Suzaku Observations of the Local and Distant Hot ISM

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Abstract

Suzaku observed the molecular cloud MBM12 and a blank field less than 3° away to separate the local and distant components of the diffuse soft X-ray background. Towards MBM12, a local (D<~275 pc) Ovii emission line was clearly detected with an intensity of 3.5 ph cm⁻² s⁻¹ sr⁻¹ (or line units, LU), and the Oviii flux was < 0.34 LU. The origin of this Ovii emission could be hot gas in the Local Hot Bubble (LHB), charge exchange between oxygen ions in the solar wind (SWCX) and geocoronal or interplanetary material, or a combination of the two. If entirely from the LHB, the emission could be explained by a region with 100 pc radius, an electron density of 0.0087 cm⁻³, and a temperature of 1.2 × 10⁸ K. However, the implied temperature and emission measure would predict 1.4 keV emission in excess of observations. There is no evidence in the X-ray light curve or solar wind data for a significant contribution from geocoronal SWCX. However, the larger spatial extent of interplanetary SWCX washes out the rapid time variations of contributions from this source. In any case, the observed Ovii flux represents an upper limit to both the LHB emission and interplanetary SWCX in this direction, and both are thought to be nearly isotropic at low to intermediate latitudes.

The off-cloud observation was performed immediately following the on-cloud. The net off-cloud Ovii and Oviii intensities were (respectively) 2.34 ± 0.33 and 0.77 ± 0.16 LU, after subtracting the on-cloud foreground emission. Assuming the LHB and SWCX components did not change, these increases can be attributed to more distant Galactic disk, halo, or extragalactic emission. If the distant Ovii and Oviii emission is from a thermal plasma in collisional equilibrium beyond the Galactic disk, a temperature of (2.1 ± 0.1) × 10⁸ K with an emission measure of (4 ± 0.6) × 10⁻³ cm⁻⁶ pc is inferred.

Key words: ISM: bubbles—plasmas—X-rays: ISM

1. Introduction

The soft (< 2 keV) diffuse X-ray background was a relatively early discovery of X-ray astronomy (see review by Tanaka & Bleeker (1977)). Unlike the diffuse hard X-ray (> 2 keV) background, whose isotropy demonstrated it was dominated by extragalactic sources, the origin of soft component was and is more uncertain. While at high Galactic latitudes extragalactic emission contributes to the observed flux, at lower latitudes the emission must be local to the Galaxy since at energies of 3/4 keV, absorption is significant (one optical depth is only NH = 2 × 10²¹ cm⁻²). Despite this, both the Wisconsin M band (McCammon et al. 1983) and the ROSAT 3/4 keV (Snowden et al. 1995) surveys showed surprisingly little latitude dependence away from the Galactic bulge.

It is now known that at high latitudes, where NH is generally less than 10²¹ cm⁻², ~ 40% of the 3/4 keV emission is due to AGN, and from the XQC sounding rocket flight we know that at least 42% of the high-latitude flux must be due to oxygen emission lines coming from z < 0.01 (McCammon et al. 2002) although it is not known if these...
are within the Galaxy or in the halo.

The situation in the Galactic plane is more confusing. Dwarf M stars must contribute some of the 3/4 keV emission (Kuntz & Snowden 2001), but at least 50% of the emission is of unknown origin (McCammon & Sanders 1990). OVII and OVIII contribute most of the line emission in the 3/4 keV band, although the fraction in lines versus continuum remains uncertain. Oxygen’s dominance is due both to its large cosmic abundance (compared to other metals), and its strong emission lines at 0.57 keV (the OVII triplet from n = 2 → 1) and 0.65 keV (the OVIII Lyα transition). Absorption limits the observed in-plane 3/4 keV emission to regions within 1-2 kpc (assuming ⟨n⟩ ∼ 1 cm−3 in the Galaxy).

Some of the 3/4 keV emission must be from the same source as the 1/4 keV X-ray background, which has been attributed to a combination of emission from a “Local Hot Bubble” (LHB) (Snowden et al. 1990) and charge exchange from solar wind ions (hereafter SWCX) (Cox 1998; Lallement 2004). In both cases, the X-rays must be truly “local”, originating within ∼100 pc in the former case or within the Solar System in the latter.

