv, effective electron densities of the laboratory plasmas in the Lawrence Livermore EBIT performed by Lepson and collaborators.
(Lepson et al. 2003, 2005) are constrained by the boron-like line ratio, as illustrated by the red-circle symbols in Figure 2. For argon plasma, the constrained electron density \((5.6^{+1.0}_{-1.1} \times 10^{10} \text{ cm}^{-3})\) agrees well with the actual density \((6.0 \times 10^{10} \text{ cm}^{-3})\) estimated by the K-shell N vi spectrum as reported by Chen et al. (2004). For sulfur plasma, the electron density is firstly estimated to be \(3.4^{+0.8}_{-0.6} \times 10^{10} \text{ cm}^{-3}\). Through laboratory measurements, Chen et al. (2004) further benchmark the line ratio of Fe xxii at the low-density limit. The experimental values are overlapped again by the red-circle symbols in Figure 2. The astrophysical ratio (dark-yellow triangle) of Fe xxii is derived for the ACIS-S observation of Capella, and shows that the constrained electron density is less than 7.6 \(\times 10^{12} \text{ cm}^{-3}\), which is consistent with previous works for the stellar corona.

5. CONCLUSIONS

Collisional-radiative model calculation reveals that the line ratio \(I(3d_{3,2}–2p_{3,2})/I(3d_{3,2}–2p_{3,2})\) of Si x, S xii, Ar xiv, and Fe xxii is sensitive to the electron density in the ranges \(n_e = 4.0 \times 10^{2}–3.0 \times 10^{10} \text{ cm}^{-3}\), \(4.0 \times 10^{8}–3.0 \times 10^{11} \text{ cm}^{-3}\), \(3.0 \times 10^{9}–4.0 \times 10^{12} \text{ cm}^{-3}\), and \(2.0 \times 10^{12}–3.0 \times 10^{15} \text{ cm}^{-3}\), respectively. This compensates the \(n_e\)-diagnostics of K-shell spectra, e.g., helium ions. We further explore the 3d–2p transition lines of boron-like ions in the stellar coronal spectra measured with the LETG spectrograph combined with HRC on board Chandra. Though the emission lines are very weak, the electron density constrained from these lines shows a good agreement with those constrained by C v and O vii K-shell spectra inactive stars, and the uncertainties can be comparable with and are even better than those estimated from the K-shell spectra. When the blending effect from third-order diffraction has been taken into account, the deduced electron density increases, and gets a better consistency with that estimated from O vii for active stars, e.g., YY Gem. We also notice that the determined electron density from S xii is higher than that constrained from Si x, which is due to its higher peak temperature of line formations in collisional equilibrium.

By using the line ratio, effective electron densities in the EBIT plasma performed by Lepson et al. (2003, 2005) at the Lawrence Livermore EBIT are constrained to be \(n_e = 3.4^{+0.6}_{-0.8} \times 10^{10} \text{ cm}^{-3}\) and \(5.6^{+1.0}_{-1.1} \times 10^{10} \text{ cm}^{-3}\) for sulfur and argon plasmas, respectively. In the case of argon, a good agreement is found with the actual electron density derived from an N vi K-shell spectrum.

In conclusion, the boron-like 3d–2p spectra provide a good \(n_e\)-diagnostics for hot plasmas and compensate the spectral diagnostic of the K-shell spectrum.

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Figure 5. Comparisons of the electron densities derived from K-shell ions (C v and O vii) and boron-like ions (Si x and S xii). The black symbols denote results from C v and Si x, and the red symbols refer to results from O vii and S xii. The line indicates the same densities from the K-shell and boron-like spectra. Symbols without error bars and arrows indicate no electron density is available. For ε Eri, YY Gem, and TW Hya, taking the third-order diffraction into account, the resulting electron density is shown by red-open symbols.

(A color version of this figure is available in the online journal)
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