We present an analysis of a pair of *Suzaku* spectra of the soft X-ray background (SXRB), obtained from pointings on and off a nearby shadowing filament in the southern Galactic hemisphere. Because of the different Galactic column densities in the two pointing directions, the observed emission from the Galactic halo has a different shape in the two spectra. We make use of this difference when modeling the spectra to separate the absorbed halo emission from the unabsorbed foreground emission from the Local Bubble (LB). The temperatures and emission measures we obtain are significantly different from those determined from an earlier analysis of *XMM-Newton* spectra from the same pointing directions. We attribute this difference to the presence of previously unrecognized solar wind charge exchange (SWCX) contamination in the *XMM-Newton* spectra, possibly due to a localized enhancement in the solar wind moving across the line of sight. Contemporaneous solar wind data from *ACE* show nothing unusual during the course of the *XMM-Newton* observations. Our results therefore suggest that simply examining contemporaneous solar wind data might be inadequate for determining if a spectrum of the SXRB is contaminated by SWCX emission. If our *Suzaku* spectra are not badly contaminated by SWCX emission, our best-fitting LB model gives a temperature of \( T_{\text{LB}} = 5.98^{+0.04}_{-0.03} \) and a pressure of \( p_{\text{LB}} / k = 13.100 - 16.100 \, \text{cm}^{-3} \, \text{K} \). These values are lower than those obtained from other recent observations of the LB, suggesting that the LB may not be isothermal and may not be in pressure equilibrium. Our halo modeling, meanwhile, suggests that neon may be enhanced relative to oxygen and iron, possibly because oxygen and iron are partly in dust.

*Subject headings:* Galaxy: halo — solar wind — X-rays: diffuse background — X-rays: ISM

*Online material:* color figures

1. INTRODUCTION

The diffuse soft X-ray background (SXRB), which is observed in all directions in the \( 0.1-2 \) keV band, is composed of emission from several different components. For many years, the observed \( 2 \) keV emission was believed to originate from the Local Bubble (LB), a cavity in the local interstellar medium (ISM) of \( 100 \) pc radius filled with \( 10^6 \) K gas (Sanders et al. 1977; Cox & Reynolds 1987; McCammon & Sanders 1990; Snowden et al. 1990). However, the discovery of shadows in the \( 2 \) keV background with *ROSAT* showed that \( \sim 50\% \) of the \( 2 \) keV emission originates from beyond the LB (Burrows & Mendenhall 1991; Snowden et al. 1991). This more distant emission originates from the Galactic halo, which contains hot gas with temperatures \( T_{\text{halo}} \) \( \sim 6-6.5 \) (Snowden et al. 1998; Kuntz & Snowden 2000; Smith et al. 2007; Galeazzi et al. 2007; Henley et al. 2007). As the halo gas is hotter than the LB gas, it also emits at higher energies, up to \( 1 \) keV. Above \( 1 \) keV the X-ray background is extragalactic in origin, and is due to unresolved active galactic nuclei (AGNs; Mushotzky et al. 2000).

X-ray spectroscopy of the SXRB can, in principle, determine the thermal properties, ionization state, and chemical abundances of the hot gas in the Galaxy. These properties give clues to the origin of the hot gas, which is currently uncertain. However, to determine the physical properties of the hot Galactic gas, one must first decompose the SXRB into its constituents. This is achieved using a technique called “shadowing,” which makes use of the above-mentioned shadows cast in the SXRB by cool clouds of gas between the Earth and the halo. Low-spectral-resolution *ROSAT* observations of the SXRB were decomposed into their foreground and background components by modeling the intensity variation due to the varying absorption column density on and around shadowing clouds (Burrows & Mendenhall 1991; Snowden et al. 1991, 1993, 2000; Kuntz et al. 1997). The same technique was used to decompose *ROSAT* All-Sky Survey data over large areas of the sky (Snowden et al. 1998; Kuntz & Snowden 2000).

With higher resolution spectra, such as those from the CCD cameras on board *XMM-Newton* or *Suzaku*, it is possible to decompose the SXRB into its foreground and background components spectroscopically. This is achieved using one spectrum toward a shadowing cloud, and one toward a pointing to the side of the cloud. The spectral shape of the absorbed background component (and hence of the overall spectrum) will differ between the two directions, because of the different absorbing column densities. Therefore, by fitting a suitable multicomponent model simultaneously to the two spectra, one can separate out the foreground and background emission components. Such a model will typically consist of an unabsorbed single-temperature (1T) thermal plasma model for the LB, an absorbed thermal plasma model for the Galactic halo, and an absorbed power-law for the extragalactic background. The Galactic halo model could be a 1T model, a two-temperature (2T) model, or a differential emission measure (DEM) model (Galeazzi et al. 2007; Henley et al. 2007; S. J. Lei et al., in preparation).

Recent work has shown that there is an additional complication, as X-ray emission can originate within the solar system, via solar wind charge exchange (SWCX; Cox 1998; Cravens 2000). In this process, highly ionized species in the solar wind interact with neutral atoms within the solar system. An electron transfers from a neutral atom into an excited energy level of a solar wind ion, which then decays radiatively, emitting an X-ray photon. The neutral atoms may be in the outer reaches of the Earth’s atmosphere...
(giving rise to geocoronal emission), or they may be in interstellar material flowing through the solar system (giving rise to heliospheric emission). It has been estimated that the heliospheric emission may contribute up to ~50% of the observed soft X-ray flux (Cravens 2000). The geocoronal emission is typically an order of magnitude fainter, but during solar wind enhancements it can be of similar brightness to the heliospheric emission (Wargelin et al. 2004). SWCX line emission has been observed with Chandra, XMM-Newton, and Suzaku (Wargelin et al. 2004; Snowden et al. 2004; Fujimoto et al. 2007). As the SWCX emission is time varying, it cannot easily be modeled out of a spectrum of the SXRB.

If SWCX contamination is not taken into account, analyses of SXRB spectra will yield incorrect results for the LB and halo gas. This paper contains a demonstration of this fact. Henley et al. (2007) analyzed a pair of XMM-Newton spectra of the SXRB using the previously described shadowing technique. One spectrum was from a direction toward a nearby shadowing filament in the southern Galactic hemisphere ($d = 230 \pm 30$ pc; Penprase et al. 1998), while the other was from a direction ~2° away. The filament and the shadow it casts in the 1 keV background are shown in Figure 1. Contemporaneous solar wind data from the Advanced Composition Explorer (ACE) showed that the solar wind was steady during the XMM-Newton observations, without any flares or spikes. The proton flux was slightly lower than average, and the oxygen ion ratios were fairly typical. These observations led Henley et al. (2007) to conclude that their spectra were unlikely to be severely contaminated by SWCX emission. Using a 2T halo model, they obtained a LB temperature of $\log (T_{LB}/K) = 6.06$ and halo temperatures of $\log (T_{halo}/K) = 5.93$ and 6.43. The LB temperature and the hotter halo temperature are in good agreement with other recent measurements of the SXRB using XMM-Newton and Suzaku (Galeazzi et al. 2007; Smith et al. 2007), and with analysis of the ROSAT All-Sky Survey (Kuntz & Snowden 2000).

We have obtained spectra of the SXRB from the same directions as Henley et al.'s (2007) XMM-Newton spectra with the X-Ray Imaging Spectrometer (XIS; Koyama et al. 2007) on board the Suzaku X-ray observatory (Mitsuda et al. 2007). The XIS is an excellent tool for studying the SXRB, due to its low non-X-ray background and good spectral resolution. Our Suzaku pointing directions are shown in Figure 1. We analyze our Suzaku spectra using the same shadowing technique used by Henley et al. (2007). We find that there is poor agreement between the results of our Suzaku analysis and the results of the XMM-Newton analysis in Henley et al. (2007). We attribute this discrepancy to previously unrecognized SWCX contamination in the XMM-Newton spectra, which means that SWCX contamination can occur at times when the solar wind flux measured by ACE is low and does not show flares.

This paper is organized as follows. The Suzaku observations and data reduction are described in § 2. The analysis of the spectra using multicomponent spectral models is described in § 3. The discrepancy between the Suzaku results and the XMM-Newton results is discussed in § 4. This discrepancy is due to the presence of an additional emission component in the XMM-Newton spectra, which we also describe in § 4. In § 5 we measure the total intensities of the oxygen lines in our Suzaku and XMM-Newton spectra. We concentrate on these lines because they are the brightest in our spectra, and are a major component of the 2–3 keV SXRB (McCammon et al. 2002). In § 6 we present a simple model for estimating the intensity of the oxygen lines due to SWCX, which
we compare with our observations. We discuss our results in § 7, and conclude with a summary in § 8. Throughout this paper we quote 1σ errors.

2. OBSERVATIONS AND DATA REDUCTION

Both of our observations were carried out in early 2006 March. The details of the observations are shown in Table 1. In the following, we just analyze data from the back-illuminated XIS1 chip, as it is more sensitive at lower energies than the three front-illuminated chips.

