

Galactic Soft X-Ray Halo Revealed with *Suzaku*

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ABSTRACT

Spectroscopic study of Oxygen emission/absorption lines is a new tool to investigate the nature of the soft X-ray background. Base on the *Suzaku* observations of 14 fields, two components of the Oxygen line emission are discovered. One component emits within ~ 300 pc of our neighborhood and most plausible origin is the solar wind charge exchange with local interstellar materials. The other shows an apparent temperature of ~ 0.2 keV with a field-to-field fluctuation of $\pm 10\%$, while the intensity varies about a factor of 4. By the combination analysis of the emission and the absorption by Oxygens, the size of the hot plasma is an order of kpc. It suggests that there is a hot halo around our Galaxy which is similar to X-ray hot haloes around several spiral galaxies.

KEY WORDS: Galaxy:disk–Galaxy:halo–X-rays:diffuse background –X-rays:ISM

1. Introduction

The origin of the soft X-ray background (SXB) is not explained by absorbed Cosmic X-ray Background which is a sum of faint extragalactic sources as shown by *ROSAT* All Sky Survey (RASS) map (Snowden et al. 1997). Observation with rocket-borne microcalorimeter showed that there is thermal emission which is characterized by emission lines of highly ionized materials like Oxygen (McCammon et al. 2002). The whole Galaxy is transparent at the Galactic latitude $b > 20^\circ$ for X-rays above 0.5 keV. If there is an X-ray halo around our Galaxy like other spirals (see ex. Strickland et al. 2004), it will play an important role in the energy and material circulation within the Galaxy and/or toward the intergalactic space. In this paper, we introduce the recent study of the SXB with *Suzaku* mainly based on the results by Yoshino et al. (2009) and Yao et al. (2009) and their interpretations.

2. Observation and Analysis

Suzaku has high energy resolving power to reveal the contribution of Oxygen emission lines in the SXB. We

used 15 observations of 14 fields as shown in Fig. 1 toward which there are no bright point sources or known diffuse sources in the field of view. An example of the spectra at the $(l, b) = (86^\circ, -20^\circ.8)$ is shown in Fig. 2. Line emissions from O_{VII} (574 eV) and O_{VIII} (653 eV) are clearly detected with surface brightness of several photons $\text{cm}^{-2} \text{sec}^{-1} \text{str}^{-1}$ (hereafter refereed as line unit or LU). From the all fields, we made energy spectra and measured the surface brightness of both lines. To remove the short term variability due to the Geocoronal emission (Fujimoto et al. 2007) and the reflection of Earth albedo, data reduction required special attention. See details in Yoshino et al. (2009) about the selection of the observation fields and the data analysis. Systematic uncertainty of the surface brightness of the lines is considered to be ~ 1 LU.

3. Results: Oxygen Emission Lines

3.1. O_{VII}-O_{VIII} correlation

We plotted the surface brightness of O_{VII} and O_{VIII} emission lines as shown in Fig. 3. The size of the dots indicate the hydrogen column density toward the observation direction. Remarkable property can be read from this plot. First, the O_{VII} and O_{VIII} surface brightness positively correlate very well. Second, all of the O_{VII} intensity

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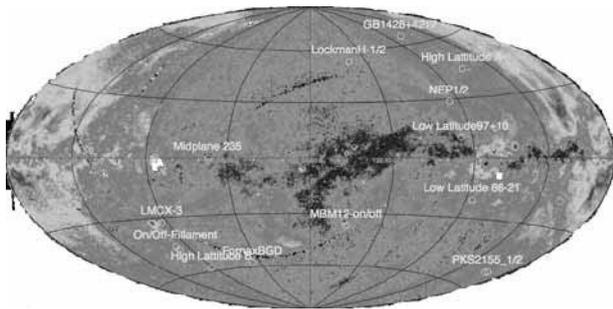


Fig. 1. *Suzaku* observations used for the soft X-ray background study overlaid on the RASS R45 band image (Snowden et al. 1997) projected as $(l, b) = (180^\circ, 0^\circ)$ at the center.

