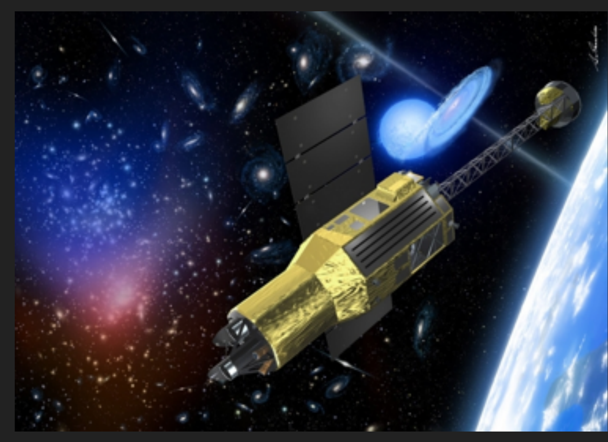
Detectability of Oxygen Emission Lines from WHIM with ASTRO-H



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Abstract: Numerical simulations indicate that more than half of the total baryons in the present universe is supposed to take warm/hot intergalactic medium (WHIM) whose typical temperature and density are 10^5 - 10^7 K and ~10^{-6} - 10^{-5} cm^{-3}, respectively. Thus, $\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$ emission lines become an efficient probe for WHIM. ASTRO-H/SXS is expected to detect these emission lines with high significance because the detector has very high energy resolution (~5 - 7 eV) also for diffuse X-ray emission. In order to investigate the detectability of oxygen emission lines from WHIM, we conducted simulations using ASTRO-H/SXS. Consequently, SXS is sensitive to the WHIM with a temperature of 0.2 - 0.3 keV and an overdensity of > 200, except for z = 0.15, where the oxygen lines are contaminated by the Galactic emission.

1. Introduction

- Cosmological simulations predict that more than 30 - 50 % of the total baryons in the present universe take a form of warm/hot intergalactic medium (WHIM) (see fig. 1 & fig. 2).
- The typical temperature and density are 10^5-10^7 K and ~10^{-6}-10^{-5} cm^{-3}. However, the X-ray continuum is very week.

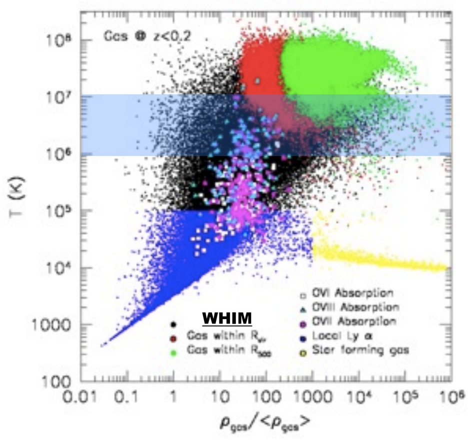

Fig. 1 (left panel): Phase space diagram of the cosmic baryons at z < 0.2 from the hydrodynamical simulation of Borgani et al. (2009). WHIM in blue-shaded region emits $\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$ lines.

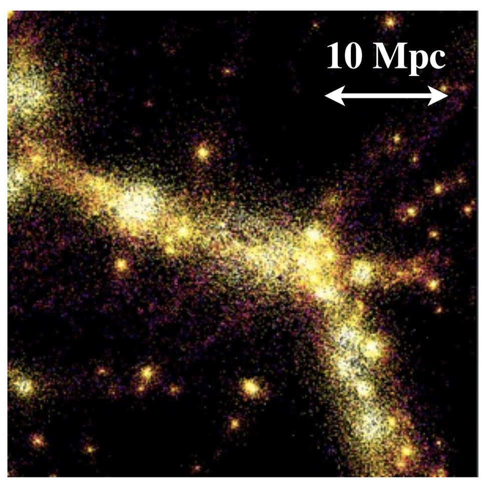

Fig. 2 (right panel): Spatial distribution of the WHIM (Yoshikawa et al. 2001). WHIM is distributed as filamentary structures between galaxies.

- We try to detect redshifted oxygen emission lines ($\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$) from WHIM.
- Observation by SXS would significantly improve our understanding of the WHIM properties.

We estimate the detectability of $\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$ emission from the WHIM by spectral simulation.

2. Spectral Model of WHIM

- We adopt **a collisionally ionized plasma model (APEC [XSPEC ver. 12])** as the spectral model of emission from WHIM (see fig. 3). In the following, parameters for APEC model and the values of typical WHIM which emit oxygen lines are shown.