Our data were initially processed at NASA Goddard Space Flight Center (GSFC) using processing version 1.2.2.3. We have carried out further processing and filtering, using HEASoft1 version 6.1.2 and CIAO2 version 3.4. We first combined the data taken in the 3 × 3 and 5 × 5 observation modes. We then selected events with grades 0, 2, 3, 4, and 6, and cleaned the data using the standard data selection criteria given in the Suzaku Data Reduction Guide.3 We excluded the times that Suzaku passed through the South Atlantic Anomaly (SAA), and also times up to 436 s after passage through the SAA. We also excluded times when Suzaku’s line of sight was elevated less than 10° above the Earth’s limb and/or was less than 20° from the bright-Earth terminator. Finally, we excluded times when the cut-off rigidity (COR) was less than 8 GV. This is a stricter criterion than that in the Data Reduction Guide, which recommends excluding times with COR < 6 GV. However, the higher COR threshold helps reduce the particle background, and for observations of the SXRB one desires

![Diagram of X-ray data analysis](image)

**Fig. 2.—** Cleaned and smoothed Suzaku XIS1 images in the 0.3–5 keV band for our on-filament (left) and off-filament (right) observations. The data have been binned up by a factor of 4 in the detector’s x- and y-directions, and then smoothed with a Gaussian whose standard deviation is equal to 1.5 times the binned pixel size. The particle background has not been subtracted from the data. The black circles outline the regions that were excluded from the analysis (see text for details). [See the electronic edition of the Journal for a color version of this figure.]

| Observation       | Observation ID | l (deg) | b (deg) | Start Time (UT) | End Time (UT) | Usable Exposure (ks) |
|-------------------|----------------|---------|---------|-----------------|---------------|----------------------|
| Off filament      | 501001010      | 278.71  | −47.07  | 2006 Mar 1 16:56:01 | 2006 Mar 2 22:29:14 | 55.6               |
| On filament       | 501002010      | 278.65  | −45.30  | 2006 Mar 3 20:52:00 | 2006 Mar 6 08:01:19 | 69.0               |

1 See http://heasarc.gsfc.nasa.gov/lheasoft.
2 See http://cxc.harvard.edu/ciao.
3 See http://suzaku.gsfc.nasa.gov/docs/suzaku/analysis/abc/abc.html.
4 See http://xmmssc-www.star.le.ac.uk/newpages/xcat_public_2xmmp.html.
5 See http://suzaku.gsfc.nasa.gov/docs/suzaku/processing/v1223.html.
amplitude (PHA) values to pulse invariant (PI) values near the Si K edge.\(^6\) We binned up our spectra so that there were at least 25 counts per bin.

We constructed a background spectrum for each observation using tools available from the \textit{Suzaku} Guest Observer Facility at GSFC.\(^7\) These tools generate a background spectrum from night-Earth observations with the same distribution of cut-off rigidities as our observations. The background spectra were subtracted from the corresponding source spectra. Within the energy range that we analyzed, there are instrumental lines in the background spectra at 1.49, 1.74, and 2.12 keV, due to Al, Si, and Au, respectively. We found that these lines were not always accurately subtracted from our source spectra, leading to spurious features in the background-subtracted spectra. We therefore removed these three lines from the background spectra, and interpolated the surrounding background continuum across this gap. In order to model these lines, we included three extra Gaussians in the models we fitted to our spectra.

We generated redistribution matrix files (RMFs) using the tool \texttt{xissimfgen}, and ancillary response files (ARFs) using the tool \texttt{xissimarfgen}\(^8\) (Ishisaki et al. 2007). This latter tool takes into account the spatially varying contamination on the optical blocking filters of the XIS sensors, which reduces the detector efficiency at low energies (Koyama et al. 2007). For the ARF calculation we assumed a uniform source of radius 20'. When generating the spectral response files, we used the set of calibration database (CALDB) files released on 2007 January 31.

3. \textsc{suzaku} Spectral Analysis

3.1. Description of Model

We fit a model to our spectra which consists of components corresponding to the LB, the Galactic halo, and the extragalactic background due to unresolved active galactic nuclei. For the LB we used a single thermal plasma model in collisional ionization equilibrium (CIE), while for the Galactic halo we used two equilibrium thermal plasma components. The use of a two-temperature halo model is well established from analyses of the \textit{ROSAT} All-Sky Survey (Kuntz & Snowden 2000; Snowden et al. 2000), and is required to get a good fit to our data (see §3.2, below). For the extragalactic background we used a power-law whose photon index was frozen at 1.46 (Chen et al. 1997). The LB component was not subject to any absorption, whereas the remaining components were. The temperatures of the thermal emission components and the normalizations of all four emission components were free parameters.

We fit the above-described model simultaneously to our on- and off-filament 0.3–5.5 keV \textit{Suzaku} spectra. Except for the adopted absorbing column densities, all of the model parameters were assumed to be the same for both spectra. The difference in absorbing column helps us to separate out the foreground emission (due to the LB) from the background emission (due to the halo and the extragalactic background). As in Henley et al. (2007) we obtained the absorbing column densities for our observation directions from the \textit{IRAS} 100 \mu m intensities for these directions (7.10 \textit{on} and 1.22 \textit{off} MJy sr\(^{-1}\); Schlegel et al. 1998). These were converted to column densities using the conversion relation in Snowden et al. (2000). The resulting on- and off-filament column densities are 9.6 x 10\(^{20}\) and 1.9 x 10\(^{20}\) cm\(^{-2}\), respectively.

We also include data from the \textit{ROSAT} All-Sky Survey in our fit (Snowden et al. 1997). The R1 and R2 count-rates help constrain the model at lower energies (below ~0.3 keV), while the higher channels overlap in energy with our \textit{Suzaku} spectra. We extracted the \textit{ROSAT} spectra from 0.5" radius circles centered on our two \textit{Suzaku} pointing directions using the HEASARC X-ray Background Tool\(^9\) version 2.3.

The spectral analysis was carried out using \texttt{XSPEC}\(^9\) version 11.3.2 (Arnaud 1996). For the thermal plasma components, we used the Astrophysical Plasma Emission Code (APEC) version 1.3.1 (Smith et al. 2001) for the \textit{Suzaku} data and the \textit{ROSAT} R4–7 bands, and the Raymond-Smith code (Raymond & Smith 1977 and updates) for the \textit{ROSAT} R1–3 bands. For a given model component (i.e., the LB or one of the two halo components), the temperature and normalization of the \textit{ROSAT} Raymond-Smith model are tied to those of the corresponding \textit{Suzaku} APEC model. We chose to use the Raymond-Smith code for the lower energy \textit{ROSAT} channels because APEC’s spectral calculations below 0.25 keV are inaccurate, due to a lack of data on transitions from L-shell ions of Ne, Mg, Al, Si, S, Ar, and Ca.\(^10\) As the upper limit of the \textit{ROSAT} R1 and R2 bands is 0.284 keV, and the R3 band also includes such low-energy photons (Snowden et al. 1997), APEC is not ideal for fitting to these energy bands.

For the absorption, we used the XSPEC phabs model, which uses cross sections from Balucinska-Church & McCammon (1992) with an updated He cross section from Yan et al. (1998). Following Henley et al. (2007), we used the interstellar chemical abundance table from Wilms et al. (2000). For many astrophysically abundant elements, these abundances are lower than those in the widely used solar abundance table of Anders & Grevesse (1989). However, recently several elements’ solar photospheric abundances have been revised downwards (Asplund et al. 2005), and are in good agreement with the Wilms et al. (2000) abundances. Therefore, like Henley et al. (2007) we take the Wilms et al. (2000) interstellar abundances to be synonymous with solar abundances.

As noted in §2, we included three Gaussians to model the \textit{Suzaku} instrumental lines from Al, Si, and Au. The parameters of these lines were independent for the two \textit{Suzaku} observations.

During the course of the spectral modeling, it became apparent that there is a discrepancy in the normalization of the extra-galactic power-law (EPL) between the two \textit{Suzaku} spectra. For a photon index of 1.46, the EPL normalizations for the 2.0–5.5 keV energy range are ~11 (on-filament) and ~8 (off) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) at 1 keV (cf. the expected value is ~10 photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\); e.g., Chen et al. 1997). We therefore allowed the normalization of the EPL to differ for the on- and off-filament spectra; however, the normalizations of the thermal plasma components were still constrained to be equal for the on- and off-filament spectra. We experimented with other methods for dealing with this discrepancy, but none of the results were significantly affected. We discuss this discrepancy further in §7.3.

3.2. Results

Our on- and off-filament \textit{Suzaku} spectra are shown in Figure 3, along with the best-fitting multicomponent spectral model described in the previous section. The model parameters are presented in Table 2 (model 1). Overall, the model gives a good fit to the data: \(\chi^2 = 734.24\) for 703 degrees of freedom. However, the fit to some of the \textit{ROSAT} bands is rather poor, as shown in Figure 4. This could be due to a discrepancy in the effective area.

\(^{6}\) See http://heasarc.gsfc.nasa.gov/docs/suzaku/about/ug2/dotani.pdf.

\(^{7}\) See http://suzaku.gsfc.nasa.gov/docs/suzaku/analysis/xisbgd0.html.

\(^{8}\) See http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xraybg/xraybg.pl.

\(^{9}\) See http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/xspec11.

