X-ray Spectroscopy of Non-thermal Equilibrium Laboratory Photo-ionized Plasma
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Abstract. Photo-ionized silicon plasma was studied using 500-eV Planckian radiation from implosion core plasma generated with Gekko-XII laser to simulate a astrophysical photo-ionized plasma. Three major features were observed in an energy range from 1.80 to 1.88 keV and origins of the features were replicated with a time-dependent collisional-radiative model including photo-ionization processes: The line at 1.865 keV is the resonance line by inner-shell photo-ionization of Li-like Si ions and that at 1.840 keV is the sum of satellite lines attributed to the inner-shell photo-ionization of Be-like ions. Emission lines in the soft x-ray/extreme ultra-violet (EUV) region (i.e., 140 to 300 eV) from the low-temperature Si plasma in prior to the photo-ionization were also identified to extract the intial temperature and density of the pre-formed Si.

1. Introduction
Photo-ionized plasma in astronomy is generated around x-ray binary star, consisting of a compact star and a companion star as Cygnus X-3 [1] and Vela X-1 [2]. In general, the observed x-ray spectra with a x-ray telescope (i.e. Chandra, XMM-Newton, Suzaku etc.) are analyzed to fit the theoretical spectra. Therefore, simulation experiments of astronomy-like plasmas in laboratory are highly important for validation of theoretical models. Creation of astronomy-like photo-ionized plasma are more difficult than the generations of collisional-ionization plasmas (i.e. solar, star etc.), because the creation high radiation temperature x-ray sources in laboratories is very difficult. Even in recent experiments, temperature of radiation source are around one hundred eV [3], was not sufficient to mimic similar situations observed in universe since the radiation temperate of the photo-ionized plasma is on the order of 1-2 keV.

In our work, x-ray sources like x-ray binary star are generated with laser driven-implosion. The compressed core plasma is known to be one of the most high radiation sources. Then astronomy-like photo-ionized plasmas are generated and x-ray spectra of the plasma were measured.

2. Experiments
Target layout for the present experiments is shown in Figure 1(a). A plastic-made spherical shell for the core plasma formation was set at the center of target-chamber, and a Si plate for photo-ionization plasma was set beside 1.2 mm away from the shell. Diameter and thickness of the shell were 505 μm and 6.4 μm, respectively. The Si plate was 1-μm-thick silicon coated on a 25-μm-thick plastic sheet and was in a square shape of 500 x 500 μm². The Si plate was irradiated with a 1-J, Nd-YAG laser pulse in prior to the core plasma generation. The pulse width of the Nd:YAG laser was 10 ns. The implosion plasma was generated with GXII laser of ~350 J/beam (in total 4.0 kJ for 12 beams) with a
pulse width of 1.2 ns in a Gaussian profile. A Ta-made slit was inserted between these two targets to choose a portion of the expanding Si plasma and to avoid debris restraints from the imploded core. The implosion plasma was observed to be like a black-body radiation source of 500 eV as shown in Figure 1(b). This means that the temperature of the x-ray source is high enough to ionize the pre-formed Si ions emitting x-ray spectra with a peak at 1.4 keV. It was experimentally checked that only when both the Si plasma and the implosion core were simultaneously generated were intense x-ray from the photo-ionized Si plasma observed [4]. X-ray emission from these plasmas were measured with an x-ray streak camera, a transmission grating spectrometer, a flat-field EUV spectrometer, and a Bragg crystal (RbAP) spectrometer attached with an x-ray CCD camera.

Figure 1(a). Experimental layout of the Si plate and the plastic shell. (b) Comparison of x-ray spectra from the implosion core plasma and Planckian spectra for various radiation temperatures. Best fit is seen for 500 eV.

Figure 2. Comparison of the measured spectra (solid line) from the pre-formed Si plasma with the calculated spectra (dashed line) by FLYCHK with the best-fit parameter. Letters shown on each line correspond to those listed in Table 1.
3. Soft x-ray spectra from pre-formed Si plasma and photo-ionized Si plasma

3.1. Identifications of lines from pre-formed Si plasma

Soft x-ray spectra from the pre-formed Si plasma were measured with a flat field grating spectrometer. The spectra are shown in Figure 2. Lines in the range of 4 – 9 nm (300 – 140 eV) are identified by NIST database [5] and the identifications were checked by a collisional-radiative model without photo-ionization process [6]. These wavelengths can only be roughly determined because of accumulations of many lines in the spectra. Line identifications are summarized in Table 1. The measured soft x-ray spectral lines of pre-formed Si plasma are identified to be Si VI – Si IX. Lines of A – H and O – T are derived from 2p – 3d transitions. Lines of I – M are by 2p – 3s transition and line of N is by 2s – 3p transition. For the estimation of electron temperature and density, the measured spectra were fit using the calculated spectra of FLYCHK code [7]. Since spectral resolution of FLYCHK is not sufficient in this energy range, the measured spectra were fit by structures of the calculated spectra. The estimated electron temperature and density were 28 eV and 8 × 10^{19} \text{cm}^{-3}, respectively.

