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Observational signatures of the warm-hot intergalactic medium and X-ray absorption lines by the halo of our Galaxy

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Abstract Approximately 30% to 50% of the total baryons of the present universe are considered to take a form of warm/hot intergalactic medium (WHIM) and to have evaded direct detection. The WHIM of $T = 10^6 - 10^7$ K is most likely detected through absorption and emission lines of Ovii and Oviii. The equivalent widths of the absorption lines are typically 0.4 eV, which is consistent with the absorption lines having redshifts indistinguishable from zero observed in the spectra of a few bright active galactic nuclei (AGN). However, from the midplane Ovii density estimated from Ovii absorption line in the Galactic X-ray source, 4U1820−303, we consider that a significant fraction of warm/hot plasma responsible for the AGN absorption lines is located in our Galaxy rather than in the local group. For a systematic study of the WHIM, survey-type observations detecting emission lines are necessary. While the typical surface brightness of Ovii and Oviii emission lines is below the detection limit of present and proposed future missions, an unambiguous detection will be feasible with a small X-ray mission dedicated for this purpose. Our proposed mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor), is sensitive to the WHIM of temperatures $T = 10^6 - 10^7$ K and can survey about 0.1 sr area to the depth of cosmological redshift $z < 0.3$ in two years.

Key words: X-rays: ISM – cosmology: miscellaneous

1 INTRODUCTION

The existence of hot ($T \sim 10^5 - 10^6$ K) interstellar medium in our Galaxy has been known since the early 1970's, mainly from two kinds of observations: the soft X-ray background (SXB) in the $0.1 - 1$ keV range (e.g. Tanaka & Bleeker 1977) and UV Ovi absorption lines (e.g. Jenkins 1978) in OB stars. After ~ 30 years of studies, the origin of the SXB is still not understood.

The SXB in the so-called 1/4 keV band is dominated by the emission from the local bubble with $\log TK \sim 6$ around the sun (Snowden et al. 1990). On the other hand, in the 3/4 keV band, where the emission is dominated by Ovii and Oviii K lines, the majority of emission comes from hot interstellar medium with $\log(T[\mathrm{K}]) \sim 6.2 - 6.4$, which is considered to be widely

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distributed in the Galactic disk, the bulge, and the halo (Kuntz & Snowden 2000, and reference therein).

McCammon et al. (2002) clearly resolved for the first time the OVII, OVIII, and a few other emission lines in the SXB at high latitude ($b \sim 60^\circ$) with a rocket-borne microcalorimeter experiment. From this result they estimate that at least 42% of the soft X-ray background in the energy band that includes the O emission lines comes from thermal emission at $z < 0.01$ and 38% from unresolved AGN. The origin of the remaining 20% (34% for a 2σ upper limit) is still unknown and could be extragalactic diffuse emission.

The OVI absorption line is considered to represent hot gas at lower temperatures, typically $\log T(\mathrm{K}) = 5.5$. The OVI absorption lines observed in 100 extragalactic objects and two halo stars by *FUSE* are consistent with a picture where the hot gas responsible for the absorption has a patchy distribution but on the average has a plane-parallel exponential distribution with an average OVI midplane density of $1.7 \times 10^{-8}\,\mathrm{cm}^{-3}$ and a scale height of $\sim 2.3\,\mathrm{kpc}$ (Savage et al. 2003). The average velocity dispersion of OVI absorption lines is $b = 60\,\mathrm{km\,s}^{-1}$ with a standard deviation of $15\,\mathrm{km\,s}^{-1}$.

On the other hand, OVII, OVIII, NeIX, and CVI absorption lines were detected in the energy spectra of bright active galactic nuclei (AGN) observed with the dispersive spectrometers on board the *Chandra* and *XMM-Newton* observatories (Nicastro et al.2002, Fang et al.2002, Rasmussen et al. 2003). Despite the fact that the redshift is indisinguishable from 0, a large fraction of the absorption is considered to arise from the hot ($\log(T[\mathrm{K}]) \sim 6.4$) plasma outside our Galaxy, i.e. the so-called warm-hot intergalactic medium (WHIM, Cen & Ostriker 1999). For example, Rasmussen et al. (2003) argued that the scale height of the hot gas should be larger than 140 kpc in order to consistently explain the equivalent width of the OVII absorption line and the intensity of the emission line at the same time. Clearly however, the hot gas in our Galaxy contributes to the absorption lines to some extent.

It was suggested from the baryon budget that a large fraction of baryons are 'missing' in the present universe (Persic & Salucci 1992, Bristow & Phillipps 1994, Fukugita et al. 1998). Subsequent cosmological simulations (e.g., Cen & Ostriker 1999, Davé et al. 2001) suggested that approximately 30% to 50% of total baryons at $z = 0$ take the form of the warm-hot intergalactic medium (WHIM) with $10^5\,\mathrm{K} < T < 10^7\,\mathrm{K}$ outside galaxies and galaxy clusters, which has evaded any direct detection so far.