\(^{10}\) See http://cxc.harvard.edu/atomdb/issues_caveats.html.
calibration between *ROSAT* and *Suzaku*. This discrepancy may be due to the uncertainty in the amount of contaminant on the XIS1 optical blocking filter. For example, if the true amount of contaminant is larger than the amount given by the contamination database (CALDB) contamination model, the calculated effective area will be larger than the true effective area, and the resulting model normalizations will be too small.

We investigated this possibility by adding a `vphabs` absorption component to our model, to model any contamination over and above that already included in the CALDB. This model component attenuated the emission from the LB, halo, and extragalactic background for the *Suzaku* spectra only. We adjusted the model oxygen abundance to give $C/O = 6$ (Koyama et al. 2007), and set the abundances of all other elements to zero. The results of this model are given as model 2 in Table 2. Figures 5 and 6 show this model compared with the *Suzaku* and *ROSAT* spectra, respectively. One can see from Figure 6 that the fit to the *ROSAT* data is greatly improved. The model implies a column density of carbon $N_C = (0.28 \pm 0.04) \times 10^{18}$ cm$^{-2}$, in addition to the amount of contamination given by the CALDB contamination model, which is $N_C = 3.1 \times 10^{18}$ cm$^{-2}$ at the center of the XIS1 chip (from the CALDB file ae_xii_contami_20061016.fits). This correction does not seem unreasonable, given that the systematic uncertainty on the contaminant thickness is $\sim 0.5 \times 10^{18}$ cm$^{-2}$.

We investigated whether or not a LB + two-temperature halo model is justified by fitting a model without a LB component to our data, and by fitting a LB + one-temperature halo model to our data. We also included a power-law to model the extragalactic background. Both these models gave poor fits to the data: $\chi^2 = 1068.63$ and 870.51, respectively, for 704 degrees of freedom (models 3 and 4 in Table 2). In both cases, the large values of $\chi^2$ are mainly due to very poor fits to the *ROSAT* R1 and R2 data.

Because CIE models give good fits to the data, we did not investigate nonequilibrium ionization models. However, it should be noted that there are a number of individual features which are not well fit. In the off-filament spectrum, there is excess emission at $\sim 0.5$ keV. This feature may be too narrow to be an emission line, but if it is it is most likely due to N v $\Pi$ Ly$\alpha$. The Ne $\Pi$ He$\alpha$ emission at $\sim 0.9$ keV is poorly fit in both spectra—in both spectra the observed emission is in excess of the model. Finally, there is excess emission in the on-filament spectrum at $\sim 1.3$ keV, just below the Al K instrumental line at 1.49 keV. This is most likely due to Mg $\rm{\Xi}\Pi$ He$\alpha$. This emission may also be present in the off-filament spectrum, although it does not show up in the residuals. Note that the Gaussian representing the Al K line in the off-filament spectrum is broader and at a lower energy than that in the on-filament spectrum. It is possible that in the off-filament spectrum the data are not good enough to distinguish clearly the Mg $\rm{\Xi}\Pi$ He$\alpha$ line and the instrumental Al K line, and that the Gaussian is in fact fitting to both lines, which would both broaden it and lower its energy.

Table 2 also shows some variants of the above model. In model 5 we fit exactly the same model to the *Suzaku* data alone. Without the *ROSAT* data, we cannot constrain the LB temperature $T_{\rm LB}$. We therefore fix it at the value determined in model 2: $T_{\rm LB} = 10^5$ K. We also fix $N_C$ for the `vphabs` contamination component at the model 2 value: $N_C = 0.28 \times 10^{18}$ cm$^{-2}$. The best-fitting model parameters are in very good agreement with those obtained by fitting jointly to the *Suzaku* and *ROSAT* spectra (compare models 2 and 5). We can only get consistent results between the *Suzaku*-ROSAT joint fit and the fit to just the *Suzaku* data by using a two-temperature model for the halo. However, note that the model 5 LB emission measure is consistent (within its error bar) with zero. This is not to say that our data imply that there is no LB at all: as noted above, we need a LB component and two halo components to get a good joint fit to the *Suzaku* and *ROSAT* data. Instead, the model 5 results imply that our *Suzaku* data are consistent with the LB not producing significant emission in the *Suzaku* band (i.e., $E \gtrsim 0.3$ keV).

Also shown in Table 2 are the results of fitting our model (without any LB component) to the on- and off-filament *Suzaku* spectra individually (models 6 and 7, respectively). As has already been noted, the normalization of the extragalactic background differs significantly between the two spectra. However, the plasma model parameters for the individual spectra are in good agreement with each other. These results seem to justify allowing the extragalactic normalization to differ between the two spectra while keeping all other model parameters equal for the two spectra.

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11 See http://www.astro.isas.ac.jp/suzaku/process/caveats/caveats_xrtxis08.html.
| MODEL | DATA SET(s) | \( T \) \(^{a}\) (K) | E.M. \(^{b}\) \((10^{-3} \text{ cm}^{-6} \text{ pc})\) | \( T \) \(^{a}\) (K) | E.M. \(^{b}\) \((10^{-3} \text{ cm}^{-6} \text{ pc})\) | \( T \) \(^{a}\) (K) | E.M. \(^{b}\) \((10^{-3} \text{ cm}^{-6} \text{ pc})\) | EPL Norm \(^{b}\) | \( N_{C} \) \(^{d}\) \((10^{18} \text{ cm}^{-2})\) | \( \chi^{2} \text{dof} \) |
|-------|------------|-------------------|------------------------|-------------------|------------------------|-------------------|------------------------|----------------|-----------------|----------------|
| 1.…… | S + R      | 5.92 ± 0.02       | 7.2 ± 0.4              | 6.12 ± 0.01       | 24.2 ± 1.8             | 6.50 ± 0.02       | 5.7 ± 0.4              | 11.1 ± 0.3     | 7.6 ± 0.3       | 374.24/703     |
| 2.…… | S + R      | 5.98 ± 0.04       | 6.4 ± 0.3              | 6.11 ± 0.01       | 34.6 ± 2.9             | 6.50 ± 0.05       | 6.5 ± 0.7              | 11.2 ± 0.3     | 7.7 ± 0.3       | 698.44/702     |
| 3.…… | S + R      | ……                | ……                    | 6.04 ± 0.01       | 69.8 ± 2.7             | 6.48 ± 0.02       | 7.6 ± 0.7              | 11.3 ± 0.3     | 7.6 ± 0.3       | 1068.63/704    |
| 4.…… | S + R      | 6.03 ± 0.03       | 8.8 ± 0.3              | ……                | ……                    | 6.35 ± 0.01       | 12.0 ± 0.8             | 11.6 ± 0.3     | 8.6 ± 0.3       | 870.51/704     |
| 5.…… | S         | 5.98 \(^{c}\)     | 1.4 ± 0.4              | 6.09 ± 0.02       | 41.7 ± 0.4             | 6.49 ± 0.02       | 6.8 ± 0.9              | 11.2 ± 0.3     | 7.6 ± 0.3       | 672.79/690     |
| 6.…… | S (on)     | ……                | ……                    | 6.09 ± 0.04       | 41.3 ± 0.04            | 6.52 ± 0.02       | 7.0 ± 0.7              | 10.9 ± 0.3     | ……              | 345.72/374     |
| 7.…… | S (off)    | ……                | ……                    | 6.08 ± 0.03       | 44.2 ± 0.03            | 6.47 ± 0.03       | 6.6 ± 0.8              | ……             | 8.0 ± 0.4       | 317.14/313     |
| 8.…… | S \(^{e}\) | 5.98 \(^{c}\)     | 0.3 ± 0.3              | 6.06 ± 0.01       | 47.8 ± 0.4             | 6.44 ± 0.04       | 7.1 ± 0.9              | 11.0 ± 0.3     | 7.6 ± 0.3       | 655.01/687     |
| 9.…… | X + R \(^{h}\) | 6.06 ± 0.02 | 18 ± 0.6               | 5.93 ± 0.04       | 170 ± 0.04             | 6.43 ± 0.02       | 11 ± 0.5               | 10 ± 0.5       | 10 ± 0.5        | 435.86/439     |
| 10…… | X + R \(^{i}\) | 6.30 ± 0.01 | 12.5 ± 0.8             | 5.73 ± 0.12       | 160 ± 0.01             | 6.56 ± 0.06       | 3.8 ± 0.1              | 11 ± 0.4       | 7.7 ± 0.1       | 442.21/439     |

Note.—Model 2 is our preferred model.

\(^{a}\) Extragalactic power-law normalization at 1 keV in photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\), assuming a photon index of 1.46.

\(^{b}\) Emission measure E.M. = \( \int n_{e}^{2} dl \).

\(^{c}\) S = Suzaku; R = ROSAT; X = XMM-Newton.

\(^{d}\) Carbon column density of the vphabs model used to model XIS contamination above that included in the CALDB (see § 3.2 for details).

\(^{e}\) Value frozen during fitting.

\(^{f}\) 2 \( \sigma \) upper limit.

\(^{g}\) Fit with variable abundances (see § 3.3 and Table 3).

\(^{h}\) From Henley et al. (2007).