To distinguish between the “local” 3/4 keV X-ray emission and the more distant Galactic and halo components, we used Suzaku to observe the nearby molecular cloud MBM12 (Lynds 1457), along with a nearby “blank-sky”position not occulted by the cloud. Earlier observations of MBM12 obtained with ROSAT (Snowden, McCammon & Verter 1993)(SMV93) and Chandra (Smith et al. 2005) had low spectral resolution (ROSAT) or were strongly affected by high background due to solar flares (Chandra). Our hope with this observation was to use Suzaku’s low background, good spectral resolution, and sizable effective area × solid angle product to measure the components of both the local and more distant contributors to the 3/4 keV emission.

As described in Smith et al. (2005), the true distance to MBM12 is uncertain, with estimates ranging from 60 ± 30 pc to 275 ± 65 pc. Our goal, however, is only to use MBM12 as a curtain that separates local components such as the LHB and SWCX from more distant components such as a hot halo or extragalactic emission. It seems unlikely there is a significant component to the soft X-ray emission that is beyond the LHB but in front of MBM12, so the distance uncertainty is not particularly important to this analysis. The total column density due to the MBM12 cloud is also somewhat uncertain. We follow Smith et al. (2005), who argued for NH = 4×1021 cm−2 as a reasonable value for the densest region of MBM12. Although the Suzaku XIS1 has more than four times the field of view of the Chandra ACIS-S3 (17.8′ × 17.8′ versus 8.5′ × 8.5′), this is of similar size to the densest part of MBM12 and so we expect a similar total column density.

ROSAT observations were only able to put a 2σ upper limit of 270 counts s−1 sr−1 on the 3/4 keV emission seen towards MBM12 (SMV93). SMV93 fit a “standard” 106 K collisional ionization equilibrium (CIE) LHB model (Raymond & Smith 1977) assuming a pathlength of ∼65 pc, and found a good match to the observed 1/4 keV emission with an emission measure of 0.0024 cm−6 pc. This model generates only ∼47 counts s−1 sr−1 in the 3/4 keV band, primarily due to ∼0.28 ph cm−2 s−1 sr−1 (hereafter LU, or “line units”) generated by the OVII triplet (based on the ATOMDB v1.3.1 atomic database). However, the ROSAT PSPC had little spectral resolution in this band and could not separate the OVII and OVIII lines from the background continuum, and possible Fe L line emission.

Smith et al. (2005) used the Chandra ACIS instrument to redo the SMV93 observations with higher spectral and spatial resolution. The results were affected by a large solar flare during part of the observation, which likely led to increased emission from SWCX (see Snowden, Collier & Kuntz (2004) for more details on SWCX). Smith et al. (2005) detected strong OVII and OVIII emission lines with surface brightnesses of 1.92±0.60 and 2.35+0.59−0.43 LU respectively, much larger than the prediction from SMV93. The OVIII emission itself was also unexpected, as Smith et al. (2005) showed that it cannot come from any of the standard LHB models, either equilibrium or strongly recombining. They suggested that the observed OVIII emission was from the SWCX, although this could not be proven.

2. Observations

The molecular cloud MBM12 (Lynds 1457) was observed by Suzaku on February 3-6, 2006 for a total of 231 ksec. The nominal pointing position was (RA, Dec) = 02h56m00s, +19°29′24″ (J2000) ((l, b) = 159.2°, −34.47°), corresponding to the most infrared-luminous and thus densest portion of the molecular cloud. Immediately thereafter (on February 6-8, 2006) an “off-cloud” pointing was obtained towards 02h45m16s, +18°20′14.3″ (J2000) ((l, b) = 157.3°, −36.8°), a position 2.79° distant from the cloud, for 168 ksec. We present data primarily from the XIS instrument (Koyama et al. 2006), using the back-illuminated CCD XIS1 which has the largest effective area at energies below 1 keV. The two fields of view are shown in Figure 1, overplotted on the IRAS 100μm image.

We used version 0.7 of the Suzaku data processing pipeline for our base dataset. The cleaned v0.7 data are by default filtered to exclude times within 436 seconds of Suzaku passing through the South Atlantic Anomaly (SAA), and when Suzaku’s line of sight is elevated above the Earth’s limb by less than 5°, or is less than 20° from the bright-Earth terminator. We decided to expand this to exclude events with Earth-limb elevation angle less than 10°, as there were some excess events in the 0.5-0.6 keV

1 We present all surface brightnesses in units of steradians, and note that 1 sr = 1.18 × 107 arcmin2.
band in the $5^\circ - 10^\circ$ range. Finally, flaring pixels were removed using the cleanxis tool with the default v0.7 parameters. Although these are a small fraction of the total number of pixels on the CCD, they contribute a sizeable background. In the case of the on-cloud data for XIS1, just 1055 flickering pixels (out of $\sim 10^6$ total pixels) contributed $\sim 46\%$ of the total counts.