The emission from the WHIM may contribute to the soft X-ray background (Croft et al. 2001, Phillips et al. 2001). Wang & McCray (1993) suggested detection of emission from such a hot intergalactic medium in the ROSAT data. Zappacosta et al. (2002) suggested a spatial coincidence of an enhancement of the SXB with that of galaxy density at $z = 0.3 - 0.6$. Recently, Finoguenov, et al. (2003) detected excess soft X-ray emission in the outskirts of Coma cluster of galaxies and argued that they are from the WHIM. However, all of these X-ray observations do not have enough energy resolution to distinguish emissions from outside and inside our Galaxy from the redshift.

In this paper we report two recent works of our group on this subject. First we discuss the observability of the WHIM of a temperature $\sim 10^6\,\mathrm{K}$ through X-ray emission lines (Yoshikawa et al. 2003) and propose a mission with a small satellite ($\sim 400\,\mathrm{kg}$) to study the large-scale structure of WHIM, detecting OVII and OVIII emission lines (Mitsuda et al. 2003, Ohashi et al. 2003). The mission, named *DIOS* (Diffuse Intergalactic Oxygen Surveyor), carries an X-ray telescope consisting of a four reflection X-ray mirror and a focal-plane TES (Transition-Edge Sensor) microcalorimeter array. By virtue of the high energy resolution of the detector (2 eV) the extragalactic and galactic emission components would be clearly resolved.

Then, we will show the first detection of OVII, OVIII, and NeIX absorption lines in the X-ray spectrum of Galactic X-ray source, 4U1820−303 in the globular cluster NGC6624 observed with the low energy transmission grating (LETG) on board the *Chandra* observatory (Futamoto et al. 2004). The result gives constraint on the midplane OVII density of our Galaxy in the solar neighborhood. Using the AGN absorption lines (Nicastro et al.2002, Fang et al.2002, Rasmussen et al. 2003), we obtain the upper limit of OVII scale height, which is 20 kpc. This suggests that a large fraction of OVII contributing to the AGN absorption lines are associated with our Galaxy.

2 OBSERVATIONAL SIGNATURES OF THE WHIM AND THE DETECTABILITY

According to cosmological simulations (e.g., Cen & Ostriker 1999, Davé et al. 2001), the typical WHIM has $\sim 1/2$ of baryon mass and occupies 0.001 of the volume. Thus, the average local density is roughly expected to be,

$$\rho_{\rm WHIM} \sim 20\rho_{\rm cr}\left(\frac{\Omega_{\rm WHIM}}{0.02}\right)\left(\frac{f_{\rm WHIM}}{0.001}\right)^{-1}. \tag{1}$$

The H column density associated with a filamentary structure will be

$$N_{\rm H} = 2\times10^{20}\,{\rm cm}^{-2}\ \left(\frac{L}{10\,{\rm Mpc}}\right)\left(\frac{\rho_{\rm WHIM}}{20\rho_{\rm cr}}\right), \tag{2}$$

where L is the typical size of a filament. The column density of O ions and the equivalent width of the absorption line in the energy spectrum of a background X-ray source in the optically-thin limit are, respectively,

$$N_{\rm O,\,ion} = 7\times10^{15}\,{\rm cm}^{-2}\ \left(\frac{A_{\rm O}}{0.1A_{\rm O,\odot}}\right)\left(\frac{f_{\rm ion}}{0.7}\right)\left(\frac{L}{10\,{\rm Mpc}}\right)\left(\frac{\rho_{\rm WHIM}}{20\rho_{\rm cr}}\right), \tag{3}$$

$$EW_{\rm O,\,ion} = 0.4\,{\rm eV}\left(\frac{f_{\rm fi}}{0.7}\right)\left(\frac{A_{\rm O}}{0.1A_{\rm O,\odot}}\right)\left(\frac{f_{\rm ion}}{0.7}\right)\left(\frac{L}{10\,{\rm Mpc}}\right)\left(\frac{\rho_{\rm WHIM}}{20\rho_{\rm cr}}\right)(1+z)^{-1}, \tag{4}$$

where $A_{\rm O}$, $f_{\rm ion}$, and $f_{\rm fi}$ are respectively the abundance of Oxygen, ionization fraction of the ion, and the oscillator strength of the transition. Those values are consistent with the more precise estimations based on the cosmological numerical simulations (Perna & Loeb 1998, Hellsten et al. 1998, Fang & Canizares 2000).