\(^{i}\) Data reanalyzed to match method used for Suzaku (see § 4 for details).
3.3. Chemical Abundances in the Halo

We investigated the chemical abundances of the X-ray-emissive halo gas by repeating the above-described modeling, but allowing the abundances of certain elements in the halo components to vary. In particular, we wished to investigate whether or not varying the neon and magnesium halo abundances improved the fits to the Ne$^9$ and Mg$^{11}$ features noted above. We also allowed the abundance of iron to vary, as iron is an important contributor of halo line emission to the Suzaku band.

For this investigation, we just fit to the Suzaku data, fixing the LB temperature at log ($T_{LB}/K$) = 5.98, and fixing the carbon column density of the vphabs contamination component at $N_C = 0.28 \times 10^{20}$ cm$^{-2}$. As we could not accurately determine the level of the continuum due to hydrogen, we could not measure absolute abundances. Instead, we estimated the abundances relative to oxygen by holding the oxygen abundance at its Wilms et al. (2000) value, and allowing the abundances of neon, magnesium, and iron to vary. Both halo components were constrained to have the same abundances.

The best-fitting temperatures and emission measures of the various model components are presented as model 8 in Table 2, and the abundances are presented in Table 3. The best-fitting model parameters are not significantly affected by allowing certain elements’ abundances to vary (compare model 8 with model 5). Iron does not seem to be enhanced or depleted relative to oxygen in the halo. Neon and magnesium both appear to be enhanced in the halo relative to oxygen, which is what one would expect from Figures 3 and 5, as the models shown in those figures under-predict the neon and magnesium emission.

We discuss these results in §7.2 and 7.5. In §7.2 we discuss the possibility that the enhanced neon and magnesium emission is in fact due to SWCX contamination of these lines, rather than being due to these elements being enhanced in the halo. On the other hand, in §7.5 we discuss the implications of neon really being enhanced in the halo with respect to oxygen and iron.

4. COMPARING THE SUZAKU AND XMM-NEWTON SPECTRA

For comparison, Table 2 also contains the results of the analysis of the XMM-Newton spectra from the same observation directions by Henley et al. (2007). The model 9 results are taken directly from their “standard” model. However, it should be noted that Henley et al. (2007) used APEC to model all of their data, whereas in the analysis described above we used the Raymond-Smith code to model the ROSAT R1–R3 bands. We have therefore reanalyzed the XMM-Newton + ROSAT spectra, this time using the Raymond-Smith code to model the ROSAT R1–R3 bands, and using APEC to model the ROSAT R4–R7 bands and the XMM-Newton spectra. This new analysis allows a fairer comparison of our XMM-Newton results with our Suzaku results. The XMM-Newton spectra we analyzed are identical to those used by Henley et al. (2007)—see that paper for details of the data reduction. We added a broken power law to the model to take into account soft-proton contamination in the XMM-Newton spectra.
This broken power law was not folded through XMM-Newton’s effective area, and was allowed to differ for the on- and off-filament data sets (see Henley et al. 2007). The presence of this contamination means we cannot independently constrain the normalization of the extragalactic background. We therefore freeze the on- and off-filament normalizations at the Suzaku-determined values.

The results of this new analysis are presented as model 10 in Table 2. As can be seen, there is poor agreement between the best-fit parameters of the Suzaku + ROSAT model (model 2) and the XMM-Newton + ROSAT model (model 10). We believe this discrepancy is due to an extra emission component in the XMM-Newton spectra. In Figure 7 we plot the differences between the XMM-Newton spectra and our best-fitting Suzaku + ROSAT model (model 2 from Table 2). To our best-fitting Suzaku + ROSAT model we have added a broken power-law to model the soft-proton contamination in the XMM-Newton spectra. The parameters of this broken power law are frozen at the values determined from the fitting to the XMM-Newton spectra described in the previous paragraph. The on-filament XMM-Newton spectra show excess line emission at ~0.57 and ~0.65 keV, most likely due to O vii and O viii, respectively. The features in the off-filament spectra are not as clear. However, there appears to be excess O viii emission in the MOS1 spectrum, and excess emission at ~0.7 keV (of uncertain origin) and ~0.9 keV (probably Ne ix) in the MOS2 spectrum. We can estimate the significance of the excess emission by calculating $\chi^2$ for the XMM-Newton data compared with the Suzaku + ROSAT model. We concentrate on the excess oxygen emission and calculate $\chi^2$ for the 0.5–0.7 keV energy range. We find $\chi^2 = 106.28$ for 24 degrees of freedom for the on-filament spectra, and $\chi^2 = 43.03$ for 22 degrees of freedom for the off-filament spectra. These correspond to $\chi^2$ probabilities of $2.5 \times 10^{-12}$ and 0.0047, respectively, implying that the excesses are significant in both sets of spectra at the 1% level.

We measure the intensities of the extra oxygen emission by fitting $\delta$-functions at $E = 0.570$ keV and 0.654 keV to the excess spectra in Figure 7. We fit these $\delta$-functions simultaneously to the on- and off-filament XMM-Newton excess spectra. The intensities of the excess oxygen emission in the XMM-Newton spectra over the best-fitting Suzaku + ROSAT model are 3.8 ± 0.5 L.U. (O vii) and 1.4 ± 0.3 L.U. (O viii).

We believe that this excess oxygen emission is due to SWCX contamination in our XMM-Newton spectra. As noted in the Introduction, this was not taken into account in the original analysis of the XMM-Newton spectra. This is because the solar wind flux was steady and slightly below average during the XMM-Newton observations, leading Henley et al. (2007) to conclude that SWCX contamination was unlikely to be significant. We discuss the SWCX contamination in our spectra further in § 6.

### 5. MEASURING THE OXYGEN LINES

As well as using the above-described method to separate the LB emission from the halo emission, we measured the total intensities of the O vii complex and O viii line at ~0.57 and ~0.65 keV in each spectrum. These lines are a major component of the SXR B, accounting for the majority of the observed ROSAT R4 diffuse background that is not due to resolved extragalactic discrete sources (McCammon et al. 2002), and are easily the most prominent lines in our Suzaku spectra.

To measure the oxygen line intensities, we used a model consisting of an absorbed power-law, an absorbed APEC model whose oxygen abundance is set to zero, and two $\delta$-functions to model

### TABLE 3

| Element | Abundance |
|---------|-----------|
| O       | 1 (fixed) |
| Ne e    | 1.8 ± 0.4 |
| Mg e    | 4.6 ± 3.5 |
| Fe e    | 1.2 ± 0.4 |

**Note.**—Abundances are relative to the Wilms et al. (2000) interstellar abundances: Ne/O = 0.178, Mg/O = 0.051, Fe/O = 0.055.

* These enhanced abundances may be an artifact of SWCX contamination; see § 7.2.
the oxygen lines. As in the previous section, the power-law models the extragalactic background, and its photon index was frozen at 1.46 (Chen et al. 1997). The APEC model, meanwhile, models the line emission from elements other than oxygen, and the thermal continuum emission. The absorbing columns used were the same as those used in the earlier Suzaku analysis. As with our earlier analysis, we multiplied the whole model by a vphabs component to model the contamination on the optical blocking filter which is in addition to that included in the CALDB contamination model (see § 3.2). We fix the carbon column density of this component at 0.28 × 10^18 cm^-2 (Table 2, model 2). We fit this model simultaneously to our on- and off-filament spectra. However, all the model parameters were independent for the two directions, except for the oxygen line energies—these were free parameters in the fit, but were constrained to be the same in the on- and off-filament spectra. We used essentially the same method to measure the oxygen line intensities in our XMM-Newton spectra. However, we did not use a vphabs contamination model, and, as before, we added a broken power-law to model the soft-proton contamination. Table 4 gives the energies and total observed intensities of the O vii and O viii emission measured from our Suzaku and XMM-Newton spectra.

We can use the difference in the absorbing column for the on- and off-filament directions to decompose the observed line intensities into foreground (LB + SWCX) and background (halo) intensities. If I_{fg} and I_{halo} are the intrinsic foreground and halo line intensities, respectively, then the observed on-filament intensity I_{on} is given by

\[ I_{on} = I_{fg} + e^{-\tau_{on}} I_{halo}, \]

where \( \tau_{on} \) is the on-filament optical depth at the energy of the line. There is a similar expression for the observed off-filament intensity \( I_{off} \), involving the off-filament optical depth \( \tau_{off} \). These expressions can be rearranged to give

\[ I_{fg} = e^{\tau_{on}} I_{on} - e^{\tau_{off}} I_{off}, \]

\[ I_{halo} = \frac{I_{on} - I_{off}}{e^{\tau_{on}} - e^{-\tau_{off}}}. \]

For the purposes of this decomposition, we use the Balucinska-Church & McCammon (1992) cross sections (with an updated He cross section; Yan et al. 1998) with the Wilms et al. (2000) interstellar abundances. We use the cross sections at the measured energies of the lines. For the Suzaku measurements, the cross sections we use are 7.17 × 10^{-22} cm^2 for O vii (\( E = 0.564 \) keV) and 4.66 × 10^{-22} cm^2 for O viii (\( E = 0.658 \) keV). For the XMM-Newton O vii emission we use a cross section of 7.03 × 10^{-22} cm^2 (\( E = 0.568 \) keV). We cannot decompose the XMM-Newton O viii emission because the on-filament O viii line is brighter than the off-filament line. This gives rise to a negative halo intensity, which is unphysical.

