Diagnostics of EUV Spectral Emission from Boron-like Ions

JIANFANG PENG AND ANIL K. PRADHAN

Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA

Recent developments of EUV diagnostics from transitions in Boron-like ions, C II, N III, O IV, Ne VI, Mg VIII, Al IX, Si X, and S XII, are discussed based on new atomic data (Zhang, Graziani & Pradhan (1994)) and systematic theoretical calculations of line intensity ratios (Peng & Pradhan 1995). The available EUV and UV lines which are good temperature and density diagnostics are summarized. Possible applications of these lines to the investigation of the physical conditions in astrophysical objects are proposed.

1. Introduction

The atomic structure of Boron-like ions affords useful diagnostics of sources in the EUV and UV spectral emissions. Previous studies have focused primarily on low-Z B-like ions C II, N III, O IV, and Ne IV, and no systematic study of the isoelectronic sequence has been done. Previous works include the C II and O IV calculations by Hayes & Nussbaumer (1984, 1983), the C II work by Lennon et al. (1985), the N III calculations by Stafford et al. (1993), and the earlier work by Luo & Pradhan (1990) and Blum & Pradhan (1992) on C II, N III and O IV. By and large, there is good agreement between all of the above calculations that have all been carried out in the close coupling approximation using the R-matrix method. Recently Zhang et al. (1994) have provided extensive results for the collisional rate coefficients for B-like ions, that include the higher members of the sequence, calculated with high precision under the auspices of the Iron Project (Hummer et al. 1993). Some of the new data has been employed in diagnostic studies of the UV lines of O IV observed in gaseous nebulae and solar spectra (O'Shea et al. 1995; Keenan et al. 1993a) and Ne VI line ratios observed from the Sun (Keenan et al. 1993b; Cook et al. 1994; Keenan et al. this meeting).

Recently a comprehensive and systematic study of the line ratios of B-like ions is reported by Peng & Pradhan (1995), using the new Zhang et al. data. Some line ratios for the EUV and UV lines are identified from the point of view of providing clean diagnostics, with the criterion that a temperature sensitive line ratio should be relatively independent of the density effects and vice-versa. While all possible line ratios in the 15-level model were considered, selected results are reported for a few of the ones that showed the best sensitivity in either the temperature or the density. In this report we focus on the EUV wavelength range with lines from B-Like ions while $Z > 8$. More extensive results of the UV lines from C, N, O ions are given in Peng & Pradhan (1995).

2. The Atomic Data and Collisional-Radiative Model

The atomic data involves the collisional rate coefficients and the radiative decay rates. The collisional rate coefficients are taken from the Zhang et al. (1994) and the radiative decay rates from the Dankworth & Trefftz (1978), Hayes & Nussbaumer (1983, 1984), and Merkelis et al. (1994). In this work B-like ions with $Z > 12$ are not considered since the collisional rate coefficients by Zhang et al. did not make a complete relativistic treatment and may not be as accurate as for the lower Z ions. The collisional calculations by Zhang et al. (1994) were carried out in a 8-state (15-level) close coupling approximation,

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TABLE 1. Selected Line Ratios For Density Diagnostics

	$\frac{^4P_{5/2} - ^2P^0_{3/2}}{^4P_{3/2} - ^2P^0_{3/2}}$	$\frac{^4P_{3/2} - ^2P^0_{3/2}}{^4P_{1/2} - ^2P^0_{3/2}}$	$\frac{^4P_{5/2} - ^2P^0_{3/2}}{^4P_{1/2} - ^2P^0_{3/2}}$	$\frac{^4P_{3/2} - ^2P^0_{1/2}}{^4P_{1/2} - ^2P^0_{1/2}}$
Ne VI	999.6/1006.1	1006.1/1010.6	999.6/1010.6	993.0/997.4
Mg VIII	773/784	784/791	773/791	764/771
Al IX	692/704	704/713	692/713	681/689
Si X	625/639	639/650	625/650	612/622
S XII	520/539	539/554	520/554	504/516

NOTES: Wavelengthes (Å) for Ne VI are in air (Morton 1991). For other ions the wavelength given are approximate.