The high resolution spectrometers on board *Chandra* and XMM-Newton can detect such absorption lines if a bright X-ray source is located behind such thick filamentary structures. The equivalent widths of absorption lines observed in AGN are in a range of $0.3 - 0.8$ eV (Rasmussen et al. 2003), and are consistent with the above estimations. However, the redshift of othe bserved lines is indistinguishable from 0. As we will show in the next section, a significant fraction of the warm/hot medium responsible for the absorptions is likely in our Galaxy.

The number of fortuitous cases in which a bright X-ray source is behind a thick filamentary structure is small. Moreover, unbiased exploration of WHIM requires a systematic survey-type observation. Thus, we investigate the detectability of O emission lines from the WHIM and possible telescope system to detect them. The surface brightness of an O emission line of a filament is estimated to be

$$F_{\rm O,\,ion} = \frac{1}{4\pi}\left(\frac{\rho_{\rm WHIM}}{\mu_{\rm H}m_{\rm H}}\right)^2 \mu_{\rm e}A_{\rm O}f_{\rm ion}\gamma_{\rm ion}(T)L(1+z)^{-3} \tag{5}$$

$$= 0.05\,{\rm photons\ s}^{-1}\ {\rm cm}^{-2}\ {\rm sr}^{-1}\times \tag{6}$$

$$\left(\frac{\rho_{\rm WHIM}}{20\rho_{\rm cr}}\right)^2\left(\frac{A_{\rm O}}{0.1A_{\rm O,\odot}}\right)\left(\frac{f_{\rm ion}}{0.7}\right)\left(\frac{L}{10\,{\rm Mpc}}\right)\left(\frac{\gamma_{\rm ion}(T)}{7\times10^{-13}}\right)(1+z)^{-3}, \tag{7}$$

where $\gamma_{\rm ion}(T)$ is the emissivity of emission line at a temperature T in the unit of photons $\rm s^{-1}\ cm^{-6}$ and we substituted the value for OVII $\rm K_\alpha$ triplets at $T = 10^6$ K. A typical spatial extent of a filamentary structure is ~ 1 degree at a distance of $z \sim 0.1$.

Yoshikawa et al. (2003) estimated the surface brightness of OVII and OVIII emission lines and created simulated X-ray images and energy spectra using an output of cosmological hydrodynamic simulations. The results (Figure 1) are consistent with the above estimation.

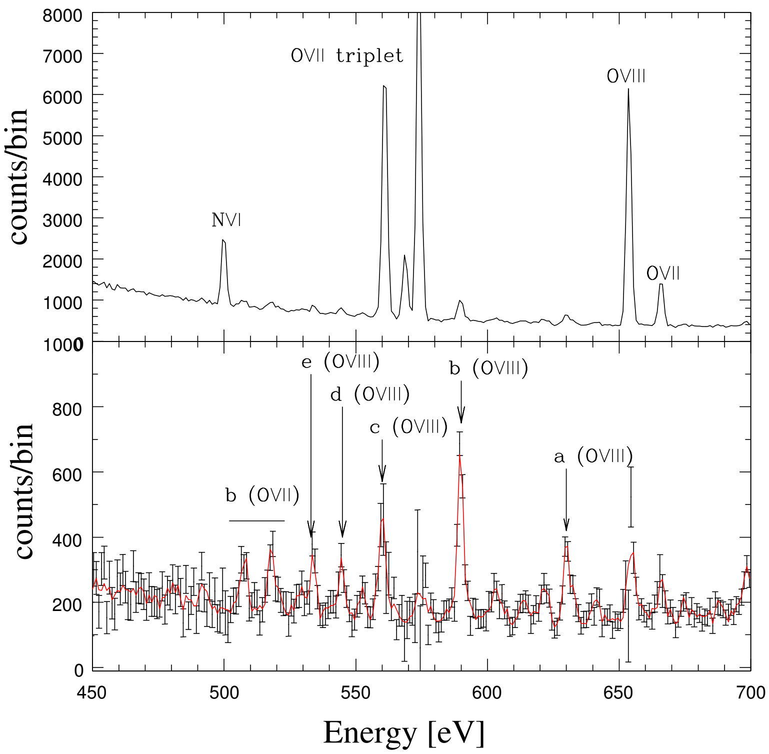

Fig. 1 Simulation spectrum of 300 ks DIOS observation. The photons of all the $1^\circ \times 1^\circ$ field of view are integrated. The upper panel shows the spectrum of all emissions including the CXB and the Galactic emission, while the lower panel shows the spectrum of WHIM after the CXB and the Galactic emission are subtracted. The emissions from different filamentary structures are labeled with different characters, a-d. See Yoshikawa et al. (2003) for more details.