The results of this decomposition are presented in Table 5. Note that the foreground oxygen intensities measured from the Suzaku spectra are consistent with zero. This is consistent with our earlier finding that the Suzaku spectra are consistent with there being no local emission in the Suzaku band (see § 3.2). The difference between the foreground O vi intensities measured from our XMM-Newton and Suzaku spectra is 5.1 ± 3.1 L.U.. This is consistent with the O vi intensity measured from the excess XMM-Newton emission over the best-fitting Suzaku + ROSAT model (3.8 ± 0.5 L.U.; see § 4). The halo O vii intensities measured from our XMM-Newton and Suzaku spectra are consistent with each other. This is as expected, as we would not expect the halo intensity to significantly change in ∼4 years.

### 6. Modeling the Solar Wind Charge Exchange Emission

In §§ 4 and 5 we presented evidence that our XMM-Newton spectra contain an extra emission component, in addition to the components needed to explain the Suzaku spectra. In particular, the O vii and O viii emission are enhanced in the XMM-Newton spectra. We attribute this extra component to SWCX emission, as it seems unlikely to be due to a change in the Local Bubble or halo emission. This extra component helps explain why our XMM-Newton and Suzaku analyses give such different results in Table 2.

Previous observations of SWCX have found that increases in the SWCX emission are associated with enhancements in the solar wind, as measured by \( \text{ACE} \). These enhancements consist of an increase in the proton flux, and may also include a shift in the ionization balance to higher ionization stages (Snowden et al. 2004; Fujimoto et al. 2007). In § 6.1 we present a simple model for heliospheric and geocoronal SWCX emission, and use contemporaneous solar wind data from the \( \text{ACE} \) and \( \text{WIND} \) satellites to determine whether or not the observed enhancement of the oxygen lines in the XMM-Newton spectra is due to differences in the solar wind between our two sets of observations.

In addition to the variability associated with solar wind enhancements, the heliospheric SWCX intensity is also expected to vary during the solar cycle, due to the different states of the solar wind at solar maximum and solar minimum (Koutrompa et al. 2006). As our two sets of observations were taken ∼4 years apart, at different points in the solar cycle, in § 6.2 we examine whether the SWCX intensity variation during the solar cycle can explain our observations.

#### 6.1. A Simple Model for Heliospheric and Geocoronal SWCX Emission

##### 6.1.1. The Basics

A SWCX line from a \( X^{+n} \) ion of element X results from a charge exchange interaction between a \( X^{+(n+1)} \) ion in the solar...
wind and a neutral atom. The intensity of that line therefore depends on the density of $X^{+}(n+1)$ ions in the solar wind, $n_{X^{+}(n+1)}$, and on the density of neutral atoms, $n_n$. The line intensity, $I$, can be written as (Cravens 2000; Wargelin et al. 2004)

$$I = \frac{1}{4\pi} \int \sigma y n_n \left( \frac{n_{X^{+}(n+1)}}{n_X} \right) \left( \frac{n_X}{n_{H_1}} \right) n_{sw} u_{sw} \, dl,$$

where $\sigma$ is the cross section for a charge exchange reaction between a $X^{+}(n+1)$ ion and a neutral, $y$ is the yield of the particular line of interest, $n_{X^{+}(n+1)}/n_X$ is the ion fraction of the $X^{+}(n+1)$ ion, $n_{X}/n_{H_1}$ is the abundance of element $X$ in the solar wind, and $u_{sw}$ and $n_{sw}$ are the proton speed and density in the solar wind. For example, we wish to calculate the intensity of the O vii emission at $\sim$0.57 keV, the “line” of interest is the blend of $n = 2 \rightarrow 1$ transitions of O vi ions, and the relevant ion fraction to insert in the integrand in equation (4) is that of O vii ions. As was stated in the Introduction, there are contributions to the SWCX emission from solar wind ions interacting with neutral interstellar H and He atoms distributed throughout the solar system (heliospheric emission), and with neutral H atoms in the outer reaches of the Earth’s atmosphere (geocoronal emission). For the heliospheric emission, one must calculate the contributions due to interactions with H and He separately, and add them. This is because the cross sections and yields for these interactions are different, as are the densities of H and He in the heliosphere.

In the following we estimate the intensities of the O vii and O viii emission due to heliospheric and geocoronal SWCX emission for our XMM-Newton and Suzaku observations. For this purpose, we adopt simple models for the density of the neutral atoms, and use contemporaneous solar wind data from the ACE and WIND satellites to insert in equation (4). To calculate the O vii intensity, we use $\sigma = 3.40 \times 10^{-15}$ and $1.80 \times 10^{-15}$ cm$^2$ for O viii interacting via charge exchange with H and He, respectively (Koutroupa et al. 2006). The yield of O vii Kα emission from interactions between O vii and He is $y = 0.86$, where $y$ is the sum of the contributions of the resonance, intercombination, and forbidden lines (Krasnopolsky et al. 2004). Yield information is not available for O vii interacting with H. However, by definition $y \leq 1$, so we can calculate an upper limit for the expected SWCX emission by setting $y = 1$. To calculate the O viii intensity, we use $\sigma = 5.65 \times 10^{-15}$ and $2.80 \times 10^{-15}$ cm$^2$ for charge exchange interactions of O vii with H and He, respectively (Koutroupa et al. 2006). The yield of the O viii Lyα line due to charge exchange with He is 0.65 (Krasnopolsky et al. 2004). Again, yield information is not available for O viii interacting with H, so we calculate an upper limit on the expected intensity by setting $y = 1$.

### 6.1.2. Solar Wind Data

We use solar wind data from the ACE and WIND satellites, downloaded from the ACE Science Center\footnote{See http://www.srl.caltech.edu/ACE/ASC/level2.} and CDAWeb\footnote{See http://cdaweb.gsfc.nasa.gov.}, respectively. The solar wind data from around the times of our XMM-Newton and Suzaku observations are shown in Figure 8. Note the different ranges on the time axes—this is because the
show that the solar wind was very steady at that time, and that the density or speed column, and so cannot be plotted in Figure 8. As can be seen in Figures 8f–8h, there is a gap in the WIND data set (plotted in black), which is almost exactly coincident with our on-filament Suzaku observation. We use data from the WIND Solar Wind Experiment (SWE) to fill in this gap; these data are plotted in red in Figures 8f–8h. In the WIND data set, good data are denoted by a quality flag of 0. Unfortunately, for the times covered by Figures 8f–8h, the WIND data set contains no good data, and hence should not be used. However, unlike the ACE SWEPAM data, densities and speeds are quoted for bad data points, so the data can still be plotted. As can be seen in Figures 8f–8h, at times when there is both WIND data and ACE data, the two satellites are in good agreement regarding the shape of the solar wind variations. This suggests that the WIND data should give a reasonably trustworthy picture of the solar wind proton flux in the gap in the ACE data. Figure 8 also shows oxygen ion data from the ACE Solar Wind Ion Composition Spectrometer and Solar Wind Ion Mass Spectrometer (SWICS/SWIMS). The data shown are 2 hr averages. Here we only show good data: those with a quality flag of 0.

The ACE data from the time of the XMM-Newton observations show that the solar wind was very steady at that time, and that the proton flux and O\textsuperscript{7+} ion fraction were slightly below their typical values. As already mentioned, these observations led Henley et al. (2007) to conclude that SWCX contamination was likely to be low in the XMM-Newton spectra. However, the results of the previous sections imply that this is not the case, and that SWCX emission makes up most of the foreground oxygen emission in the XMM-Newton spectra.

Around the time of the Suzaku observations, the solar wind was much more variable. In particular, the proton flux rises by a factor of \(~4\) during the last third of the on-filament Suzaku observation. However, we find no increase in the soft X-ray (0.3–2.0 keV) count-rate associated with this increase in the proton flux. Furthermore, the results of our Suzaku spectral fitting do not significantly change if we use an on-filament spectrum that excludes the final third of the observation, instead of a spectrum from the whole of the on-filament observations. These results suggest that there are not changes in the SWCX emission directly associated with the changes in the solar wind during the Suzaku observations.

From the data shown in Figure 8, we obtain values of \(n_{\text{O}^{7+}}/n_{\text{H}}\), \(n_{\text{O}^{7+}}\), and \(u_{\text{sw}}\) to insert into equation (4), in order to estimate the expected O\textsuperscript{vii} intensity due to SWCX during our XMM-Newton and Suzaku observations. These values are shown in Table 6. The ACE data we obtained do not include the O\textsuperscript{8+} ion fraction, which is needed to estimate the expected O\textsuperscript{vii} intensity. Instead, we use the ratio O\textsuperscript{8+}/O\textsuperscript{7+} = 0.35 from Schwadron & Cravens (2000) and our measured O\textsuperscript{7+} ion fractions to estimate the O\textsuperscript{8+} ion fraction. In principle we could also obtain \(n_{\text{O}^{8+}}/n_{\text{H}}\) from ACE. In practice this would be measured from the He/O ratio from SWICS/SWIMS. However, these data exhibit an unexpected 6-month periodicity, meaning that they are unreliable (K. D. Kuntz 2007, private communication). Instead, we use a canonical slow solar wind oxygen abundance of \(n_{\text{O}}/n_{\text{H}} = 5.6 \times 10^{-4}\) (Schwadron & Cravens 2000).

