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Collisional-Radiative Model for Fe Ions and X-Ray Spectra from Early-Type Stars

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Abstract

We constructed a collisional-radiative model for L-shell Fe ions and analyzed X-ray spectra from early type star (OB stars) observed with *Chandra*. Our model includes a large number of energy levels from H-like to Mg-like Fe ions. Assuming quasi-steady states we can also construct the model of non-equilibrium ionization by solving the rate equations for excited states. Atomic data are calculated mainly by the Hullac code. Using our model, we analyzed three early type stars observed by *Chandra* and estimated electron density and temperature of the X-ray emitting plasma from the intensity ratios of X-ray spectral lines.

Keywords:

early type star, Chandra, X-ray, collisional-radiative model, L-shell Fe ion

1. Introduction

X-rays from early-type massive stars were serendipitously discovered by the Einstein satellite in 1978 [1, 2]. Soon after that, two models for their X-ray emission mechanism were proposed. One is coronal model [3] and the other one is stellar wind-shock model [4]. X-ray line profile is expected to be different depending on these models. In case of the corona model, line profiles are expected to be symmetric and sharp. On the other hand, in case of the stellar wind shock model, line profiles are expected to be blue-shifted and asymmetric. Recently, high resolution spectral observation by *Chandra* makes it possible to study the actual line profile of the early type stars [5, 6]. Analysis of the Chandra HETG spectrum of ζ Pup using the stellar wind-shock model, which considers Doppler shifts and photoelectric absorption, indicates that the most inner radius of the X-ray emission region, R_{in}, is roughly 1.3~1.4 times of the stellar radius, R_*, and the optical depth is roughly 4 [6]. However the radius of the X-ray emission region derived from the intensity ratio between the forbidden and the intercombination lines of He-like ions is $\sim 4.0R_*$ [7].

The observed spectra show not only lines from H-like and He-like ions, but also those from L-shell Fe ions. Therefore, we constructed a collisional-radiative model for L-shell Fe ions in order to deduce information, electron density and electron temperature etc., of the plasma by analyzing intensity ratios of the measured spectra of L-shell Fe ions with the similar method.

Compared with other models [8, 9], our model includes high excited states $n > 7$ in order to calculate the population density in non-ionization equilibrium and to calculate correct ionization balance. In this paper, we estimated electron density and temperatures using six lines of Ne-like Fe ions observed in the spectra from three early type stars, τ Sco, δ Ori and ζ Pup assuming optically thin plasma and ionization equilibrium.

2. Observation

The analyzed spectral data are obtained by MEG (medium energy grating) and HEG (high energy grating) of HETG (high energy transmission grating) onboard *Chandra*. The Data are reduced using tools of CIAO v3.0 and extracted the dispersed spectral data restricting the area of the CCD image. We created the auxiliary response file using the CIAO tools and used the response matrix file of the detector supplied by the hard ware team. Our analyzed three stars, τ Sco, δ Ori and ζ Pup, were observed with the exposure time of 72.1 ks, 49.0 ks and 67.6 ks, respectively.

Some selected lines, mainly H-like ions Lyα and Ne-like Fe ions lines, of three early type stars are fitted by a

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Gaussian function and the velocity by the line centroid shift and HWHM (half width half maximum) velocity are calculated. For τ Sco, X-ray lines have no centroid shift and the HWHM velocity of about 200 km s^{-1}. For δ Ori, X-ray lines have almost no centroid shift and the HWHM velocity are ranging between 400 km s^{-1} and 600 km s^{-1}. Centroid shifted and HWHM velocity for ζ Pup are $-600 \sim -800$ km s^{-1} and $600 \sim 1000$ km s^{-1}, respectively. Note that the negative centroid shift means blue shift of line center. Thus we can recognize that emission lines of the early type stars show variety of their profiles, suggesting the other unknown parameter in the X-ray emission mechanism.

3. Collisional-radiative model for L-shell Fe ions

We constructed a collisional-radiative model for L-shell Fe ions. This model includes energy levels of single excited states, nl for H-like, $1snl$ for He-like, $1s^2nl$ for Li-like, $1s^22snl$ and $1s^22pnl$ for Be-like, $1s^22s^2nl$, $1s^22s2pnl$ and $1s^22p^2nl$ for B-like, $1s^22s^22pnl, 1s^22s2p^2nl$ and $1s^22p^3nl$ for C-like, $1s^22s^22p^2nl, 1s^22s2p^3nl$ and $1s^22p^4nl$ for N-like, $1s^22s^22p^3nl, 1s^22s2p^4nl$ and $1s^22p^5nl$ for O-like, $1s^22s^22p^4nl, 1s^22s2p^3nl$ and $1s^22p^6nl$ for F-like, $1s^22s^22p^5nl$ and $1s^22s2p^6nl$ for Ne-like, $1s^22s^22p^6nl$ for Na-like and $1s^22s^22p^63lnl'$ for Mg-like Fe ions. Energy levels of $2 \leq n \leq 5$ are treated with fine structure, those of $6 \leq n \leq 9$ are distinguished by their configuration and those of $10 \leq n$ are treated with l-averaged configuration. Maximum principal and orbital quantum number of our model are $n_{max} = 20$ and $l_{max} = 4 (l = 0, 1, 2, 3, 4)$, respectively. Some of these excited states are in autoionizing states. The contributions of the autoionizing states are included as dielectronic recombination processes. The following atomic processes are included in our model; excitation / de-excitation by electron impact, ionization / three-body recombination, radative transition, radiatve recombination, autoionization / dielectronic capture and dielectronic recombination. We used atomic data of $2 \leq n \leq 5$ calculated by HULLAC code [10]. Atomic data of $n > 6$ were approximated by data of hydrogen-like ions.