The bright intermediate polar XY Ari was serendipitously included in the on-cloud observations; this source will be discussed in a separate paper. XY Ari is sufficiently highly absorbed (Salinas & Schlegel 2004) that no photons below 1 keV are expected from the source. However, a smoothed image of the 0.4 - 1.0 keV band (see Figure 2[Left]) shows low-energy emission from XY Ari, likely due to the tail of the CCD response curve. We therefore excluded a $2^\prime$ radius region around XY Ari (marked with a red circle in Figure 2[Left]) in order to reduce this background. This had the effect of substantially reducing the total background at all energies while excluding only a small fraction of the total $17.8^\prime \times 17.8^\prime$ field. In addition, there were two other weaker sources found which were also previously found in the Chandra observation of MBM12. These are marked in Figure 2[Left] with a $1^\prime$ radius blue circle (02:55:48, +19:29:12, J2000) and a white circle (02:55:51, +19:26:21, J2000). Both had hard spectra with no significant flux below 1 keV in either the Suzaku or Chandra data. In the off-cloud data (Figure 2[Right]) we discovered a bright source at 02:45:09, +18:21:30 (J2000) (red circle) which does not appear in the ROSAT All-Sky Survey or any other catalog. We leave analysis of these sources for a future paper, and concentrate on the diffuse soft X-ray emission.

2.1. Background

As the goal of the observation was to extract the soft X-ray background, which fills the field of view, other background components cannot be estimated directly from the observation. Therefore our first focus was on understanding the importance of the three major background components: particle contamination, scattered solar X-rays, and solar wind charge exchange. We did not exclude the corners of the detectors which contained the onboard calibration sources in our analysis, but instead fit these lines (which are all $> 1$ keV) as part of our source and background models.

2.1.1. Particle Background

Suzaku is in a low-Earth orbit, so it is significantly shielded from the particle background that strongly affects XMM-Newton and Chandra. The effectiveness of this shielding is dependent upon the “Cut-Off Rigidity” (COR) of the Earth’s magnetic field, which varies as Suzaku traverses its orbit. During times with larger COR values, fewer particles are able to penetrate to the satellite and to the XIS detectors. We considered using the default value (COR $> 4$ GV) but finally chose to use a stronger constraint (COR $> 8$ GV) for both observations, as the lowest background was desired. This tighter constraint eliminates 27% (28.5 ksec) of the total on-cloud observation time but 35% of all the XIS1 counts. After this cut, we were left with 71.7 ksec of “good” time for the on-cloud observation and 51.85 ksec for the off-cloud pointing.

Although it is reduced by the Earth’s magnetic field, Suzaku still has a noticeable particle background. Fortunately, we can estimate the background level quite accurately as a part of most observations is spent observing the Earth at night, and these data are a good proxy for the pure particle background. Phenomena such as aurorae have been observed to contribute X-rays to the Earth’s night sky (Bhardwaj 2006), but these processes tend to be transient and thus are easily removed from the data. We used $\sim 400$ ksec of night Earth observations from the SWG phase of the mission. The data were filtered to remove flares, and to ensure that Suzaku’s line-of-sight elevation from the Earth-limb was less than $-5^\circ$ while observing the dark Earth. We also required the same cut-off rigidity constraint (COR $> 8$ GV) as used for the on- and off-cloud observations when extracting the particle background spectrum.

2.1.2. Scattered Solar X-rays

As Suzaku orbits the Earth maintaining a fixed pointing, the column density of atmosphere along the look direction varies rapidly. Solar X-rays can scatter off the atmosphere into the telescope, either via Thompson scattering or by fluorescence (Snowden & Freyberg 1993). Fluorescence of oxygen atoms and molecules is our greatest concern, as it would give rise to emission lines around 0.54 keV which could blend with the O VII line. We modeled the Earth’s atmosphere using the NRLMSISE-00 empirical model (Hedin et al. 1990), and combined this with the Suzaku orbital parameters to calculate the total solar-illuminated column density of oxygen atoms and O$_2$ molecules as a function of time.