Observed with an X-ray telescope of an effective area of S, a field of view of Ω (solid angle) where $\sqrt{\Omega}$ is assumed to be smaller than the spatial extent of a filamentary structure, and an energy resolution of ΔE for an exposure time of t, the signal to noise ratio of the emission line, S/N, is expected to be,

$$(S/N)^2 = \frac{F_{\rm O,ion} S \Omega t}{\Delta E / EW + 1}\,, \tag{8}$$

where EW is the equivalent width of the line defined against the sum of all other spectral components including background, namely,

$$EW = \frac{F_{\rm O,ion}}{f_{\rm WHIM} + f_{\rm gal} + f_{\rm CXB} + f_{\rm in}}\,. \tag{9}$$

Here $f_{\rm WHIM}$, $f_{\rm gal}$, $f_{\rm CXB}$, and $f_{\rm in}$ are the continuum emission from the WHIM, the emission from the hot gas in our Galaxy, the cosmic X-ray background, and the detector intrinsic background, respectively. At the energy of O emission lines (561, 568, and 574 eV for O VII K_α and 653 eV for O VIII K_α at rest frame), the galactic emission, $f_{\rm gal}$, dominates the continuum spectrum, and the typical intensity is $30\,{\rm photons\,sec^{-1}\,cm^{-2}\,sr^{-1}\,keV^{-1}}$. Thus the equivalent width of the O emission lines will be $EW = 2\,{\rm eV}$. If it is observed with an X-ray detector of an FWHM energy resolution of $\Delta E \lesssim 2\,{\rm eV}$, the detection sensitivity is determined by photon statistics rather than by background/continuum emissions. Such a high energy resolution is also necessary to avoid contamination of O emission lines from our Galaxy, which is nearly one hundred times brighter than the WHIM ($\sim 4\,{\rm photons\,sec^{-1}\,cm^{-2}\,sr^{-1}}$, McCammon et al. 2002), and also distinguish emission from individual filamentary structures. An energy resolution of $\Delta E \sim 2\,{\rm eV}$ corresponds to $z = 0.003$. We thus impose the first requirement on the X-ray detector system,

$$\Delta E \lesssim 2\,{\rm eV}.$$

With $\Delta E \sim 2\,{\rm eV}$, a value of $S\Omega t = 4000\,{\rm s\,cm^2\,sr} = 1.3 \times 10^7\,{\rm s\,cm^2\,deg^2}$ is required to obtain $S/N = 10$. Assuming a typical integration time of a single direction to be 100 ks, which is two days of observations assuming $\sim 60\%$ observation efficiency, we find the second requirement on the instrument,

$$S\Omega \gtrsim 100\,{\rm cm^2\,deg^2}.$$

None of the X-ray missions existing or planned so far satisfy the above conditions. On the other hand, the conditions can be satisfied by the short-focus X-ray telescope system realized by a four-reflection optics (Tawara et al. 2003) and a high resolution imaging TES (Transition Edge Sensor) microcalorimeter array (e.g. Ishisaki et al. 2003). This system fits on a small spacecraft of $\sim 400\,{\rm kg}$ and is now under serious discussion as the *DIOS* mission (Mitsuda et al. 2003, Ohashi et al. 2003). With $\Omega = 1\,{\rm deg}^2$, *DIOS* can survey about 0.1 sr (i.e. $\sim 1\%$ of whole sky) to the depth of cosmological redshift $z < 0.3$ in two years. The parameters and the sensitivities of present and future high energy resolution missions are summarized in Table 1.

Table 1 Specification and Detection limit of emission lines for various future and current X-ray missions.

Mission	year	$S_{\rm eff}$ [cm^2]	$S_{\rm eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	$F_{\rm lim}$ (100 ks, 10σ) [photons s^{-1} cm^{-2} sr^{-1}]
Chandra ACIS-S3	1999	600	12	80	1.0
XMM-Newton EPIC-pn	1999	1200	100	80	0.3
Astro-E II XIS	2005	90×4	36	80	0.6
Astro-E II XRS	2005	90	0.23	6	20
Const-X SXT+TES	mid-2010's	3000	5.6	2	0.7
XEUS-I	mid-2010's	60000	16.7	2	0.3
DIOS	$\sim$ 2010	100	100	2	0.06

3 IONIZED O AND NE ABSORPTION LINES IN A GALACTIC X-RAY SOURCE AND ITS IMPLICATION ON THE WHIM

The intensity of the SXB and the absorption lines of distance object reflect the emission measure and the density of the warm/hot medium integrated over the line of sight to virtually infinity. Thus, they do not constrain the spatial structure of the medium along the line of sight. However, an absorption line in the energy spectrum of a Galactic X-ray source whose distance is well known, and which is located at relatively low Galactic latitude, can constrain the ion density near the galactic plane, and will thus constrain the vertical structure of the hot gas of our Galaxy.