Assumed parameters of APEC and The Values of typical WHIM

- Temperature T: kT = 0.1 - 0.4 keV
- Over-density δ = ~10 - 100

$$\delta = \frac{n_{\rm H}}{\overline{n}_{\rm H}}$$

$n_{\rm H}$: density of hydrogen in WHIM
$\overline{n}_{\rm H}$: mean density of hydrogen in universe

$$\overline{n}_{\rm H} = 1.77 \times 10^{-7}(1+z)^3 {\rm cm}^{-3}$$

(Takei et al. 2007)

- Line-of-sight depth: several Mpc
- Abundance: 0.1- 0.2 solar

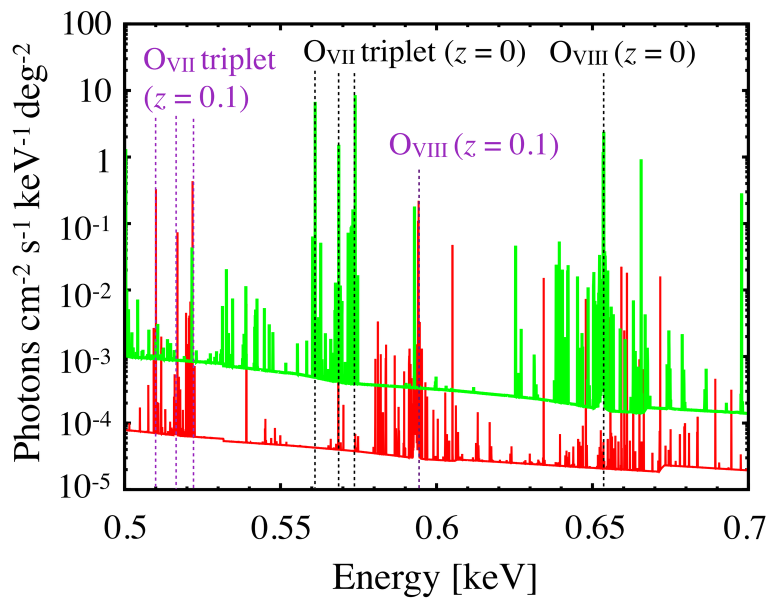

Fig. 3: Spectrum model. Red: WHIM (assumed δ = 80, kT = 0.2 keV, abundance = 0.2 solar, z = 0.1) Green: Soft X-ray background.

3. Components of Background

- Assumed backgrounds are (1) soft X-ray foreground components and (2) non X-ray background.

(1) *Soft X-ray background components*

We assume the following components (Werner et al. 2008);

✓ *Cosmic X-ray background*
Model: power-law (Γ = 1.41, $F_{0.3\text{-}10\,{\rm keV}} = 2.2 \times 10^{-11}$ erg s^{-1} cm^{-2} deg^{-2})

✓ *Local hot bubble* (+ *solar wind charge exchange*)
Model: collisionally-ionized diffuse gas model
(kT = 0.08 keV, $F_{0.3\text{-}10\,{\rm keV}} = 3.4 \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2})

✓ *Galactic halo*
Model: collisionally-ionized diffuse gas model
(kT = 0.17 keV, $F_{0.3\text{-}10\,{\rm keV}} = 2.9 \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2})

◉ The metal abundance for the plasma emission of the galactic components is assumed to be 1 solar value. In addition, we assume the Galactic absorption of $N_{\rm H} = 1.6 \times 10^{20}$ cm^2.

(2) *Non X-ray Background; NXB*

The NXB model used here is shown in section 4.

4. Simulation

- The temperature of WHIM which be able to emit $\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$ lines is kT = 0.1 - 0.4 keV (see fig. 4).
- In order to investigate the detectability of oxygen lines, we create mock spectra of WHIM which has the following parameter range;
  - kT = 0.1-0.4 keV (step: 0.1 keV)
  - Over-density δ = 40, 80, 200, 400
  - Line-of-sight depth: 2 Mpc fixed
  - Abundance: 0.1 - 0.2 solar
  - Redshift: 0.05 - 0.20 (step: 0.05)

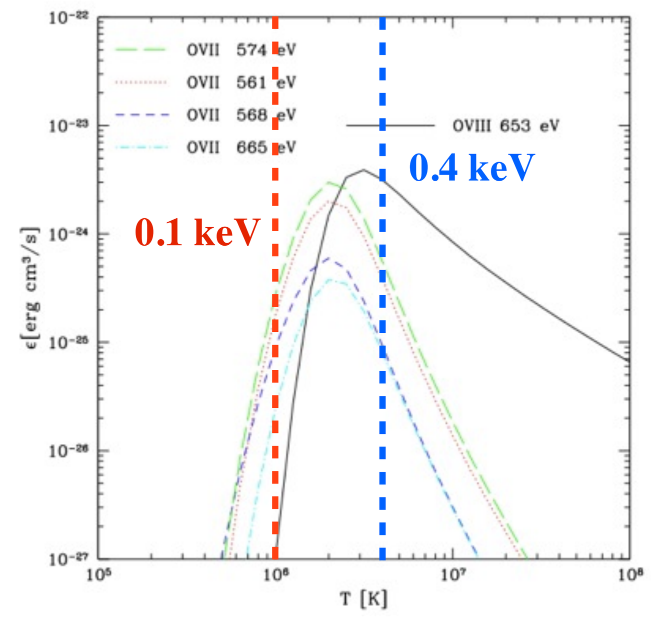

Fig. 4: Emissivity of $\mathrm{O_{VII}}$ and $\mathrm{O_{VIII}}$ lines in collisional ionization equilibrium (Yoshikawa et al. 2003).