We then extracted the count rate as a function of time in the 0.4-1.0 keV band and compared this to the oxy-
gen column density $N_\text{O}$. In Figure 3 we show the correlation plot for the uncleaned data. When the illuminated atmospheric $N_\text{O}$ exceeds $\sim 10^{15}$ cm$^{-2}$, the count rate rises sharply due to scattered solar X-rays. We fit the data with $N_\text{O}$ between $0-10^{17}$ cm$^{-2}$ to a linear model and found that they are well described by the function $0.04 + (1.18 \pm 0.01) \times 10^{-16} N_\text{O}$ cts/s. In Figure 4 we show the same plot (with a linear abscissa) after the standard filters are applied. All the lines of sight with column densities above $\sim 10^{14}$ cm$^{-2}$ have been eliminated (at least for this observation) by the requirements that the look direction be elevated by at least $10^\circ$ and at least $20^\circ$ away from the bright Earth terminator. Figure 4 shows that most times have either negligible oxygen column or $N_\text{O} \sim 10^{13}$ cm$^{-2}$. Applying our linear fit, we see that the integrated contamination due to fluorescent oxygen is less than $\sim 0.001$ cts/s. A similar result holds for the off-cloud observation as well. We therefore expect that the scattered solar X-ray contribution to our data is negligible.

\subsection*{Solar Wind Charge Exchange}

Diffuse soft X-ray emission can also be generated by ions in the solar wind interacting with neutral interplanetary or geocoronal material. However, the appearance and strength of emission lines emitted by SWCX is poorly characterized. It is expected that the density, velocity, and ionization balance of the solar wind should correlate with the variable SWCX contribution, which is largely from the geocorona, but there may also be a more nearly constant component of the SWCX emission from interplanetary space. Figure 5 shows some of the relevant values for the two Suzaku observations and, for comparison, during an instance of strong SWCX emission seen by XMM-Newton.
Snowden, Collier & Kuntz (2004) analyzed an *XMM-Newton* observation of the Hubble Deep Field North that showed substantial SWCX emission. That observation occurred during a period characterized by a strong solar proton flux (in only a few percent of observations are stronger fluxes seen), as well as high O$^{+7}$/O$^{+6}$, but low O$^{+8}$/O$^{+7}$. The proton speed was low, $\sim 350$ km s$^{-1}$. Enhanced O$^{vii}$ (7.39±0.79 LU) and (despite the low O$^{+8}$/O$^{+7}$ ratio) O$^{viii}$ (6.54±0.34 LU) emission was seen during this observation, along with a number of other species. In contrast, our *Suzaku* observations were done at a time characterized by a moderate proton flux in the solar wind, with the exception of one short period of the on-cloud observation. The O$^{+7}$/O$^{+6}$ ratio during both observations was close to the mean ratio for the solar wind. The proton speed during both *Suzaku* observations was exceptionally low, typically < 350 km s$^{-1}$, which is seen in only a few percent of observations.

Nonetheless, there were some similarities in the solar wind parameters during the *XMM-Newton* observation that showed strong SWCX contamination and our *Suzaku* observations. In both, the solar wind was slow and dense. However, the peak proton flux during the *Suzaku* observations was less than half the proton flux responsible for the SWCX emission in the *XMM-Newton* observation, and the mean proton flux is even lower. Further, the *XMM-Newton* line of sight observed through the densest portion of the Earth’s magnetosheath, whereas the *Suzaku* observations are through the flanks of the magnetosheath, thus further reducing the target neutrals with which the solar wind produces the X-ray emission. Unfortunately, our understanding of how the solar wind characteristics, satellite orbits, and observing directions interact to generate observed SWCX emission is still quite limited. Nonetheless, the combination of the solar wind strength and the look direction, as well as the fact that the ion ratios are close to the mean values, suggests that whatever the SWCX surface brightness was during our *Suzaku* observations, it is typical for observations of the diffuse soft X-ray background.

2.2. XIS Response

For this work, we focused on the back-illuminated XIS1 detector, which has the largest effective area of low energy X-rays. As these observations were performed early in the mission, very little degradation of the CCD response had occurred. Unfortunately, however, the time- and space-varying contamination layer which was discovered early in the mission has complicated observations at low energies (Koyama et al. 2006).

We calculated the XIS detector effective area using the tool *xissimarfgen*, which includes both the time and spatial effects of the contamination layer. We assumed a field-filling source, and used a detector mask which removed the bad pixel regions, along with the region excluded due to the bright source XY Ari. The model of the contamination layer is based on in-flight observations and has its own uncertainties. Combining these with other known sources of systematic error, we estimate that at 0.6 keV there is
a ∼ 13% systematic error on the final effective area×solid angle product, in addition to the given statistical errors.