4U1820−303 is a Low-Mass X-ray Binary (LMXB) located in the globular cluster NGC 6624 at (l, b) = (2.8°, −7.9°). The distance of the star cluster is determined from the optical reddening, and the brightness of horizontal-branch and main-sequence turn-off stars (Richtler et al. 1994, Kuulkers et al. 2003). Adopting the distance of 7.6 ± 0.4 kpc (Kuulkers et al. 2003), 4U1820−303is located 1.0 kpc above the Galactic disk. The neutral hydrogen column density towards the source is estimated to be $N_{\rm H} = N_{\rm HI} + 2N_{\rm H_2} = 1.9 \times 10^{21}\,{\rm cm}^{-2}$ from E(B-V)= 0.32 ± 0.03 (Kuulkers et al. 2003, Bohlin et al 1978). This is consistent with the total HI column density of our Galaxy, $N_{\rm HI} = 1.5 \times 10^{21}\,{\rm cm}^{-2}$ from 21 cm radio observations (Dickey & Lockman 1990). Because of the low $N_{\rm H}$ value, this source is suited for the study of interstellar O and Ne absorption lines.

3.1 Analysis and results

4U1820−303 was observed with the LETG/HRC(High Resolution Camera)-S for 15.1 ks on March 10, 2000 (obsID 98). We retrieved the archival data from the CXC (Chandra X-ray Center) and reprocessed it by the software CIAO 2.3 with the calibration data in CALDB 2.21.

According to the LETGS calibration report at the CXC, the wavelength calibration of LETGS spectra is accurate to 0.02%. This is an order of magnitude smaller than the statistical errors of wavelength determined in the following analyses.

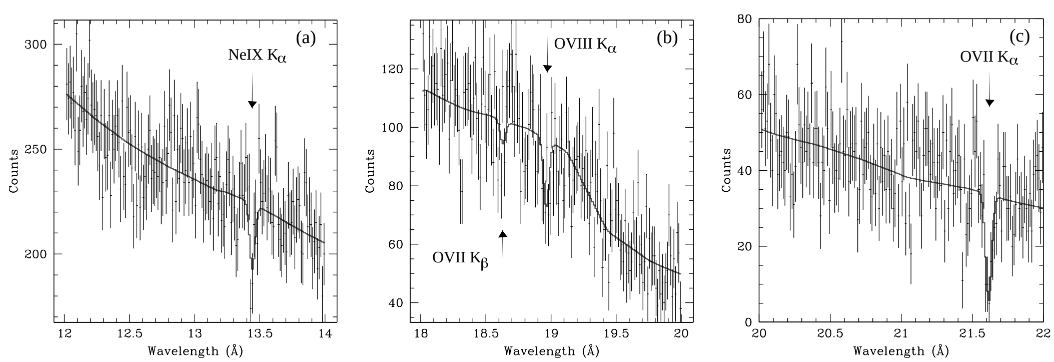

Fig. 2 Observed spectrum of 4U1820−303 in the wavelength ranges used for spectral fits for (a) NeIX, (b) OVIII, and (c) OVII K_α absorption lines (data points with $1-\sigma$ vertical error bars) and best fit model functions convolved with the telescope/detector response functions.

In the observed spectrum of 4U1820−303, we clearly found an absorption line at $\lambda \sim$21.6 Å (see Figure 2(c)) in addition to the neutral-O absorption structures near $\lambda \sim$23 Å. From the wavelength, the absorption line can be identified as the OVII K_α resonant line. We also noticed absorption lines corresponding to OVIII K_α and NeIX K_α (Figure 2(a)(b)). We also looked at the wavelength corresponding to OVII K_β, but the absorption line was not clear. In order to estimate the centroid wavelength, the intrinsic width, and the equivalent width of the lines, we fitted the spectra in the wavelength ranges shown in Table 2. The best-fit parameters of the absorption lines are summarized in the same table. We modeled the absorption line by adding a negative Gaussian to the continuum model represented by a power-law function with absorption by a neutral medium. In the table we express the intrinsic width of the line with the parameter b, which is related to the Gaussian σ of the fitting model as $b/c = \sqrt{2}\sigma/\lambda$ (c is the velocity of light). Thus, b is related to the temperature as $b = \sqrt{2k_{\rm B}T/m_i}$ in the case of thermal Doppler broadening where $k_{\rm B}, T, m_i$ are, respectively, the Boltzmann constant, the temperature, and the mass of the ion.

Table 2 OVII, OVIII, and NeIX absorption line features observed in 4U1820−303.

