Intensity ratio of EUV emission lines in Fe XV studied with electron beam ion traps

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Abstract. We present emission spectra of highly charged Fe ions in the extreme ultraviolet range obtained with two electron beam ion traps. The intensity ratio between the 3s3p 3P2 - 3s3d 3D3 (233.9 Å) and 3s3p 1P1 - 3s3d 1D2 (243.8 Å) transitions in Fe XV is given for various electron beam parameters. The experimental ratios are compared with theoretical model calculation as well as our previous experiment, where significant discrepancy with theoretical model was found. The present result, which has been obtained with a higher resolution spectrometer to investigate possible line blending, confirms that the discrepancy is not due to line blending.

1. Introduction
The electron density dependence of Fe ion spectra in the extreme ultraviolet (EUV) range is very important for the spectroscopic diagnostics of the solar atmosphere. In our previous study [1], the electron density dependence of the intensity ratio was measured for several density-sensitive emission lines in Fe XIII, XIV, and XV with a compact electron beam ion trap (EBIT) called CoBIT [2]. Although good quantitative agreement was obtained between the experiment and our model calculation for Fe XIII and XIV, a significant discrepancy was found for the intensity ratio between the 3s3p 3P2 - 3s3d 3D3 (233.9 Å) and 3s3p 1P1 - 3s3d 1D2 (243.8 Å) transitions in Fe XV. The discrepancy for this line ratio has also been found so far from solar observations (for example, see ref. [3]), and line blending has often been pointed out as the origin of the discrepancy [3, 4, 5]. In this paper, we re-examine the Fe XV spectra with two EBITs in Tokyo. In particular, a spectrometer with a higher resolution is applied to investigate possible line blending.

2. Experiment
In the previous study [1], CoBIT and a flat field grazing incidence spectrometer [6] were used to observe the EUV spectrum of Fe XV. The spectrometer employed a variable line spacing concave grating (Shimadzu 30-002) with an average groove number of 1200 grooves/mm and a
radius of curvature of 5649 mm. The distance from the grating to the focal plane was 235 mm and the dispersion was 7.0 Å/mm on the focal plane.

On the other hand, in the present study, a concave grating with a larger radius of curvature (Hitachi 001-0660) was used to obtain higher dispersion. Figure 1 shows the schematic drawing of the present spectrometer installed to CoBIT. Although the average groove number is the same as that of the previous grating, the larger radius of curvature (13450 mm) and the larger distance from the grating to the focal plane (563.2 mm) makes the dispersion on the focal plane higher as 2.6 Å/mm. In addition, in the present study, not only CoBIT but also the Tokyo-EBIT [7, 8] was used. As shown in Fig. 1, the spectrometer is used in the slit-less configuration in which the thin line shaped source in an EBIT is regarded as an entrance slit. The “slit width” is determined by the electron beam width because short lifetime EUV transitions occur immediately after the ion is excited by a beam electron. It is thus possible to obtain higher resolution with the Tokyo-EBIT because higher compression of the electron beam is possible with a magnetic field higher than that in CoBIT. To produce Fe ions, a vapor of ferrocene at a room temperature was introduced from a gas injector for the experiment with CoBIT, whereas a vapor of metal iron heated in an effusion cell [9] was introduced for the experiment with the Tokyo-EBIT. Typical spectra are shown in Fig. 2. The spectral resolution in the present study was 0.4 Å with CoBIT and 0.2 Å with the Tokyo-EBIT, which has been much improved from the previous study where it was 0.8 Å. The improved resolution has a beneficial role in investigating possible line blending.

3. Results and discussion

Figure 3 shows the experimental intensity ratios between the $3s3p^3P_2 - 3s3d^3D_3$ (233.9 Å) and $3s3p^1P_1 - 3s3d^1D_2$ (243.8 Å) transitions in Fe XV obtained with various EBIT parameters (electron current, electron energy, central magnetic field, etc.). For the CoBIT experiment, the electron density was experimentally determined with an electron beam imaging device (see Fig. 1) similarly to the previous study [1]. For the Tokyo-EBIT experiment, since no imaging device could be applied, the electron density was determined by applying the experimental ratio between the $3s^23p^2P_{3/2} - 3s^23d^2D_{5/2}$ (211.3 Å) and $3s^23p^2P_{3/2} - 3s^23d^2D_{5/2}$ (219.1 Å) transitions in Fe XIV to the model calculation, which was confirmed in the previous study to reproduce the experimental ratio well for these transitions. The solid line in the figure is the
Figure 2. (color online) EUV spectra of Fe ions obtained with (a) the Tokyo-EBIT (610 eV - 12 mA), (b) CoBIT (500 eV - 13 mA), (c) Spectra obtained in previous study [1] with CoBIT (500 eV - 15 mA).

Figure 3. (color online) Intensity ratio between the $3s3p \, ^3P_2 - 3s3d \, ^3D_3$ (233.9 Å) and $3s3p \, ^1P_1 - 3s3d \, ^1D_2$ (243.8 Å) transitions in Fe XV. Black open squares: previous results with CoBIT [1]; blue open circles: present results with CoBIT; red closed circles: present results with the Tokyo-EBIT.

As seen in the figure, although the scatter of data is found to be relatively large, the general tendency that experimental ratios exceed the model calculation is confirmed. The same tendency in solar observation was already pointed out by Dufton et al. [3] in 1990. They analyzed four solar flare spectra obtained with the Naval Research Laboratory’s S802A instrument on Skylab, and found that the observed ratio exceeded theoretical high density limit (0.59) substantially for three of them, and was almost on the limit value for another one. The origin of this discrepancy has been discussed in their and several subsequent papers [4, 5, 10], and some of them pointed out the influence of possible blending of Ni XVIII at 233.8 Å or Ar XIV at 243.8 Å. However, in the present study with EBITs, the possibility of Ni and Ar is completely excluded. Possible contaminants in EBITs are C, N, O, Ba, and W, but none of them has meaningfully intense line at the Fe XV lines of interest. In particular, there is no evidence of any contaminants in the high resolution spectra obtained with the Tokyo-EBIT (Fig. 2(a)), whereas some lines from O ions were confirmed for the CoBIT spectra. We thus consider that the discrepancy with the theoretical model is not due to line blending, but the accuracy of the atomic data used in the model.

4. Summary and outlook
We have re-examined the previous observation of Fe XV, where a significant discrepancy in intensity ratio with a theoretical model. Possible line blending has been carefully investigated using a higher resolution spectrometer, and we conclude that the discrepancy is not due to line blending.

Since sensitivity correction was not applied in this study, an intensity ratio between lines at close wavelengths was studied. To obtain the ratio between lines at distant wavelengths,
sensitivity correction should be applied because the diffraction efficiency of a grating and the quantum efficiency of a CCD depend on wavelength. For this purpose, a manipulation system has been installed to insert a metal wire into the trap region of CoBIT. Sensitivity correction using bremsstrahlung radiation from an inserted wire is in progress.

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