3. Results

3.1. On-Cloud Emission

Although MBM12 absorbs almost all distant emission below 0.7 keV, we cannot say if the foreground low energy emission is local to the solar system or tens of parsecs away. Our first goal, however, is to simply model the spectrum seen towards MBM12 since this is likely the ‘darkest’ high latitude line of sight in the Galaxy at soft X-ray energies.

3.1.1. Raw Count Model

The data clearly showed a feature near 0.56 keV, so we began by simply fitting a linear continuum plus a Gaussian to the observed count rates (with no background subtraction) for the on-cloud data on XIS1 between 0.4-1.0 keV in PI channels. This approach is admittedly simplistic, but it gives a baseline measurement, useful when comparing to a more complicated physical model. Figure 6 shows the best-fit result, which has 229±32 counts in the line and a centroid at PI channel 151 adjusted for the PI channel width. The best-fit temperature was lower (kT = 200 keV, and a total absorbed surface brightness kT = 5.5 × 10^{22} cm^{-2}, 0.4-7 keV) of 1.4 above 1.2 keV and steepening significantly below 1 keV as observed by ROSAT and Chandra. A Gaussian line was added to represent the blended Nvii triplet and C vi Lyβ line, and a final Gaussian was included to represent the Ovii emission. The broken power-law components fit the composite total AGN spectrum, giving a slope of 1.4 above 1.2 keV and steepening significantly below 1 keV; our best-fit value was 2.36 ph cm^{-2} s^{-1} sr^{-1} at 1 keV. Both components were assumed to be absorbed with column density N_H = 4 × 10^{21} cm^{-2}, using the value for MBM12 found in Smith et al. (2005).

Fig. 6. The on-cloud spectrum between 0.4-1.0 keV (channels 110-273) in channel units. The best fit line plus Gaussian is shown.

Despite the exclusion of the region within 2′ of XY Ari from the spectrum, the source is so bright that its scattered emission contributes significantly to the overall spectrum above 1 keV. This contribution was modeled as absorbed bremsstrahlung emission with an additional iron line. The best-fit value had N_H = 5.5 × 10^{22} cm^{-2}, kT = 200 keV, and a total absorbed surface brightness (0.4-7 keV) of 1.25 × 10^{-7} erg cm^{-2} s^{-1} sr^{-1}. The best-fit Fe line was at 6.98 keV, with FWHM 0.4 keV and surface brightness 1.3 LU. We note that, while this model fits the X-ray spectrum of XY Ari reasonably well, we do not claim it is a correct physical model of the emission. An initial fit to the XY Ari data itself (using data from the central 2′) showed that the scattered flux is ∼ 22% of the total source flux, in agreement with the expected value (19%) based on the XRT PSF after excluding the central 2′.

3.1.2. Physical Model

To expand upon these simple results, we then considered a more realistic physical model which explicitly included the detector background along with known astrophysical sources. We restricted the energy range to 0.4-7 keV, as above 7 keV the particle background rises sharply. The background was fit to the night Earth data (see §2.1.1) using a model consisting of the sum of a power-law, a constant, and the five emission lines expected in this energy range (see Table 6.2 in the Suzaku Technical Description\footnote{http://heasarc.gsfc.nasa.gov/docs/suzaku/prop_tools/suzaku_td/}). The emission lines were modeled as Gaussians (see Table 1). Note that the best-fit energies agree with the laboratory energies to within 1%. The variation in the FWHM is not completely understood, but the large value at 2.13 keV is probably due to the multiple lines found in the Au M complex. The power-law term (with best-fit Γ = 1.02 and amplitude 0.011 counts s^{-1}keV^{-1} at 1 keV) and the constant (amplitude 0.00723 counts s^{-1}keV^{-1}) were not folded through the effective area curve. These two terms account for the observed particle background, after the COR > 8 GV and ELV > 10^6 filters.