Table 1. Line identification table. Wavelengths were estimated by energy levels data of NIST database.

| Spectrum | letter | \( \lambda \) (nm) | Transitions |
|----------|--------|-------------------|-------------|
| Si VI    | A      | 8.04 – 8.07       | 2s^2 2p_2^2 \text{P} – 2s^2 2p^4(\text{D}) 3d^2 S, P, D, F |
|          | B      | 8.30 – 8.35       | 2s^2 2p_2^2 \text{P} – 2s^2 2p^4(\text{P}) 3d^2 S, P, D, F |
| Si VII   | C      | 6.81 – 6.87       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{P}) 3d^1 P, D |
|          | D      | 6.94 – 6.98       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3d^1 S, P |
|          | E      | 7.01 – 7.03       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3d^1 D, P |
|          | F      | 7.14 – 7.23       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3d^1 P, D, F |
|          | G      | 7.31 – 7.34       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{S}) 3d^1 D |
|          | H      | 7.52              | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3d^1 P |
|          | I      | 7.92              | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{P}) 3s^1 P |
|          | J      | 8.15 – 8.20       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3s^1 D |
|          | K      | 8.41              | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{D}) 3s^1 D |
|          | L      | 8.52 – 8.57       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{S}) 3s^1 S |
|          | M      | 8.80 – 8.88       | 2s^2 2p_1^3 \text{P} – 2s^2 2p^3(\text{P}) 3s^1 P |
| Si VIII  | N      | 5.89              | 2s^2 2p_3^4 \text{S} – 2s^2 2p^3(\text{S}) 3p^3 P |
|          | O      | 6.14 – 6.19       | 2s^2 2p_3^4 \text{D} – 2s^2 2p^3(\text{D}) 3d^2 D, F |
|          | P      | 6.26              | 2s^2 2p_3^4 \text{P} – 2s^2 2p^3(\text{D}) 3d^2 S |
|          | Q      | 6.28 – 6.33       | 2s^2 2p_3^4 \text{P} – 2s^2 2p^3(\text{P}) 3d^2 P, D |
|          | R      | 6.37 – 6.39       | 2s^2 2p_3^4 \text{P} – 2s^2 2p^3(\text{P}) 3d^2 F |
|          | S      | 6.54 – 6.55       | 2s^2 2p_3^4 \text{P} – 2s^2 2p^3(\text{P}) 3d^4 D |
| Si IX    | T      | 5.53 – 5.54       | 2s^2 2p_3^4 \text{P} – 2s^2 2p^3(\text{D}) |

3.2. Identifications of laboratory photo-ionized plasma spectral lines

The measured spectra of Figure 3(a) were analyzed with a time-dependent collisional-radiative model including photo-ionization processes [8]. In the measured spectra, the line at 1.865 keV is the resonance lines (1s^2 1S_0 – 1s2p 1P_1) and that at 1.840 keV is a sum of the Li-like satellite lines for the resonance line. The model calculation shows that the resonance line is attributed to the photo-ionization of 1s^2 2p states of Li-like Si ions, and they are also produced by photo-ionization of the pre-formed Si plasma consisting mostly of N- and O-like ions. In the same manner, the satellite lines are to the inner-shell photo-ionization of 1s^2 2s2p and 1s^2 2p^3 states of Be-like ions. Ion densities of these p-states increase by collisions between s- and p-states. However the line at 1.853 – 4 keV in the measured spectra could not appear in the calculated spectra for the present experimental conditions. A value of the x-ray energy corresponds to the intercombination line (1s^2 1S_0 – 1s2p 3P_0). Figure 3(b) and 3(c) show the observed spectra from Cygnus X-3 and Vela X-1 with Chandra. Spectra of Cygnus
X-3 seem to consist of two strong broad lines, and spectra of Vela X-1 consist of two strong lines and one weak line. In astronomy, these lines are believed to be those from He-like ions lines, resonance, inter-combination, and forbidden lines \((ls^2S_0 - ls2s^2S_f)\).

Figure 3. Comparison of (a) the measured spectra from the present work, (b) Cygnus X-3 and (c) Vela X-1 with Chandra.

4. Conclusions
We generated astronomy-like photo-ionized plasma with GXII laser. The radiation source derived from implosion fits well with a black-body radiation of 500 eV. Soft x-ray spectra from the pre-formed Si plasma generated with 1J Nd:YAG laser were identified and electron temperature and density of the pre-formed plasma were estimated to be 28 eV and \(8 \times 10^{19}\) cm\(^{-3}\), respectively. When the radiation source and pre-formed Si plasma were simultaneously generated, photo-ionized Si plasma were generated and strong x-rays from the plasma were measured. Then origins of lines in the measured spectra were identified by the theoretical model.

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