including the terms: $2s^22p(^2P^o_{1/2,3/2})$, $2s2p^2(^4P_{1/2,3/2,5/2}$, $^2D_{3/2,5/2}$, $^2S_{1/2}$, $^2P_{1/2,3/2})$, $2p^3$ $(^4S^o_{3/2}$, $^2D^o_{3/2,5/2}$, $^2P^o_{1/2,3/2})$. They also examined the effect of including the n=3 terms, $2s^23s(^2S)$, $2s^23p(^2P^o)$ and $2s^23d(^2D)$, and found these to enhance the excitation rate coefficients for some transitions in Ne VI. The Zhang et al. results are in agreement with those obtained earlier by Hayes (1992) for Ne VI and appear to indicate a general tendency for the resonances converging on to the $n = 3$ thresholds to enhance significantly the excitation of some of the higher $n = 2$ states (i.e. those dominated by $2p^3(^4S^o, ^2D^o, ^2P^o)$). Recently, Keenan et al. (1994) used the 11-state data and calculated the Ne VI line ratios for comparison with solar UV observations. In the present work we study similar line ratios for Mg VII and Si X. Our collisional-radiative model includes the 15 levels as mentioned above. The level populations are determined by solving the coupled set of equations for the 15 levels system and intensity ratios are carried out in the optical thin plasma.

3. EUV Line Ratios of Density and Temperature Diagnostics

There are a number of transitions in the EUV that could potentially be employed as temperature or density diagnostics in B-like ions. The present work involved a comprehensive study of all the line ratios along the isoelectronic sequence as functions of temperature and density. Below we present selected results (line ratios for other ions and lines may be obtained on request from the authors).

Fig. 1 shows a typical intensity ratios $I(^4P_{5/2} - ^2P^o_{3/2})/I(^4P_{3/2} - ^2P^o_{3/2})$ for the ions considered in the low density regime. The wavelengths of the UV and the EUV lines in the line ratio $(^4P_{5/2} - ^2P^o_{3/2})$ $/(^4P_{3/2} - ^2P^o_{3/2})$ range from the $\lambda\lambda$ (2327.6, 2329.1) pair in C II, to $\lambda\lambda$ (520.3, 539.3) in S XII. The densities range from 10^2 cm^{-3} for C II up to 10^{12}cm^{-3} for S XII. The criterion used here is that the temperature sensitivity be small and the value of line ratio be not too small or large. Depending on the ion charge, the line intensities involving the ^4P levels are sensitive to wide range of electron densities. Table 1. gives ratios of wavelengths of lines involving the ^4P levels for the various ions that were found to be reasonably temperature-independent so as to serve as good density diagnostics.

Unlike density sensitive lines temperature sensitivity requires that the energy differences between the upper levels should be large enough so as to affect a temperature-dependence through the electron excitation rate coefficients. Further, to minimise density dependence the radiative decay rates should be much larger than the collisional

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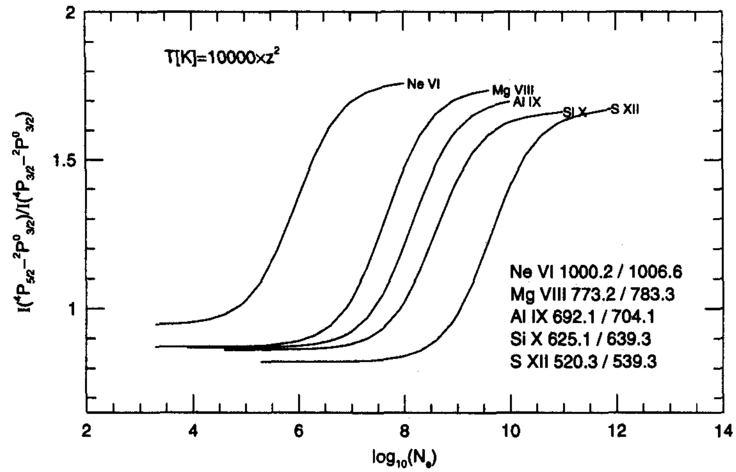

FIGURE 1. Density Diagnostic Line Ratios

TABLE 2. Selected Line Ratios For Temperature Diagnostics

ION	$\frac{^2P_J - ^2P^0_{J'}}{^2D_J - ^2P^0_{J'}}$
C II	905/1337
N III	687/992
O IV	556/791
Ne VI	403/563
Mg VIII	317/437
Al IX	287/393
Si X	261/356
S XII	222/300

NOTE: Wavelengthes (Å) are not observed but caculated.

de-excitation or redistribution rates from, or between, the upper levels. The $2s2p^2$ ($^2D_{3/2,5/2}$, $^2S_{1/2}$, $^2P_{1/2,3/2}$) levels, lying above the metastable ^4P term, fulfill these criteria and give rise to a number of lines that could be used as good temperature diagnostics. All possible line ratios were investigated and it was found that the ratios of lines $^2D_J -^2 P^o_{J'}$ and $^2P_J -^2 P^o_{J'}$ are particularly sensitive to electron temperature. Table 2 gives a wavelength ratios for these multiplets in the ions considered. The individual fine structure components are very close in wavelength and most have not been observed.