The source model included two absorbed broken power-laws to account for the cosmic X-ray background (CXRUB) and an absorbed bremsstrahlung plus Fe line for the remaining XY Ari emission (see below). A Gaussian line was added to represent the blended Nvii triplet and C vi Lyβ line, and a final Gaussian was included to represent the Ovii emission. The broken power-law components fit the composite total AGN spectrum, giving a slope of 1.4 above 1.2 keV and steepening significantly below 1 keV; our best-fit value was 2.36 ph cm^{-2} s^{-1} sr^{-1} at 1 keV. Both components were assumed to be absorbed with column density N_H = 4 × 10^{21} cm^{-2}, using the value for MBM12 found in Smith et al. (2005).

\[\text{Counts} \times \text{channel units} \times \text{PI channel width} \times \text{ROI area} \times \text{solid angle product} \times \text{sky background}\]
who used K-band spectroscopy to determine that XY Ari’s secondary is an M0V star, with an $A_V = 11.5 \pm 0.3$, corresponding to a hydrogen column density of $2.2 \times 10^{22} \text{cm}^{-2}$. However, Luhman (2001) showed that most stars within the MBM12 cloud have $A_V < 2$, while background stars generally have values between $A_V = 3 \sim 8$. The origin of the discrepancy between these values and Littlefair, Dhillon & Marsh (2001) is unknown, but may be due to an inadequate model for the X-ray spectrum of XY Ari. The absorbing material may be near XY Ari itself, although it is also possible that MBM12 has a larger column density along this line of sight that the average value we assumed. This will not affect our results since our model already has little to no flux in the 0.5-0.7 keV band from beyond MBM12. In any event, a more detailed analysis of the XY Ari data is in progress, and we are certain the effect on the continuum below 1 keV is small.

The contribution from the Local Hot Bubble itself is normally modeled as a thermal plasma in CIE with $T \sim 10^6 \text{K}$. However, most of the LHB emission is in the 0.1-0.3 keV bandpass, where Suzaku has some effective area but is not yet accurately calibrated. With our lower energy limit of 0.4 keV, the only strong lines expected from the LHB are from the N\text{vii} triplet at $\sim 0.43 \text{keV}$, along with C\text{vii}Ly$\beta$ emission at the same energy. We therefore included a single Gaussian to represent these lines, and ignored the continuum since this is negligible in a thermal plasma with $T \sim 10^6 \text{K}$. The best-fit position was $0.42 \pm 0.03 \text{keV}$, with FWHM 0.058 keV and surface brightness $2.4_{-0.60}^{+0.62} \text{LU}$.

The final term was a Gaussian to represent the oxygen emission. The best-fit parameters put the line at $0.556 \pm 0.003 \text{keV}$, with FWHM 0.071 keV and a total surface brightness of $3.53 \pm 0.26 \text{LU}$. The line position is nearly identical to that found in §3.1.1, while the surface brightness is increased by 60%. In this model, the continuum (due to particle background, the tail of the CCD response, and the absorbed CXRB) is very low at the O\text{vii} line, as opposed to the simple model which assumed a flat continuum under the line. The best-fit spectrum, including the background night Earth data, is shown in Figure 7.

In the simple model, we were able to put a $2\sigma$ upper limit on any O\text{viii} contribution by adding a delta function at the expected position of an O\text{viii} line. Likewise here we added a delta function to the model at 0.653 keV, to represent the O\text{viii} Ly$\alpha$ line. The best-fit result is a marginal detection of a feature with surface brightness $0.24 \pm 0.1 \text{LU}$, which when included in the model reduces the O\text{vii} surface brightness to $3.34 \pm 0.26 \text{LU}$. The O\text{viii}/O\text{vii} surface brightness ratio is then $7.2 \pm 3.0\%$. Smith et al. (2005) noted that the O\text{vii} $n = 3 \rightarrow 1$ transition (at 0.666 keV) line can contribute as much as 6% of the flux of the main O\text{vii} $n = 2 \rightarrow 1$ triplet. Although we do not claim this as a detection, it seems more likely that this emission is from this O\text{vii} line and not O\text{viii}.

### 3.2. Off-Cloud Emission

The off-cloud observations were taken immediately following the on-cloud data and as shown in §2.1.3, the solar wind parameters were relatively stable during this period. So assuming the SWCX contribution is stable, we can use the difference between these observations as an estimate of distant Galactic disk and halo emission.