Line ID	fitting range (Å)	centroid λ (Å)	cz ($\rm km\,s^{-1}$)	Width (b) ($\rm km\,s^{-1}$)	EW (eV)
OVII K_α	20–22	$21.612^{+0.011}_{-0.006}$	–79 to +150	< 420	$1.19^{+0.47}_{-0.30}$
OVIII K_α	18–20	$18.962^{+0.021}_{-0.015}$	–230 to + 330	(1)	$0.54^{+0.23}_{-0.25}$
OVII K_β	18–20	18.629		(1)	< 0.48
NeIX K_α	12–14	$13.442^{+0.009}_{-0.016}$	–350 to +200	(1)	0.50 ± 0.20

(1) The error domain for OVII K_α line is assumed for the estimation of the error domain (or the upper limit) of the equivalent width.

The centroid wavelengths of three lines are consistent with OVII K_α, OVIII K_α, and NeIX K_α at zero redshift, respectively. Those lines are statistically significant at the 6.5σ, 3.1σ, and 4.5σ levels, respectively. We obtained only an upper limit for the equivalent width of the OVII K_β line.

In order to constrain the ion column densities, we performed curve of growth analysis (e.g. Nicastro et al. 1999, Kotani et al. 2000). We adopted the oscillator strength and the transition probability from Verner et al. (1996) for OVII K_α, K_β, and OVIII K_α, and from Behar & Netzer (2002) for NeIX K_α. From the analysis, we obtain the equivalent width of the line as a function of the ion column density and the velocity dispersion. In Figure 3, we show the curves of growth of the four ions for several different values of b. For the maximum value of b, we adopted the upper limit of the intrinsic width of the OVII K_α absorption line. The lowest value of b in Figure 3 corresponds to thermal motion at a temperature of 1×10^6 K. We show in Figure 4 the OVII, OVIII, and the NeIX column densities for 4U1820−303 as functions of b. The error domains and the upper limit of the OVII column density ($N_{\rm OVII}$), obtained from K_α and K_β lines, do not overlap each other for $60 \geq b \geq 140\,\rm km\,s^{-1}$, suggesting the velocity dispersion is either as small as the thermal velocity of $T \sim 10^6$ K or $b \gtrsim 200\,\rm km\,s^{-1}$.

We re-determined $N_{\rm OVII}$ for $b \geq 200\,\rm km\,s^{-1}$, minimizing the sum of the two χ^2 of the K_α and K_β spectral fits;

$$\chi^2 = \chi^2_{K_\alpha}(EW_{K_\alpha}(N_{\rm OVII})) + \chi^2_{K_\beta}(EW_{K_\beta}(N_{\rm OVII})),$$

where all other spectral parameters were respectively optimized. The best fit values are plotted in Figure 4 (a).

3.2 Origin of absorption lines

4U1820−303 is known to be an extremely small system with an orbital period of 685 s. The size of the binary system is smaller than $0.1R_\odot$ (Stella et al. 1987). If the plasma is located at a distance r from the X-ray star, the ionization parameter is $\xi = L_{\rm X}/(nr^2) \sim L_{\rm X}/(N_{\rm H}r) > 10^5$ for a luminosity of $2 \times 10^{37}\,\rm erg\,s^{-1}$ and $r < 10^{10}$ cm. Then, O will be fully photo-ionized (Kallman & McCray 1982). If the companion star is a He white dwarf, the matter in the binary is He rich. In that case, O should be even more ionized because of the smaller number of

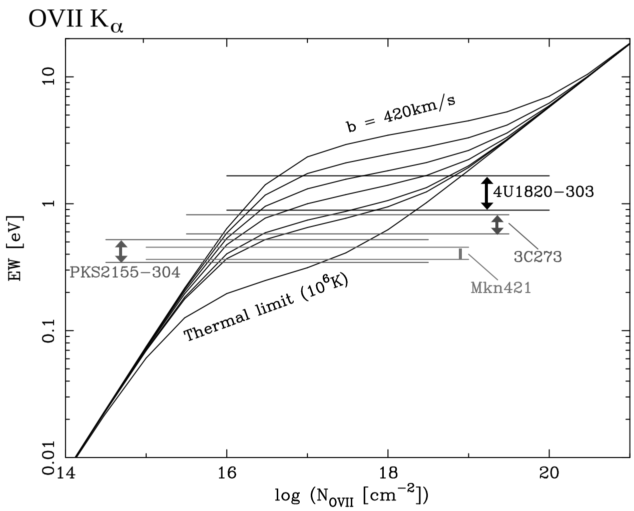

Fig. 3 Curve of growth for O vii K_α. The different curves correspond to different values of velocity dispersion parameter, $b = 32$, 60, 100, 140, 200, 280, and $420\,\mathrm{km\,s^{-1}}$. The minimum value of b corresponds to thermal motion with $T = 10^6\,\mathrm{K}$, and the maximum, $420\,\mathrm{km\,s^{-1}}$, to the upper limit of the intrinsic line width of the O vii K_α line. The horizontal lines indicate the equivalent width constrained from observations. We show the equivalent width of AGN from Rasmussen et al. (2003) in addition to 4U1820−303.