6.1.3. Geocoronal Emission

For the geocoronal emission, we assume that the neutral H density varies with geocentric distance \(r_g\) as \(n_{\text{H}}(r_g) = n_{\text{H}}(10R_E/r_g)^{3}\), where \(n_{\text{H}} = 25 \text{ cm}^{-3}\) is the exospheric neutral H density at 10\(R_E\), where \(R_E\) is the radius of the Earth (Wargelin et al. 2004). We also assume that the solar wind ion density is zero inside the magnetosphere, and constant everywhere outside (Wargelin et al. 2004). With these assumptions, equation (4) yields

\[
I_{\text{O}^{vii}}(\text{geocoronal}) = \frac{1}{4\pi} \alpha \sigma \gamma \eta \rho_{\text{He}}(1 - \rho_{\text{sw}}/\rho_{\text{He}}) \int_{r_{\text{min}}}^{r_{\text{Earth}}} \left(\frac{10R_E}{r_g}\right)^3 dr_g,
\]

where \(\sigma = \gamma(n_{\text{O}^{vii}}/n_{\text{H}})(\rho_{\text{He}}/\rho_{\text{H}})\), \(n_{\text{He}}\) is the solar wind density at 1 AU, and \(r_{\text{min}}\) is the distance from the Earth to the heliopause. For simplicity, we have integrated equation (4) radially away from the Earth, rather than along the line of sight from the satellite. This approximation is likely to have a bigger effect on the XMM-Newton result, as Suzaku is in a low-Earth orbit. In principle, a more accurate intensity could be obtained by integrating equation (4) numerically along the line of sight. However, as the geocoronal emission is an order of magnitude fainter than the heliospheric emission (see below), the approximation used in equation (5) is unlikely to affect our conclusions.

For our observations, the angle between the line of sight and the direction toward the Sun was approximately 80°. From Figure 7 in Wargelin et al. (2004) we estimate that \(r_{\text{min}} \approx 13R_E\) for this viewing angle. Given the other approximations in the model, a more accurate estimate of \(r_{\text{min}}\) is not warranted.

6.1.4. Heliospheric Emission

To estimate the heliospheric contribution to the SWCX emission, one needs to know the density of neutral H and He throughout the heliosphere. Neutral H and He are depleted in the inner solar system, due to photoionization and charge exchange (Cravens 2000). This effect is stronger for H than for He. Although it is possible to construct detailed models of the density distributions of interstellar neutrals in the solar system (e.g., Koutoumpa et al. 2006; see § 6.2 below), for this simple estimate we follow Cravens (2000) and use \(n_{\text{H}}(r_h) = n_{\text{H}}(10R_E/r_h)^{3}\), where \(r_h\) is the heliocentric distance, \(n_{\text{H}}\) is the interstellar density, and \(\lambda\) is the attenuation length. We adopt \(n_{\text{H}} = 0.15 \text{ cm}^{-3}\) and \(\lambda = 5 \text{ AU}\) for H, and \(n_{\text{He}} = 0.015 \text{ cm}^{-3}\) and \(\lambda = 1 \text{ AU}\) for He (Cravens 2000). We also assume that the solar wind is isotropic, so the solar wind density \(n_{\text{sw}}\) varies as \(n_{\text{sw}}(r_h) = n_{\text{sw0}}(r_h/r_0)^{3}\); as before, \(n_{\text{sw0}}\) is the solar wind density at \(r_0 = r_h = 1 \text{ AU}\). We integrate from the Earth to the edge of the heliosphere. As the distance to the heliopause is much larger than \(\lambda\), we can replace the upper limit with infinity. If, for simplicity, we were to integrate radially away from the

\[
I_{\text{H}}(r) = \frac{1}{4\pi} \alpha \beta \gamma \eta (1 - \rho_{\text{H}}/\rho_{\text{He}}) \int_{r_{\text{min}}}^{r_{\text{Earth}}} \left(\frac{10R_E}{r_g}\right)^3 dr_g,
\]

where \(\alpha = \beta \gamma (n_{\text{H}}/n_{\text{He}})(\rho_{\text{He}}/\rho_{\text{H}})\), \(n_{\text{He}}\) is the solar wind density at 1 AU, and \(r_{\text{min}}\) is the distance from the Earth to the heliopause.

### Table 6: Solar Wind Parameters Used in SWCX Model

| Satellite          | \(n_{\text{H}}\)\textsuperscript{-cm\textsuperscript{3}} | \(u_{\text{sw}}\)\textsuperscript{b} (km s\textsuperscript{-1}) | \(n_{\text{O}^{vii}}/n_{\text{H}}\) | \(n_{\text{O}^{vii}}/n_{\text{H}}\)\textsuperscript{d} |
|--------------------|----------------|-----------------|-------------------------------|-------------------------------|
| Suzaku             | 8.3            | 360             | 0.13                          | \(5.6 \times 10^{-4}\)       |
| XMM-Newton         | 4.2            | 420             | 0.15                          | \(5.6 \times 10^{-4}\)       |

\(\textsuperscript{a} \) Solar wind proton density (from ACE and WIND).
\(\textsuperscript{b} \) Solar wind speed (from ACE and WIND).
\(\textsuperscript{c} \) Solar wind O\textsuperscript{7+} ion fraction (from ACE).
\(\textsuperscript{d} \) Solar wind oxygen abundance (from Schwadron & Cravens, 2000).
The results are shown in Table 7.

An alternative approach, developed by Koutroumpa et al. (2006) separately considers the contributions of the slow and fast solar winds to the heliospheric SWCX emission, and how these contributions change with direction and in relation to the solar cycle. They use a more sophisticated, self-consistent model for the distribution of interstellar neutrals within the solar system, taking into account the effects of gravity, radiation pressure, and losses due to charge exchange and photoionization. They also calculate self-consistently the distribution of ions in the solar wind, in which there is no O$^+$ and so no contribution to the O$^+$ emission. In contrast, at solar maximum there are contributions to the heliospheric O$^+$ emission all along the line of sight to the heliopause.

In a follow-up to Koutroumpa et al. (2006), Koutroumpa et al. (2007) calculate heliospheric oxygen intensity for various XMM-Newton and Suzaku observations of the SXRB, including those discussed here. In Table 7 we give the O$^+$ and O$^+$ intensities predicted by their “ground level” model for our observations. These “ground level” values are calculated assuming the solar wind parameters are at their nominal values, without taking into account possible enhancements in the solar wind.

6.3. Comparison with Observations

As well as the SWCX intensities predicted by the models discussed above, Table 7 contains the limits on the amount of SWCX oxygen emission observed by Suzaku and XMM-Newton. The upper limits determined from the Suzaku spectra are the 2σ upper limits on the foreground oxygen intensities presented in Table 5. We cannot make these upper limits any tighter, as we do not know a priori how much of the foreground emission is due to the LB, and how much is due to SWCX. In § 4 we measured the intensities of the oxygen lines in the XMM-Newton spectra above the best-fitting Suzaku + ROSAT model. If we make the reasonable assumption that this excess emission is due to SWCX, the excess oxygen line intensities are lower limits on the SWCX oxygen emission observed by XMM-Newton. They are lower limits because we cannot rule out the possibility that our Suzaku spectra (which we use as a baseline) contain some SWCX emission. We can obtain an upper limit on the SWCX oxygen emission observed by XMM-Newton by adding to this lower limit the upper limit on the amount of SWCX emission in the Suzaku spectra.

There is poor agreement between the predictions of the model discussed in § 6.1 and the observed O$^+$ line intensities. The model overpredicts the O$^+$ intensity observed by Suzaku, and underpredicts that observed by XMM-Newton. As the discrepancies are in opposite senses for the two data sets, they cannot be
reduced by altering input model parameters, such as the cross sections, line yields, or the attenuation lengths \( \lambda \) of neutral H and He in the heliosphere (see § 6.1.4). This is because the same set of parameters is used to model both data sets, so reducing one discrepancy will increase the other.

It is likely the model presented in § 6.1 overpredicts the SWCX O vii intensity for Suzaku because we essentially assume an isotropic slow solar wind when integrating equation (4) to calculate the heliospheric intensity. This is not valid for observations taken at solar minimum (i.e., the Suzaku observations) as much of the line of sight passes through the fast solar wind, which produces less O vii and O viii emission because of the lower O viii and O vii ion fractions (Koutroumpa et al. 2006). However, the Koutroumpa et al. (2006) model does take into account the state of the solar wind at solar minimum, and one can see from Table 7 that it predicts lower heliospheric oxygen intensities for the Suzaku observations than our model (Koutroumpa et al. 2007). The solar minimum oxygen intensities predicted by the Koutroumpa et al. model are consistent with the Suzaku observations.

As our model assumes an isotropic slow solar wind, the predicted intensities should be more applicable to observations taken at solar maximum (i.e., the XMM-Newton observations). The O vii intensity predicted by our SWCX model is consistent with the SWCX O vii intensity observed by XMM-Newton, while the Koutroumpa et al. (2006, 2007) model slightly underpredicts the O vii intensity. However, both models underpredict the SWCX O vii intensity observed by XMM-Newton.