We assumed the “background” (actually a foreground in this case) for the off-cloud spectrum is the same as the on-cloud spectrum without the contribution from XY Ari. We assume that the “distant” emission originates beyond most of the Galactic gas (with $N_\text{H} = 8.7 \times 10^{20} \text{cm}^{-2}$) seen in this direction. Figure 8 shows the best-fit to the off-cloud spectrum between 0.4-1.5 keV. We added two Gaussian lines to the model to represent the “distant” emission from O\text{vii} and O\text{viii}, as well as a third (with FWHM set to 0 to force the fit to reflect a single line, rather than a very wide blend) to fit the excess between 0.85-0.9 keV. The “local” Oxygen emission lines measured in the on-cloud observation were also included in this fit, so these new lines measure only the “distant” compo-

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Fig. 7. The on-cloud spectrum with the best-fit model (red line) with the background spectrum and best-fit model (blue line) between 0.4-1.4 keV.
null
cally high ambient ISM pressure \((p/k > 3 \times 10^4 \text{ cm}^{-3} \text{K})\). In addition, these types of models typically predict significant amounts of high-velocity \(\text{OVI}\), which have not been observed (Shelton 2002).

We therefore consider models in collisional equilibrium. A CIE plasma at 10\(^6\) K, the “typical” temperature for the LHB (SMV93), has an \(\text{OVI}\) triplet emissivity of \(\Lambda = 5.7 \times 10^{-16} \text{ph cm}^3\text{s}^{-1}\), assuming the oxygen abundance relative to hydrogen is 8.51 \times 10^{-4} (Smith et al. 2001). This rises rapidly with temperature, reaching \(1.5 \times 10^{-15} \text{ph cm}^3\text{s}^{-1}\) at 12.6 \times 10\(^6\) K, and peaking (for \(T = 2 \times 10^6\) K) at \(6.4 \times 10^{-15} \text{ph cm}^3\text{s}^{-1}\). However, the 2\(\sigma\) upper limit on the \(\text{OVI}/\text{OVII}\) ratio of 13\% puts an upper limit on the equilibrium temperature of 1.7 \times 10^6 K (where \(\Lambda = 4.8 \times 10^{-15} \text{ph cm}^3\text{s}^{-1}\)).

Using these values, and assuming a constant density and temperature throughout the LHB, we can express the total surface brightness of \(\text{OVI}\) as:

\[
L_S(\text{OVII}) = \frac{1}{4\pi} R_{\text{LHB}} \frac{n_e^2}{1.2} \Lambda_{\text{OVII}}
\]

(1)

where \(L_S\) is in LU, \(n_e\) is the electron density and \(R_{\text{LHB}}\) is the bubble radius. This assumes that hydrogen and helium are fully ionized, so \(n_e \approx 1.2n_H\). Taking our lower value of 2.3 LU of \(\text{OVII}\), Equation (1) gives \(n_e^2R_{\text{LHB}} = 0.020\text{cm}^{-6}\text{pc}\) at 10\(^6\) K, or 0.0075 \text{cm}^{-6}\text{pc} at 12.6 \times 10^6 K. We can obtain a lower limit of 0.0023 \text{cm}^{-6}\text{pc} on this value using our upper limit of \(T = 1.7 \times 10^6\) K. This final value is similar to the emission measure found by SMV93 (0.0024 \text{cm}^{-6}\text{pc}), although at a significantly higher temperature. Assuming \(R_{\text{LHB}} = 100\text{pc}\), we require electron densities of 0.014, 0.0087, or 0.0048 \text{cm}^{-3}, and a pressure of \(p/k = 3.0, 2.2,\) or \(1.7 \times 10^4\text{K}\) at \(T = 10^6\) K, \(1.2 \times 10^6\) K, or \(1.7 \times 10^6\) K, respectively.

Interestingly, Cox (2005) found that the midplane pressure required to support the various layers of the Galaxy (\(e.g.\) cold and warm H\(_i\), diffuse H\(_i\), etc.) is \(2.2 \times 10^4\text{K}\), in agreement with our value at \(T = 1.2 \times 10^6\) K. In addition, Snowden et al. (2000) used X-ray shadows (such as those created by MBM12) seen in the ROSAT All-sky Survey observations at 1/4 keV to measure the temperature of the local diffuse soft X-ray component. They also found a best-fit temperature of 1.2 \times 10^6 K, although this is based on the Raymond \\& Smith (1977)/(RS77) plasma code. In particular, using this temperature and the pressure with the 1993 update to the RS77 plasma code (using solar abundances) would predict \(3\times\) the observed 1/4 keV band surface brightness seen by ROSAT. This could perhaps be explained if the Si, Fe, and other high-Z elements that create the 1/4 keV band emission were depleted relative to oxygen in the LHB; more modelling is needed to test this hypothesis.