Fig. 2 shows four ions considered. With increasing ion charge there is a larger spread with density. However, the line ratios given provide an example of the lines that might be used as temperature indicators in the EUV. The temperatures considered are scaled with ion charge as z^2.

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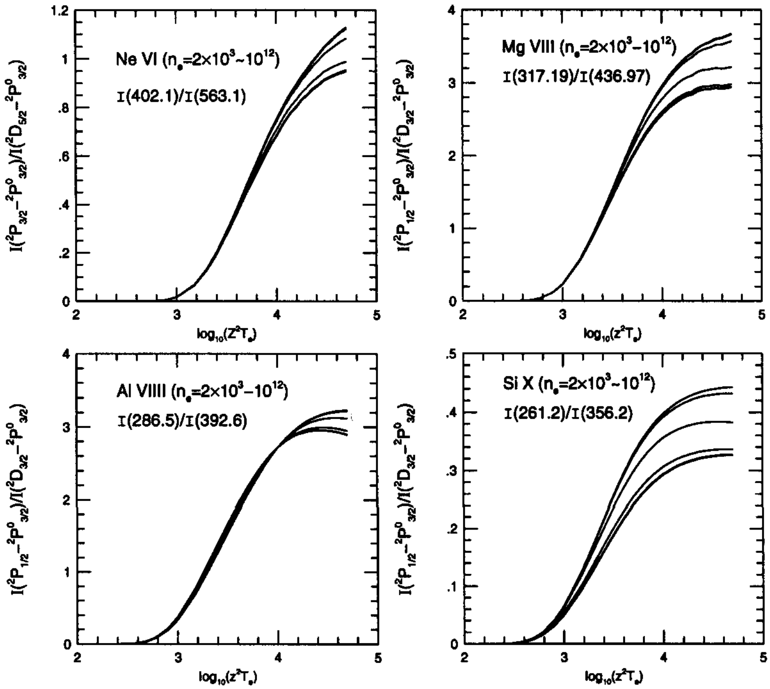

FIGURE 2. Temperature Disagnostic Line Ratios

4. Conclusion

A sample of the extensive study of temperature and density dependent EUV and UV line ratios of B-like ions has been summarized. Line ratios are investigated for pairs of transitions along the isoelectronic sequence, making it possible to employ a given diagnostic ratio for more than one ion in the sequence for the same or similar sources, and to enable a study of the temperature and density dependence as function of ion charge. These line ratios should be applicable to the astronomical objects like QSQs, AGNs, nova and hot stars.

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REFERENCES

BLUM, R. D., & PRADHAN, A. K. 1992, ApJS, 80, 425
DANKWORTH, W. & TREFFTZ, E. 1978, A&A, 65,93
HAYES, M. A. & NUSSBAUMER 1984, A&A, 134,193
HAYES, M. A. & NUSSBAUMER 1983, A&A, 124,279
HAYES, M. A. 1992, J. Phys. B, 25,2649

https://doi.org/10.1017/S0252921100036587 Published online by Cambridge University Press

HUMMER, D. G., BERRINGTON, K. A., EISSNER, W., PRADHAN, A. K., SARAPH, H. E. & TULLY, J. A. 1993, A&A, 279, 298

LUO, D. & PRADHAN, A. K. 1990, Phys. Rev. A, 41,165

LENNON, D. J., DUFTON, P. L., HIBBERT, A., KINGSTON, A. E. 1985, ApJ, 294, 200

KEENAN, F. P., CONLON, E. S., BOWDEN, D. A., DWIVEDI, B. N. & WIDING 1994a, Solar Phys., 149, 137

KEENAN, F. P., WARREN, G. A., DOYLE, J. G., BERRINGTON, K. A., KINGSTON, A. E. 1994b, Solar Phys., 150, 61

KEENAN, F. P., FOSTER, V. J., REID, R. H. G., DOYLE, J. G., ZHANG, H. L. & PRADHAN, A. K. 1994, private communication

MERKELIS, G., VILKAS, M. J., GAIGALAS, G. & KISIEULIUS, R. 1994, Physica Scripta, submitted

O'SHEA, E., FOSTER, V. J., KEENAN, F. P., DOYLE, J. G., REID, R. H. G., ZHANG, H. L., & PRADHAN, A. K. 1995, A&AS, submitted

PENG, J. F. & PRADHAN, A. K. 1995, A&AS, submitted

PENG, J. F. & PRADHAN, A. K. 1994, ApJ, 432, L123

ZHANG, H. L., GRAZIANI, M. & PRADHAN, A. K. 1994, A&A, 283, 319

STAFFORD, R. P., HIBBERT, A., & BELL, K. L. 1993, MNRAS, 260, L11

https://doi.org/10.1017/S0252921100036587 Published online by Cambridge University Press