The implications of these results are discussed in the following section.

7. DISCUSSION

7.1. Solar Wind Charge Exchange in the XMM-Newton Spectra—Evidence for a Localized Solar Wind Enhancement

To summarize the preceding sections, we have found evidence that the oxygen line intensities in our XMM-Newton spectra are enhanced with respect to those in our Suzaku spectra. These enhanced intensities are most likely due to SWCX emission. Models for heliospheric SWCX emission imply that at least part of the difference between the XMM-Newton and Suzaku spectra can be explained by a change in the global state of the solar wind between solar maximum and solar minimum (Koutroumpa et al. 2006, 2007). This is because at solar maximum there are more of the high-stage oxygen ions which give rise to heliospheric oxygen emission, leading to brighter heliospheric oxygen lines.

However, the “ground level” (Koutroumpa et al. 2006, 2007) model, which uses typical values for the various relevant solar wind parameters, underpredicts the SWCX oxygen intensities measured with XMM-Newton. This implies there is an additional source of SWCX emission, in addition to that which is generally expected at solar maximum. We suggest that the increased oxygen emission during our XMM-Newton observations was due to a localized enhancement in the solar wind moving across the line of sight. This enhancement could have been a region of increased density, or a region of enhanced oxygen abundance. Koutroumpa et al. (2007) have also suggested that there was an enhancement in the solar wind during the XMM-Newton observations, which they attribute to a coronal mass ejection starting 2.3 days before the start of the XMM-Newton observations.

The “localized solar wind enhancement” scenario we have suggested to explain our observations could have important implications for determining whether or not a SXRB spectrum is likely to be contaminated by SWCX emission. Previous observations of SWCX emission in the SXRB have found that times of increased SWCX emission appear to be associated with enhancements in the solar wind as measured by satellites such as ACE (Snowden et al. 2004; Fujimoto et al. 2007). However, in the scenario suggested above, the solar wind enhancement during the XMM-Newton observations was away from the Earth, and so not detectable by ACE. As a result, the ACE data from around the time of the XMM-Newton observations show no unusual features (Fig. 8), which led Henley et al. (2007) to conclude that SWCX was unlikely to be significantly contaminating their spectra. Indeed, if contemporaneous solar wind data are used as an indicator of SWCX contamination, Figure 8 suggests at first glance that the SWCX emission would be higher during the Suzaku observations than during the XMM-Newton observations, which is the exact opposite of what we observe. Our results therefore imply that simply inspecting contemporaneous solar wind data from ACE or other satellites might not be sufficient for determining whether or not a SXRB spectrum is contaminated by SWCX emission.

7.2. Solar Wind Charge Exchange in the Suzaku Spectra?

Our analysis suggests that while the XMM-Newton spectra are badly contaminated by SWCX emission, particularly in the oxygen lines, the oxygen lines in the Suzaku spectra are not badly contaminated. Other existing XMM-Newton and Suzaku observations yield oxygen line intensities due to SWCX of \( \sim 5\)–7 L.U. for O viii and O vii (Snowden et al. 2004; Fujimoto et al. 2007). The upper limits on the SWCX oxygen emission in our Suzaku spectra are much less than these values (see Table 7).

However, although the oxygen lines are apparently uncontaminated in our Suzaku spectra, there do appear to be other lines in the spectra which may be due to SWCX (see Fig. 3). The off-filament Suzaku spectrum shows excess emission at \( \sim 0.5 \) keV. For the six adjacent channels which make up this feature, \( \chi^2 = 14.6 \) when compared with our preferred model (model 2 in Table 2). For 6 degrees of freedom, this corresponds to a \( \chi^2 \) probability of 0.024, implying the feature is significant at the 5% level. As noted in § 3.2, this feature may be too narrow to be an emission line. However, if it is an emission line, it could be N vii Ly\( \alpha \) produced by SWCX. The line is unlikely to be due to scattering of solar X-rays off atmospheric nitrogen, as the line remains in the spectrum even if we exclude times when the elevation of the line of sight above the Earth’s limb is less than 20° or 25°, instead of the default 10° used in § 2.

The Ne ix feature at \( \sim 0.9 \) keV also exhibits excess emission over the best-fitting model—in this case the excess emission is seen in both Suzaku spectra. This excess emission could be due to an overabundance of neon in the halo (see Table 3). An alternative explanation is that the excess Ne ix emission is due to SWCX.

There is also excess emission in the on-filament Suzaku spectrum at \( \sim 1.3 \) keV, which is probably from Mg xi. By fitting a Gaussian to this feature, we have measured its intensity to be 0.10 ± 0.07 L.U., which implies it is only a marginal detection. As mentioned in § 3.2, Mg xi emission may also be present in the off-filament Suzaku spectrum, where it causes the Gaussian that is modeling the Al K instrumental line to shift to a lower energy and increase in width. The Mg xi emission could originate from the halo if the magnesium abundance is enhanced by a factor of \( \sim 4 \) relative to oxygen (see Table 3). However, as with neon, an alternative explanation is that the Mg xi emission is due to SWCX. SWCX emission from Mg xi has been observed in other XMM-Newton and Suzaku spectra of the SXRB. Snowden et al. (2004) found Mg xi emission due to SWCX among a set of XMM-Newton spectra of the Hubble Deep Field North, with an
intensity of 0.40 ± 0.08 L.U., while Fujimoto et al. (2007) measured a Mg xi SWCX intensity of 0.73 ± 0.16 L.U. from a Suzaku spectrum of the North Ecliptic Pole. These other results imply that the Mg xi feature in our on-filament Suzaku spectrum is not unusually bright for SWCX emission.

The observation of SWCX emission from Mg xi requires the presence of H-like Mg$^{11+}$ ions in the solar wind. Mg$^{11+}$ is the dominant ionization stage of magnesium in the temperature range ~7–9 × 10^6 K (Mazzotta et al. 1998). As the solar wind ions that give rise to SWCX originate in the solar corona, and are frozen into the plasma as it expands away from the Sun (Cravens 2002), the observation of SWCX emission from Mg xi may imply very high temperatures in the solar corona. However, more detailed modeling is needed to determine if the observed Mg xi SWCX intensities imply an unusually high Mg$^{11+}$ ion fraction in the solar wind. Such modeling of the Mg xi and other SWCX lines is beyond the scope of this paper. Nevertheless, the presence of these lines in our Suzaku spectra raises an interesting question: if there is SWCX emission from Mg xi, and possibly Ne ix and N viii, why is there not significant SWCX emission from O vii and O viii?

7.3. The Normalization of the Extragalactic X-Ray Background

As was noted in § 3.1, and as can be seen in Table 2, the normalization of the extragalactic background is different in our two Suzaku spectra, with the off-filament value (7.7 ± 0.3 photons cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at 1 keV) lower than the expected value of ~10 photons cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ (e.g., Chen et al. 1997). One possible reason for this is incorrect subtraction of the particle background: if the particle background spectrum used for our off-filament observation is too bright, this would result in our background-subtracted SXRB spectrum being fainter than expected. However, we do not think this is likely to be the cause. At high energies we do not expect any cosmic X-ray emission, and so any counts in our Suzaku spectra at these energies will be due to the particle background. For each observation, the 10–12 keV count-rates in the non-background-subtracted source spectrum and in the particle background spectrum (generated from night-Earth data) agree within 8%. In contrast to this, the particle background flux would have to be reduced by ~30% in order to increase the off-filament extragalactic normalization to 10.5 photons cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$. It therefore does not seem likely that an incorrect particle background normalization is the reason for this discrepancy in the on- and off-filament extragalactic normalizations.

As well as allowing the extragalactic normalization to differ between our two Suzaku spectra, while keeping everything else the same, we also tried two other methods for dealing with this discrepancy. First, we simply ignored the discrepancy, and forced the model to be identical for both the on- and off-filament data sets. Second, we tried multiplying our entire model (Local Bubble + halo + EPL) by a variable factor $f_{off}$ when fitting it to our off-filament Suzaku spectrum; this multiplicative factor was an additional free parameter in the fit. The second method essentially assumes that the discrepancy is due to an increase of ~20% in Suzaku’s sensitivity between the on- and off-filament observations. We do not think this is plausible, but we still tried out this model.

We found that these two new methods gave temperatures in good agreement with each other and with those in Table 2, although the emission measures of the Local Bubble and of the cool halo component varied by up to ~15% and ~25% between the models, respectively. Of the three methods we tried, our original method (i.e., that presented in Table 2) gave the best fits to the data. Also, when we fitted our multicomponent model to our on- and off-filament spectra individually, we found that the plasma model components are in good agreement with each other (Table 2, models 6 and 7). As was noted in § 3.2, this seems to support our method for handling the discrepancy in the extragalactic normalization.

In summary, we do not know why the extragalactic normalization differs between our two spectra. It seems unlikely to be due to incorrect particle-background subtraction, or to a ~20% increase in Suzaku’s sensitivity in the space of a few days. We have tried several different methods for handling this discrepancy, and the results they give are generally in good agreement with each other. We therefore conclude that, despite the discrepancy with the extragalactic normalization, the plasma model parameters we have obtained should be reasonably robust.