- Assumed exposure times are 200 ksec and 1 Msec.
- We use the response file of SXT+SXS and the NXB file listed below.
  - ✓ ARF: sxt-s_100208_ts02um_flatsky-vig1kev_intallpxl.arf
  - ✓ RMF: ah_sxs_7ev_basefilt_20090216.rmf
  - ✓ Non X-ray background: sxs_nxb_7ev_20110211_1Gs.pha

(see the URL: http://astro-h.isas.jaxa.jp)

5. Result

We investigate the significance of detection of oxygen emission lines by F-test.

- In the case of 0.1 solar abundance, we detect one $\mathrm{O_{VIII}}$ line in the case : δ = 200, kT = 0.3 keV and z = 0.1 with significance level > 2 σ in the exposure time of 200 ks.
- However, several emission lines are detected in the case of 0.2 solar abundance (see table 1).

Table 1: The combinations of the overdensity and temperature in which the redshfited $\mathrm{O_{VIII}}$ (653 eV) and $\mathrm{O_{VII}}$ (574 eV and 561 eV) emission lines are detected with 2-3 sigmas (orange), 3-4 sigmas (blue) and 4-5 sigmas (red). The exposure time is assumed to be 200 ks. The abundance is assume to be 0.2 solar.

z = 0.05

kT \ δ	40	80	200	400
0.1				
0.2			OVIII/ OVII	OVIII/ OVII
0.3			OVIII	OVIII/ OVII
0.4				OVIII

z = 0.1

kT \ δ	40	80	200	400
0.1				
0.2			OVIII/ OVII	OVIII/ OVII
0.3			OVIII	OVIII
0.4				

z = 0.15

kT \ δ	40	80	200	400
0.1				OVII
0.2			OVII	OVII
0.3				OVII
0.4				

z = 0.2

kT \ δ	40	80	200	400
0.1				OVII
0.2			OVIII/ OVII	OVIII/ OVII
0.3			OVIII/ OVII	OVIII
0.4				

The followings are results of the case of exposure time of 1 Ms and 0.1 solar abundance.

- We detect several oxygen emission lines from WHIM (see table 2 & fig. 5).
  - We are not able to detect $\mathrm{O_{VIII}}$ emission line from WHIM at z = 0.15 because $\mathrm{O_{VIII}}$ emission line is contaminated by our galactic $\mathrm{O_{VII}}$ emissions (574 eV).

Table 2: The combinations of the overdensity and temperature in which the redshfited $\mathrm{O_{VIII}}$ (653 eV) and $\mathrm{O_{VII}}$ (574 eV and 561 eV) emission lines are detected with 2-3 sigmas (orange), 4-5 sigmas (red). The exposure time is assumed to be 1 Ms. The abundance is assumed to be 0.1 solar.

z = 0.05

kT \ δ	40	80	200	400
0.1				
0.2		OVIII	OVIII/ OVII	OVIII/ OVII
0.3			OVIII	
0.4				

z = 0.1

kT \ δ	40	80	200	400
0.1				
0.2		OVIII	OVIII/ OVII	OVIII/ OVII
0.3			OVIII	
0.4				

z = 0.15

kT \ δ	40	80	200	400
0.1				OVII
0.2			OVII	OVII
0.3		OVII		
0.4				

z = 0.2

kT \ δ	40	80	200	400
0.1			OVII	OVII
0.2			OVIII/ OVII	OVIII/ OVII
0.3			OVIII/ OVII	OVIII
0.4				

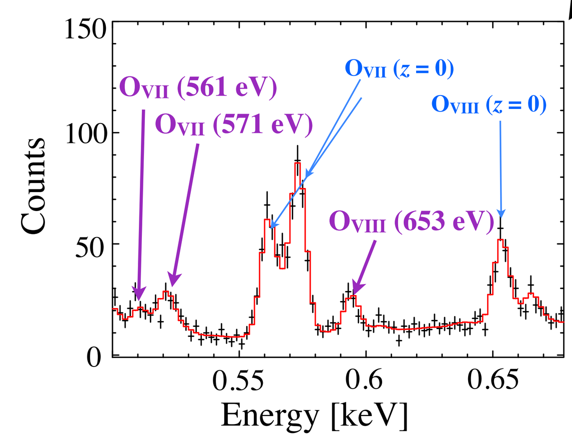

Fig. 5: Mock spectrum of WHIM (assumed δ = 400, kT = 0.2 keV, abundance = 0.1 solar, z = 0.1) and Soft X-ray background. Exposure time is 1 Ms. Purple arrows show oxygen lines from WHIM (the energy at rest frame indicated in parentheses). Blue arrows show oxygen lines of foreground.

✓ If WHIM has a high overdensity (> ~200) and 0.2 solar abundance, we can detect the several oxygen emission lines even in 200 ksec observation.

✓ For 1 Ms observations, we can detect WHIM with smaller overdensity (< 100).

Reference: [1] Borgani et al., 2009, ApJ, 697, 328 [2] Yoshikawa et al. 2001, ApJ, 558, 520 [3] Takei, Y. et al. 2007, PASJ, 59, S339 [4] Werner et al., 2008, A&A, 482, L29 [5] Yoshikawa et al. 2003, PASJ, 55, 879