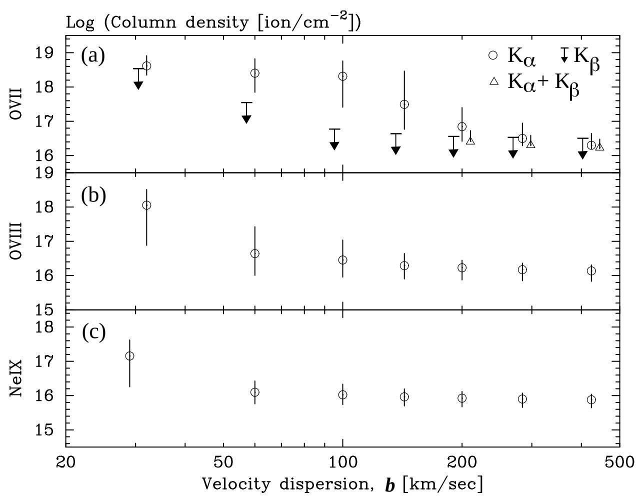

Fig. 4 Column densities of (a) OVII, (b) O viii, and (c) Ne ix for 4U1820−303 as functions of assumed value of the velocity dispersion parameter b. In panel (a), the column density obtained from the O vii K_α line (circles), from O vii K_β lines (upper limits, data points shifted in $-b$ direction), and from combined fits of O vii K_α and K_β lines (triangles, only for $b \geq 200\,\mathrm{km\,s^{-1}}$ and data points shifted in $+b$ direction) are respectively plotted.

electrons per nucleon. Since the above estimation is only valid for optically thin plasmas without an additional heat source, we ran the numerical simulation code, CLOUDY96b4 (Ferland 2002) to estimate the O ionization state for more general cases to find that $r \geq 10^{12}$ cm is required to account for the OVII to OVIII absorption equivalent widths.

Thus, it is very unlikely that the absorption lines observed in 4U1820−303 are due to photo-ionized plasma associated with the binary system. It is most likely that the warm/hot plasma is in the interstellar.

3.3 Midplane OVII density and the scale height

We estimated, as functions of the velocity dispersion b, (a) the temperature of the hot medium from the OVII to OVIII line ratio assuming the ionization equilibrium of O, (b) the Ne to O abundance ratio assuming ionization equilibrium between O and Ne, and (c) the hydrogen column density of the hot plasma, $N_{\rm H}$(hot), assuming a solar abundance. The results are shown in Figure 5. From the figure, we find that if $b < 140\,{\rm km\,s^{-1}}$, $N_{\rm H}$(hot) is comparable to or even larger than the $N_{\rm H}$ of neutral medium, and that the Ne/O abundance ratio must be significantly smaller than the solar value. Since both are unlikely, we can exclude small b. Thus it is likely that $b \gtrsim 200\,{\rm km\,s^{-1}}$, and we obtain the constraints: $\log N_{\rm H}({\rm hot}) = 19.41 - 20.21$, $\log N_{\rm OVII} = 16.20 - 16.73$, and $\log(T[{\rm K}]) = 6.19 - 6.34$. Dividing the column densities by the distance, we obtain the densities averaged over the volume of the column, $\langle n_{\rm H}({\rm hot})\rangle = (1.1 - 7.0) \times 10^{-3}\,{\rm cm^{-3}}$ and $\langle n_{\rm OVII}\rangle = (0.7 - 2.3) \times 10^{-6}\,{\rm cm^{-3}}$, respectively. The hot plasma is likely to have a patchy distribution. Thus, the local densities are higher than the volume average. The volume filling factor is estimated to be ~ 0.5 in the solar vicinity, although there are large uncertainties (Mathis 2000).

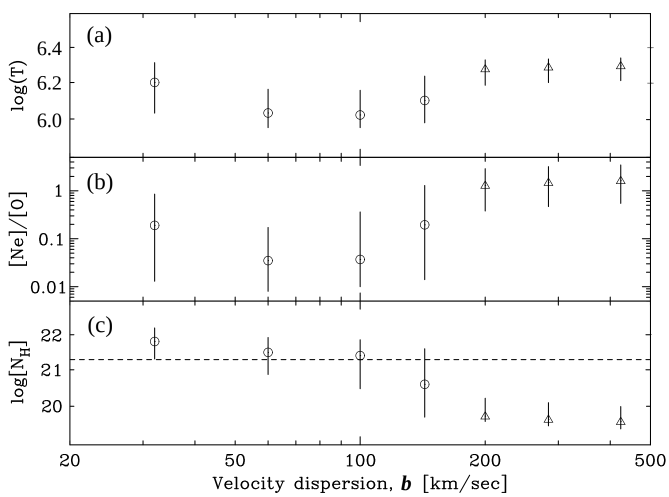

Fig. 5 Temperature (a), Ne to O abundance ratio in the unit of solar ratio (b), and H column density (c) as functions of assumed value of the velocity dispersion parameter, b. For $b \leq 140\,{\rm km\,s^{-1}}$, the OVII column density estimated from the K_α line is used to evaluate the plotted values, while for $b \geq 200\,{\rm km\,s^{-1}}$, the combined analysis of K_α and K_β lines is used. The horizontal broken line in panel (c) indicates the neutral H column density to 4U1820−303.