Despite the suggestive agreement in temperature and pressure described above, there are issues in other wavebands. Hurwitz et al. (2005) has placed a 95\% upper limit on the emission measure of a local 10\(^6\) K component of 0.0004 \text{cm}^{-6}\text{pc}, based on CHIPS observations of diffuse EUV iron lines and assuming a solar abundance for iron. Even if iron is fully depleted, they still find a 95\% upper limit of \(\sim 0.005\text{cm}^{-6}\text{pc}\) for any CIE model with \(T< 1.6 \times 10^6\) K, based on the non-detection of \(\text{OV}\) and \(\text{OVI}\) lines near 171-173\AA. The fully-depleted Hurwitz et al. (2005) upper limit disagrees with our value of 0.0075 \text{cm}^{-6}\text{pc} by a factor of at least 50\%. In addition, the solar-abundance CHIPS limit strongly disagrees with the value found by SMV93 and from the ROSAT All-Sky Survey in the 1/4 keV band (\(\sim 0.0018-0.0058\text{cm}^{-6}\text{pc}\)) which also assumes solar abundances (Snowden et al. 1998). Hurwitz et al. (2005) noted these discrepancies and suggested that some depleted abundance pattern might exist that brings the X-ray and EUV observations into agreement. Nonetheless, as it stands the fully-depleted CHIPS limits suggest that at least a third of the \(\text{OVII}\) we detect is not from the LHB.

One possibility is that this emission comes from SWCX. More analysis of the solar wind data will be needed to determine if the observations were truly done during a period of relative quiescence; for example, the absolute \(O^{+7}\) and \(O^{+8}\) fluxes can be derived from ACE data with additional effort. While Figure 5, based on the automatically processed ACE data, does not show any signs of increased oxygen flux, more data are needed to confirm this.

4.2. “Distant” emission

Figure 5 shows that the solar wind conditions were similar during both observations, and the LHB intensity is not expected to change over an angle of less than \(3^\circ\). If both oxygen lines are from an unabsorbed plasma in CIE, the \(\text{OVIII}/\text{OVII}\) ratio (0.33 \pm 0.08) implies \(T = (2.2^{+0.1}_{-0.2}) \times 10^6\) K. At this temperature, the predicted emission measure is \((1.9 \pm 0.3) \times 10^{-3}\text{cm}^{-6}\text{pc}\) using ATOMDB v1.3.1 emissivities (Smith et al. 2001). If, as is more likely, the plasma is behind the Galactic hydrogen layer (\(N_H = 8.7 \times 10^{20}\text{cm}^{-2}\)), then the unabsorbed \(\text{OVIII}/\text{OVII}\) ratio would be 0.26 \pm 0.06. In this case, \(T = 2.1 \pm 0.1 \times 10^6\) K and the emission measure is \((4.0 \pm 0.6) \times 10^{-3}\text{cm}^{-6}\text{pc}\). In either case, our results consistent with previous measurements of distant hot halo gas. However, our result does not touch on the question of whether the halo has one (Pietz et al. 1998) or two (Kuntz et al. 2000) dominant temperatures; further \textit{Suzaku} observations will be necessary to address this question.

The line at 0.876 keV is a mystery, although we stress it is at best a 3\(\sigma\) detection. Between 0.7-1.3 keV, the strongest emission lines in a collisional plasma are typically from neon or iron. The closest strong neon line to 0.876 keV is the Neix forbidden line, but this would require a 5\% gain error in the XIS1. The oxygen lines at lower energies show < 2\% gain shift, and the calibration lines at higher energies (see Table 1) have less than 1\% gain shift. The strongest iron lines near this energy are from \(2p^53d \rightarrow 2p^5\) transitions in Fe XVIII, but any identification with an Fe line is problematic since many other lines of FeXVIII (such as the \(2p^53s \rightarrow 2p^5\) line at 0.775 keV) would also be expected. In particular, the 2\(\sigma\) upper limit on the FeXVII 0.826 keV line of 0.19 LU strongly limits any Fe line identification for the line at 0.876 keV. It is
possible it is an as-yet unidentified weak instrumental line, although this raises the question of why it is not present in the on-cloud data.

Intriguingly, the Lyman limit for O\textsuperscript{viii} is 0.8704 keV, so it is possible that this is not a line, but rather a recombination edge resulting from cool electrons interacting with O\textsuperscript{+8} ions. If so, we wonder at the origin of the O\textsuperscript{+8} ions—are they local to the Solar system due to a sudden change in the solar wind during the off-cloud observation, or from a distant recombining plasma? As more data from ACE and Suzaku becomes available, we may be able to answer this question.

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