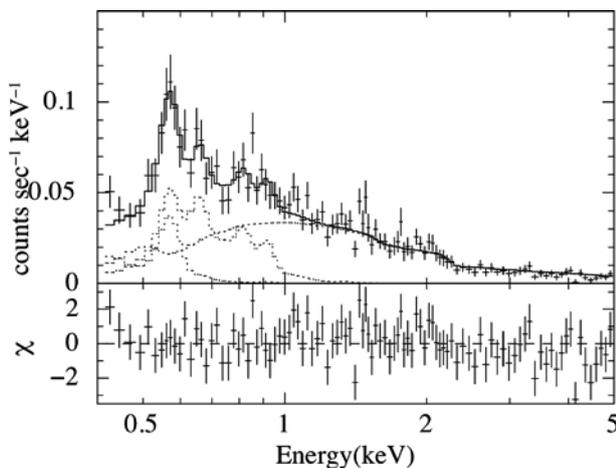


Fig. 2. A sample spectrum of a blank sky field at $(l, b) = (86^\circ, -20^\circ.8)$. Line emissions from O_{VII} (574 eV) and O_{VIII} (653 eV) are clearly detected.

is above about 2 LU, while O_{VIII} intensity reached to \sim zero. The simplest interpretation is that there are at least two components of emission in the SXB. One is called a "floor" component which emit 2 LU of O_{VII} emission lines. The other emit both O_{VII} and O_{VIII} lines with a fixed ratio of about $O_{VII}:O_{VIII}=2:1$, which might come from the halo of our Galaxy as shown in later discussion.

3.2. Origin of the "Floor" component

About the origin of the floor component, absorption column density gave us a hint. Three out of five fields whose O_{VII} surface brightness are almost at 2 LU have a large absorption column density corresponding to an attenuation length < 300 pc. It means that this floor component locates within 300 pc from us. Smith et al. (2007) also showed same level of O_{VII} emission line with an MBM-12 shadowing observation. If we assume that the emission comes from a hot plasma, it requires an emission measure of $0.0075 \text{ cm}^{-6} \text{ pc}$ for $T = 1.7 \times 10^6$ K. The emission measure of the "Local Bubble" or "Local Cavity" (see review by Cox and Reynolds 1987) can be

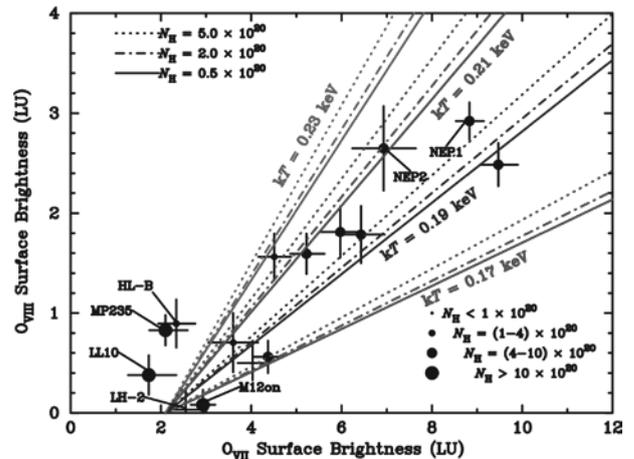


Fig. 3. Correlation of the surface brightness of O_{VII} and O_{VIII} emission lines from 15 pointings. Size of dots indicate the absorption column density toward the observing direction.

estimated from previous observations. EUV observation by *CHIPS* gave an upper limit of $0.0004 \text{ cm}^{-6} \text{ pc}$ for a hot gas with temperature between $10^{5.6}$ and $10^{6.3}$ K. This discrepancy indicates that the origin of the "floor" component is not the hot gas filling the Local Cavity.

Lallement (2004) suggested that the long term enhancement of RASS observations are produced by the heliospheric solar wind charge exchange process with interstellar neutral wind. A simulation predicted that the intensity of O_{VII} line emission is about 1.5 LU during the solar minimum, and spatially smooth at high ecliptic latitude ($\beta > 25^\circ$). In our selected fields, 12 out of 14 have $\beta > 38^\circ$. With these considerations, we conclude that the most plausible origin of the "floor" component is the heliospheric solar wind charge exchange process.

3.3. Origin and nature of the "Halo" component

As shown in Fig. 2, the line intensity ratio between O_{VII} and O_{VIII} is almost constant at 2:1. If we assume a thin thermal plasma of single temperature, it gives a very narrow range of temperature, as $kT = 0.2 \text{ keV} \pm 10\%$, even though the surface brightness of O_{VIII} varies from 0 to 3. There could be some physical mechanism to make a fixed temperature plasma in our Galaxy. In Fig. 4, we plot the line intensities as a function of the Galactic latitude b . The negative correlation is clear at $b > 20^\circ$. In case of any plasma distribution whose emissivity is defined as a function of the distance from the Galactic plane ("plane-parallel" distribution), the surface brightness will follow $\propto 1/\sin(b)$. It means that the surface brightness at $b = 20^\circ$ is about 3 times larger than that at $b = 90^\circ$. The observational result in Fig. 4 is steeper than $\propto 1/\sin(b)$ plus the "floor" component. The trend can be explained if the scale height of the hot plasma increase at the outer region of the Galactic disk, which