The SXB map observed with ROSAT shows enhancement in the circular region of $\sim 40^\circ$ radius centered on the Galactic center (Snowden et al. 1997), in which 4U1820−303 is located. This suggests a significant density gradient along the line of sight towards 4U1820−303. We estimated the correction factor of this effect on the present results using the polytropic models of the hot gas constructed by Wang (1998) and Almy et al. (2000) which reproduce the all sky SXB map. They assumed nonrotating hot gas of polytropic index 5/3 in hydrostatic equilibrium with the Galactic potential (Wolfire et al. 1995). The model is described by two parameters, the normalization factor of the polytrope k and the pressure at the Galactic center P_0. Taking into account the uncertainties of the model parameters, the ratio, r, of the OVII density at the solar vicinity $\langle n_{\rm OVII,S}\rangle$ to the average over the line of sight for 4U1820−303 is restricted as $r \equiv \langle n_{\rm OVII,S}\rangle / \langle n_{\rm OVII}\rangle \geq 0.5$ (see Futamoto et al. (2004) for more details). Using r, we can write $\langle n_{\rm OVII,S}\rangle = (0.4 - 1.2) \times 10^{-6} (r/0.5)\,{\rm cm}^{-3}$ from the observations. This is consistent with the previous estimate of the hot plasma density in the solar neighborhood (Snowden et al. 1990).

We can now estimate the scale height of hot gas assuming a vertical exponential distribution and using a midplane density at the solar vicinity as estimated above and the high latitude AGN absorption lines. The column densities of OVII for 3C 273, Mkn 421, and PKS 2155−304 are respectively estimated to be in the ranges of $\log(N_{\rm OVII}) = 16.0 - 16.4$, $15.7 - 15.9$, $15.7 - 16.0$ assuming the velocity dispersion of b =200 − 420 km/s and the equivalent widths from Rasmussen et al. (2003) (see Figure 3). The result is a scale height of $h = (2 - 20) \times (r/0.5)^{-1}$ kpc. This scale height is consistent with the polytrope model, which predicts $h = 8$ kpc at the solar neighborhood. Furthermore, the intensity of the OVII triplet lines in the direction of $(l, b) = (70^\circ, 60^\circ)$ is estimated to be $(2 - 20)(r/0.5)^2(h/10\,{\rm kpc})(1/f)$ photons ${\rm sec}^{-1}\,{\rm cm}^{-2}\,{\rm sr}^{-1}$, where f is the volume filling factor of the hot gas. This count rate is consistent with 4.8 ± 0.8 photons ${\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$, as obtained by McCammon et al. (2002). These suggest that a significant portion of the OVII absorption observed in the AGN spectra is of Galactic origin.

4 CONCLUSIONS

We have investigated the observational signatures and the detectability of the warm/hot intergalactic medium (WHIM) for temperatures of $\sim 10^6 - 10^7$ K. An equivalent width of ~ 0.4 eV is expected for OVII and OVIII absorption lines. This is consistent with the absorption lines observed in the bright AGN, 3C 273, Mkn 421, and PKS 2155−304 with cosmological redshift $z = 0$. However, the from midplane OVII density estimated from OVII absorption lines observed in the Galactic X-ray source, 4U1820−303, we consider that a significant fraction of warm/hot plasma is located in our Galaxy rather than in the local group. A search for absorption lines in other Galactic sources, in particular located in non-bulge regions, is urged to quantitatively estimate the amount of possible contributions.

With an X-ray mission with a large effective area - field of view product ($S\Omega \gtrsim 100\,{\rm cm}^2\,{\rm deg}^2$) and high spectral resolution ($\Delta E \sim 2$ eV) in the energy band of 500 − 700 eV, it is possible to detect OVII and OVIII emission lines from the WHIM in $z \lesssim 0.3$ and to distinguish them from the Galactic emission for redshift $z > 0.003$. This kind of mission would unambiguously establish the existence of the WHIM and enable a systematic survey of the WHIM to reveal its 3-dimensional structure. A small mission named *DIOS* with the above capabilities is now under serious consideration in Japan.

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