7.4. The Local Bubble

Because of the SWCX contamination of the oxygen lines in the XMM-Newton spectra, and the apparent lack of such contamination in the Suzaku spectra, the best-fitting model of the LB we have derived from our Suzaku spectra is quite different from that in Henley et al. (2007). In that project, all the foreground oxygen emission in the XMM-Newton spectra was thought to be from the LB, leading to a higher LB temperature than we have obtained from our Suzaku + ROSAT analysis: log ($T_{LB}/K$) = 6.06, instead of log ($T_{LB}/K$) = 5.98. The lower foreground oxygen intensities in the Suzaku spectra cannot be explained by simply lowering the LB emission measure, as the ROSAT R12 data place a constraint on the LB emission measure.

Note that our LB emission measure (0.0064 ± 0.0003; Table 2) is roughly one-third of the value determined by Henley et al. (2007). However, this is merely because we used different plasma emission codes to model the ROSAT R12 data. We used the Raymond-Smith code to model the R12 data, whereas Henley et al. (2007) used APEC. For temperatures around 10^6 K, the Raymond-Smith code predicts ~3 times as much 1/4-keV flux as APEC. This means that for a given observed flux the Raymond-Smith-derived emission measure will be ~3 times smaller than the APEC-derived value, which is exactly what we find. Our LB emission measure is in reasonable agreement with the range of LB emission measures determined from the ROSAT All-Sky Survey 1/4-keV data (0.0018 – 0.0058 cm$^{-6}$pc; Snowden et al. 1998), which was also modeled using the Raymond-Smith code.

The LB temperature that we measure (log ($T_{LB}/K$) = 5.98+0.03; Table 2) is lower than the temperatures obtained from other recent shadowing observations made with XMM-Newton and Suzaku: log ($T_{LB}/K$) = 6.04–6.06 (Galeazzi et al. 2007, using MBM 20 as a shadow) and ≥6.08 (Smith et al. 2007, using MBM 12). The range of values from Galeazzi et al. (2007) are from their results for different abundance tables (Anders & Ebihara 1982; Anders & Grevesse 1989; Grevesse & Sauval 1998; Lodders 2003). Their derived LB temperature is fairly insensitive to the set of abundances that they used. If we repeat our spectral analysis using Anders & Grevesse (1989) abundances, we obtain log ($T_{LB}/K$) = 6.07 ± 0.05, which is consistent with the Galeazzi et al. (2007) and Smith et al. (2007) temperatures. However, when we use the other abundances tables used by Galeazzi et al. (2007) we obtain LB temperatures of log ($T_{LB}/K$) = 5.98+0.05;0.04 (Anders & Ebihara 1982), 5.97 ± 0.04 (Grevesse & Sauval 1998), and 5.96 ± 0.04 (Lodders 2003). These values are closer to our original LB temperature, obtained using Wilms et al. (2000) abundances (which were not used by Galeazzi et al. 2007). Hence, while the LB temperature we obtain using Anders & Grevesse (1989) abundances is in good agreement with that of Galeazzi et al. (2007) the temperatures obtained using other abundance tables (Anders &
Ebihara 1982; Grevesse & Sauval 1998; Lodders 2003) are systematically lower than those of Galeazzi et al. (2007). These results imply that the LB may not be isothermal.

If we were to assume that the LB is isothermal, it would make it more difficult to explain the lower foreground O vii intensity measured from our Suzaku spectra: $1.1^{+1.1}_{-0.7}$ L.U. (see Table 5), compared with $2.63 \pm 0.78$ L.U. (Galeazzi et al. 2007) and $3.53 \pm 0.26$ L.U. (Smith et al. 2007). In an isothermal LB, a larger X-ray intensity in a given direction can be explained by the LB being of greater extent in that direction. Analysis of the ROSAT All-Sky Survey suggests that the LB radius toward the filament is similar to that toward MBM 20, and the LB radius toward MBM 12 is roughly two-thirds of this value (Snowden et al. 1998, their Fig. 10). This means that the different observed O vii intensities cannot be explained by the LB being of different extent in different directions. However, if the LB temperature is higher toward MBM 20 and MBM 12, this would give rise to brighter O vii emission in these directions.

If we assume the radius of the LB is 100 pc in the direction we have analyzed, our emission measure gives an electron density of 0.0080 cm$^{-3}$. Combining this with our LB temperature gives a LB thermal pressure of $p_{\text{LB}}/k = 1.92 n_{\text{e}} T_{\text{LB}} = 14,700$ cm$^{-3}$ K (13,100–16,100 cm$^{-3}$ K). Galeazzi et al. (2007) obtained $p_{\text{LB}}/k = 16,200–19,500$ cm$^{-3}$ K, while Smith et al. (2007) obtained $p_{\text{LB}}/k = 22,000$ cm$^{-3}$ K (assuming $\log [T_{\text{LB}}/K] = 6.08$). These results suggest that the LB might not be in pressure equilibrium. Alternatively, they may indicate that the spectra analyzed by Galeazzi et al. (2007) and Smith et al. (2007) are contaminated by SWCX emission.

7.5. The Halo

As we found in § 3.3, a possible explanation for the excess Ne xix emission visible at $\sim 0.9$ keV in Figures 3 and 5 is that neon is enhanced in the halo, relative to oxygen and iron. (The alternative is that this emission is due to SWCX, as mentioned in § 7.2.) If neon is really enhanced relative to oxygen and iron in the halo (or, equivalently, if oxygen and iron are depleted relative to neon), this may be evidence that some of the oxygen and iron in the halo is in dust, rather than in the hot gas. Neon, being chemically inert, does not condense into dust.

Our best-fitting halo model predicts $\sim 300$ L.U. for the intrinsic O vi $\lambda\lambda 1032, 1038$ doublet intensity (using data from ATOMDB). Note that this value is much smaller than that in Henley et al. (2007). This is because their cooler halo component was cooler than ours, and had a larger emission measure (compare models 2 and 9 in Table 2). Our model O vi intensity is $\sim 20$ times smaller than the intrinsic halo O vi intensity determined by Shelton et al. (2007) from an off-filament Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum. This implies that there is both hot, X-ray-emitting gas and warm, ultraviolet-emitting gas in the Galactic halo. Shelton et al. (2007) present a model for the distribution of warm and hot gas in the halo, using O vi and ROSAT data as constraints. Further modeling of the hot gas distribution in the halo, using the Suzaku data discussed here, will be presented elsewhere (S. J. Lei et al., in preparation).

8. SUMMARY AND CONCLUSIONS

We have analyzed a pair of Suzaku spectra of the SRXB, obtained from pointings toward and to the side of a nearby absorbing filament in the southern Galactic hemisphere. We used a shadowing technique to decompose the spectra into their various thermal emission components, due to the LB and the Galactic halo, using ROSAT $\frac{3}{2}$ keV data to help constrain the model at lower energies. We find that our best-fitting model parameters (temperatures and emission measures) do not agree with those determined by Henley et al. (2007) from a pair of XMM-Newton observations in the same directions as our Suzaku observations. We attribute this discrepancy to SWCX contamination in the XMM-Newton spectra, particularly in the oxygen lines, which was not taken into account in the original analysis.

Our results suggest that inspecting contemporaneous solar wind data might not be sufficient for determining if a SRXB spectrum is contaminated by SWCX emission. We have reached this conclusion by comparing our observations with models for SWCX emission. The simple model of heliospheric and geocoronal SWCX emission that we have presented, which assumes an isotropic solar wind and uses contemporaneous solar wind data from ACE and WIND, cannot explain the different amounts of SWCX oxygen emission observed by XMM-Newton and Suzaku. The more sophisticated heliospheric emission model of Koutroumpa et al. (2006); Koutroumpa et al. (2007) which takes into account the change in the global state of the solar wind between solar maximum, can partly explain why more SWCX emission is observed by XMM-Newton than by Suzaku. However, this model underpredicts the amount of oxygen emission observed by XMM-Newton at solar maximum. Instead, the excess SWCX emission in the XMM-Newton spectra may have been due to a localized enhancement in the solar wind moving across the line of sight during the XMM-Newton observations. If this enhancement was not near the Earth, it would not have shown up in the solar wind data from ACE and WIND.

While it appears that the oxygen lines in our Suzaku spectra are not badly contaminated by SWCX emission, we cannot be certain of the true level of SWCX emission in our spectra. Indeed, it is possible that there is SWCX emission from nitrogen, neon, and magnesium in our Suzaku spectra. However, if in general the level of SWCX contamination is low in our Suzaku spectra, as we think is the case, then our best-fitting models of the LB and halo should be more accurate than those obtained by Henley et al. (2007). Our best-fitting LB temperature is lower than the temperatures obtained from other recent XMM-Newton and Suzaku observations (Galeazzi et al. 2007; Smith et al. 2007), suggesting that the LB is not isothermal. Our LB model also yields a lower pressure than these other LB models, implying that the LB may not be in pressure equilibrium. Our modeling of the halo emission, meanwhile, suggests that oxygen and iron may be depleted relative to neon, possibly because they are partly in a dust phase.

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