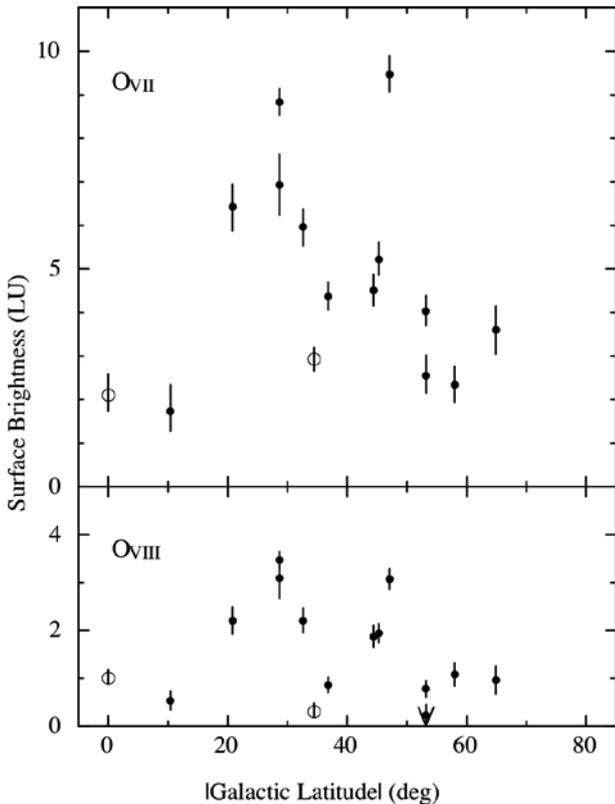


Fig. 4. O_{VII} and O_{VIII} emission line intensity as a function of Galactic latitude

is also shown in the scale height of the neutral Hydrogen (HI) (Nakanishi & Sofue 2003). It could indicate that X-ray emitting hot plasma is somewhat balanced with other interstellar materials or Galactic gravitational potential.

3.4. Hot blobs

In the energy spectra in 4 fields out of 14, we found strong emission of Neon K and Iron L lines. The spectral fits required an overabundance of Ne/O and Fe/O of about 3–4 times the solar value or another hot plasma component with $kT = 0.6\text{--}0.7$ keV. One of these fields is a Lockman hole field observed in 2005. While other Lockman hole observation in 2006 at $0^\circ.42$ degree away from the field observed in 2005 does not exhibit such hot or overabundant emission. As there is still systematic uncertainty of ~ 1 LU in the removal of short term variability due to the SWCX, it implies existence hot or dense blobs or patchy structure with some values of filling factor.

4. Combined Analysis of Emission and Absorption Lines

We do not obtain the density and the depth of the plasma separately only with the emission spectrum and intensities, because the emission measure is defined as $\frac{1}{4\pi} \int n_e n_i \Lambda(T) ds$. Combined analysis of the absorption

line which gives column density $\int n_i ds$ with the emission line can basically solve the question. In Yao et al. (2009), we used the absorption spectrum of LMC X-3 with *Chandra* LETG and the emission spectrum taken by *Suzaku* from the region at $30'$ away from LMC X-3. An uniform temperature and density model failed to reproduce the emission and absorption spectra simultaneously. We assumed an exponential disk model as $n_e = n_0 e^{-z/h_n}$ and $T = T_0 e^{-z/\gamma h_n}$ where z is the height from the Galactic plane and obtained a scale height of $h_n = 2.8(1.0\text{--}6.4)$ kpc and the gas density at the Galactic disk as $n_0 = 1.4(0.3\text{--}3.4) \times 10^{-3} \text{cm}^{-3}$. Another analysis was performed with an extragalactic source of PKS2155-304 (Hagihara et al. in this proceedings). We obtained a scale height of $h_n = 9.6(6.3\text{--}17.7)$ kpc and other parameters are marginally consistent with LMC X-3 case, even though we assumed a plane-parallel (i.e. constant scale heights) throughout the disk for simplicity. Although the two scale heights differs each other, the halo has a scale height of kpc order, or the other words, it is a Galactic scale phenomena. Total mass and luminosity estimated from this fit is $10^8 M_\odot$ and $10^{39} \text{erg s}^{-1}$ respectively. These are almost same as the hot halo around a spiral galaxy NGC 4631 whose star forming ratio is $\sim 3 M_\odot \text{yr}^{-1}$ (Yamasaki et al. 2009). The emissivity of Oxygen lines as a function of the height from the Galactic plane is shown in Fig. 5 where we used the best-fit values by PKS 2155-304, $T_0 = 10^{6.65} \text{K}$ ($kT = 0.37$ keV) and $h_n = 9.6$ kpc. The O_{VIII} lines emit almost within 2 kpc and O_{VII} line arises around $3\sim 4$ kpc from the Galactic plane. The ratio between the integrated line emissivity is consistent with a single temperature plasma of $kT = 0.21$ keV, which is consistent with previous blanks sky observations. If the parameter γ , which is defined as the ratio between the scale heights of the temperature and the density, is constant throughout the halo, the apparent temperature of the emission spectra becomes constant. The γ is $0.4(0.2\text{--}1.4)$ and $0.5(0.1\text{--}1.7)$ for LMC X-3 and PKS2155-304 respectively.