Our model includes all atomic processes between levels of L-shell Fe ions except the dielectronic recombination from the excited states. Dielectronic recombination processes are included for the excited levels for $2 \leq n \leq 5$. The dielectronic recombination rate coefficient was calculated by using branching ratio $A^a/(\sum A^a + \sum A^r)$. The current calculation of ionization balance by our model is not enough, because of insufficient inclusion of dielectronic recombination.

We constructed rate equations as;

$$\frac{dN_i}{dt} = -\sum_j W_{ij}N_i + \sum_j W_{ji}N_j, \qquad (1)$$

where W_{ij} are total transition rates from i to j. Then we calculated the population density of excited states assuming quasi-steady states, where population densities N_i of an excited state i is expanded by population densities N_k of a ground state k as follows,

$$N_i = \Sigma_k r_i{}^{(k)} N_e N_k, \qquad (2)$$

where N_e is the electron density and $r_i^{(k)}$ is the population density coefficient. From a state k to a state k' by assuming quasi-steady state for ground states, effective excitation, de-excitation, ionization and recombination rate coefficients $S^{CR}_{kk'}$,

$$S^{CR}_{kk'} = \Sigma_i r_i{}^{(k')} W_{k,I} \qquad (3)$$

are calculated. By constructing rate equations of the ground states using effective transition rate coefficients, ionization balance is calculated without assumption of complete steady state and population densities in non-ionization equilibrium are also calculated using eq.(2).

4. Estimation of Te and Ne

Electron density and temperature are estimated from the line intensities of L-shell Fe ions, especially of Ne-like Fe ions. Electron density is estimated by using intensity ratio of $2s^22p^53s(J = 1)$ to $2s^22p^53s(J = 2)$ [11] where a density effect in population densities between $2s^22p^53s(J = 1)$ and $2s^22p^53s(J = 2)$ is used, as shown in Fig.1. Figure 2 shows the intensity ratio as a function of electron density. The intensity ratio has a large dependence on the electron density between 10^{12} cm^{-3} and 10^{15} cm^{-3}. On the other hand, the ratio has a small dependence on the electron temperature. The intensity ratio of the measured line spectra was determined by C-statistic fitting used Gaussian function profile. We show determined 90% confidence regions of the intensity ratios in Fig.2, where centroide shift velocity of two 3s lines of δ Ori and ζ Pup were assumed to that of Ne-like Fe ions at 16.7800 Å. Electron density by the ratio of τ Sco was determined to be $N_e < 5\text{x}10^{12}$ cm^{-3}. However that of δ Ori and ζ Pup could not be determined by large error range, because of broad line shape of Fe XVII (17.0510 Å) and Fe XVII (17.0960 Å). We have to note that the intensity ratio is also affected by optical light, although we neglected it.

Electron temperature is estimated by using an intensity ratio of $2s^22p^53d$ to $2s^22p^53s$ states [12]. The intensities of 3d and 3s lines are obtained from the sum of

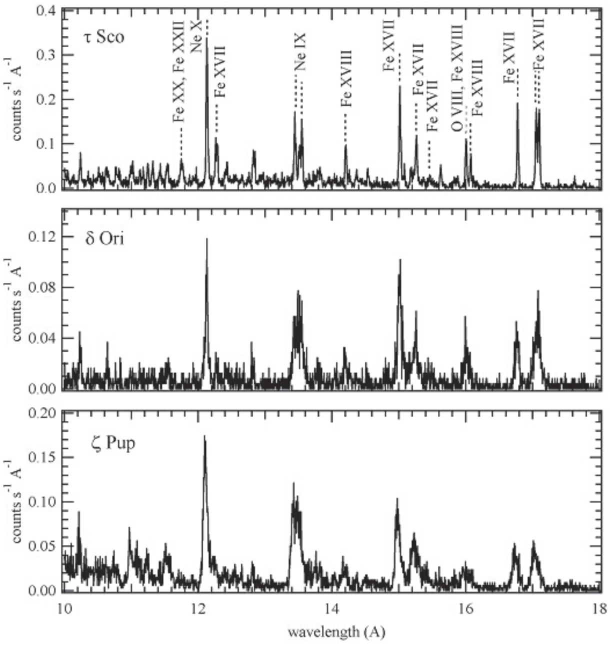

Fig. 1 The measured X-ray spectra of MEG +1/–1 order of three early type stars with *Chandra*. Top, middle and bottom panels are X-ray spectra in range of 10~18 Å of τ Sco, δ Ori and ζ Pup