5. Conclusions and Future Prospects

Suzaku observations of Oxygen lines revealed following at present;

1. ~ 2 LU of O_{VII} line emission in the SXB comes within ~ 300 pc from us. Most of them are likely to originate from the charge exchange process between the solar wind and the neutral ISM.
2. A hot halo of our Galaxy is confirmed by Oxygen emission lines. Apparent temperature determined by O_{VII} and O_{VIII} line ratio are in very narrow range, $kT \sim 0.2$ keV with a field-to-field fluctuation of 10% for 14 blank fields, though the intensity varies about a factor of 4.

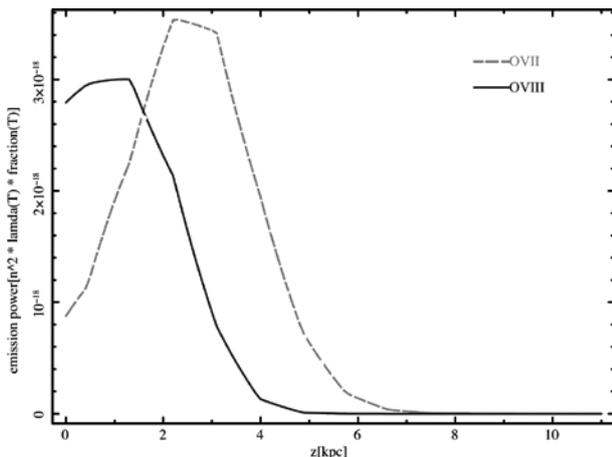


Fig. 5. O_{VII} and O_{VIII} emissivity toward PKS 2155-304 as a function of the height from the Galactic plane based on the best-fit parameters of combined analysis (Hagihara et al. 2009)

3. The spatial distribution is not plane-parallel. The larger scale height at the larger Galactic radius is suggested.
4. Combined analysis of the absorption and the emission spectra indicate temperature and density gradient of a scale height of kpc. Narrow range of apparent temperature might be caused by an equation of state of the hot gas in the halo.
5. Hot ($kT=0.6-0.8$ keV) or overabundant blobs are suggested in 4 in 14 fields.

These results suggest that there is a hot halo around our Galaxy same as several spiral galaxies. Dahlem et al. (1998) showed with *ROSAT* and *ASCA* that five normal galaxies have hot halos and joint spectral fits indicates two gas phases of $kT = 0.2-0.4$ keV and $kT = 0.65-0.9$ keV. Strickland et al. (2004) presented 10 *Chandra* observations of edge-on disk galaxies including starburst and normal spiral galaxies, and found X-ray halo of 2–4 kpc scale except two low-mass spiral galaxies. The mean temperature of the halo varies $kT = 0.18-0.36$ keV. These phenomena has been interpreted as a results of star formation activities. Several idea like chimneys and fountains from star-forming regions have been proposed about disk-halo interaction, which is considered to have played an important role in chemical evolution of the intergalactic material in early "Galactic wind" phase. Precise study of X-ray hot halo of our Galaxy, such as the pressure and thermal balance between the hot halo and other ISM components will improve the understanding of physical mechanism of this disk-halo interactions.

Systematic research of the emission spectra of the SXB with *Suzaku* will be helpful to understand the spatial structure of the hot halo, but current observation were

not planned for this purpose, and a substantially larger sampling of blank fields systematically chosen to investigate global diffuse emission is needed. The physical conditions to determine the apparent temperature of keV is not yet understood in our Galaxy or in other spirals. In our Galaxy case, correspondence between the temperature ($kT = 0.2$ keV) and the gravitational potential which gives a rotation velocity of ~ 200 km s^{-1} is suggestive.

The dynamical motion of the hot halo is an essential in modeling the chemical evolution of galaxies and intergalactic material, as it determines whether the materials in the hot halo will be recycled in or escape from galaxies. The SXS onboard ASTRO-H will enables us to know the velocity of the hot gas with ~ 100 km s^{-1} accuracy. After we understand the halo contribution in the SXB, we will be ready to study the extragalactic background in the soft X-ray band.

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