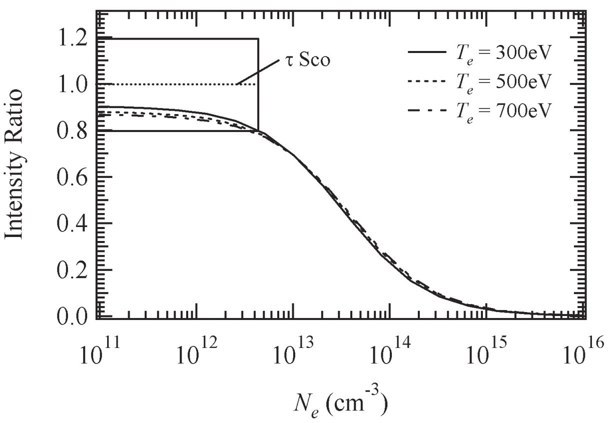

Fig. 2 The intensity ratio of 3s ($J=1$) to 3s ($J=2$) as a function of electron density. Solid, dashed and dot-dashed lines are at $T_e = 300$ eV, 500 eV and 700 eV, respectively. A dotted straight line is lower limit of 90 % confidence level on the intensity ratio of τ Sco. For ζ Pup and δ Ori, ranges of 90 % confidence level on the intensity ratio exceed the intensity range of this figure.

three transitions among levels of fine structure levels. The intensity ratio as a function of electron temperature is shown in Fig.3. Electron temperatures of τ Sco and δ Ori were determined to be $60 - 180$ eV and < 120 eV, respectively. The temperature is very low comparing to $T_m = 432$ eV of Ne-like Fe ions, T_m is temperature at maximum emissivity. For underestimation of T_e, we considered two problems, an effect of N_H, where N_H is column density for stellar absorption, and weak dependence of the ratio for T_e. Photoelectric absorption cross sections assumed solar abundance are 3.5x10^{-22} cm^2 and 4.8x10^{-22} cm^2 around 15 Å and 17 Å, respectively. In case of τ Sco, using $N_H = 3.16\text{x}10^{20}$ cm^{-2} [13], the intensity ratio increases about 5%. Since the calculated ratio is approximately flat at $T_e = 100 - 500$ eV, insufficient estimation of the ratio may be a fatal. For L-shell Fe ions, high precious atomic data are also required. In addition to that, influence of the contamination of lines around 15 Å isn't small in analysis for broad line shape as δ Ori and ζ Pup. We note that we neglect the resonance scattering effects which strongly affect the resonance transition.

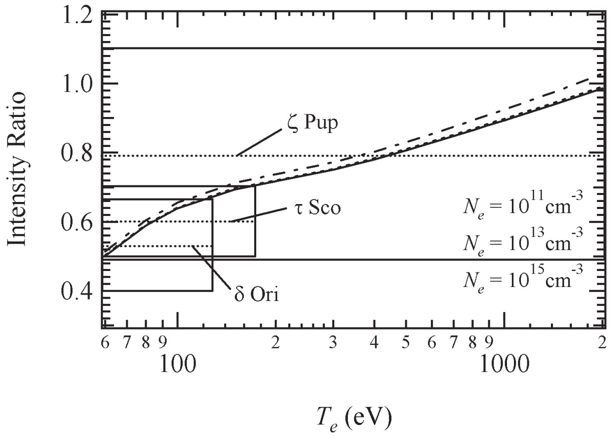

Fig. 3 The intensity ratio of 3d to 3s lines as a function of electron temperature. Boxes in this figure indicate a parameter error range. The height of box is range of 90 % confidence level for intensity ratio and the side of box is error range of electron temperature.

5. Summary

We constructed a collisional-radiative model for L-shell Fe ions in optical thin plasma. Our model is generalized model to assume quasi-steady state for non-ionization equilibrium. In this paper, we analyzed the measured intensity ratios of three early type stars with *Chandra*. Electron density and temperature by assuming optical thin plasma are estimated. In order to estimate electron densities and temperatures more accurately, the absorption in optical around 5500 ~ 6500 Å(~ 2 eV) and the resonance scattering are required to be taken into account. We will develop our calculation of ionization balance on fine structure including all dielectronic recombination and photoionization. We will improve our calculation of line profiles by considering the radiative transfer.

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