HOT GAS IN THE GALACTIC THICK DISK AND HALO NEAR THE DRACO CLOUD

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ABSTRACT

This paper examines the ultraviolet and X-ray photons generated by hot gas in the Galactic thick disk or halo in the Draco region of the northern hemisphere. Our analysis uses the intensities from four ions, C iv, O vi, O vii, and O viii, sampling temperatures of \( \sim 10^5 \) to \( \sim 3 \times 10^6 \) K. We measured the O vi, O vii, and O viii intensities from FUSE and XMM-Newton data and subtracted off the local contributions in order to deduce the thick disk/halo contributions. These were supplemented with published C iv intensity and O vi column density measurements. Our estimate of the thermal pressure in the O vi-rich thick disk/halo gas, \( p_k/k = 6500 \pm 250 \text{ K cm}^{-3} \), suggests that the thick disk/halo is more highly pressurized than would be expected from theoretical analyses. The ratios of C iv to O vi to O vii to O viii intensities were compared with those predicted by theoretical models. Gas which was heated to \( 3 \times 10^6 \) K then allowed to cool radiatively cannot produce enough C iv or O vi-generated photons per O vi or O vii-generated photon. Producing enough C iv and O vi emission requires heating additional gas to \( 10^5 K < T < 10^6 K \). However, shock heating, which provides heating across this temperature range, overproduces O vi relative to the others. Obtaining the observed mix may require a combination of several processes, including some amount of shock heating, heat conduction, and mixing, as well as radiative cooling of very hot gas.

Key words: Galaxy: general – Galaxy: halo – ISM: general – ISM: individual objects (Draco) – ultraviolet: ISM – X-rays: diffuse background

1 INTRODUCTION

Observations of C iv, O vi, O vii, and O viii show that hot gas extends a few kiloparsecs above the plane (e.g., Savage & Wakker 2009; Yao et al. 2009) into a region historically called the halo and more recently called the thick disk. This is an active and dynamically important region of the Galaxy. On-going star formation has been seen in the thick disks of other spiral galaxies (Reuff & Howk 2010), implying that these thick disks continue to experience the winds and supernova (SN) explosions that result from young stars. In addition, thick disks churn as outflows from the thin disk, long postulated theoretically (Shapiro & Field 1976) and more recently seen in numerical simulations having normal SN rates (Joung & Mac Low 2006; de Avillez & Breitschwerdt 2007), make their way into the thick disk. Estimates based on the observed C iv, O vi, 1/4 keV, and 3/4 keV intensities at high southern latitudes indicate a large radiative loss rate; the region above the thin disk is so luminous that it radiates 2/3 of the Galaxy’s SN power (Shelton et al. 2007). Since most of the Galaxy’s SN energy is injected nearer to the midplane, a large luminosity produced above the thin disk suggests the sort of churning seen in simulations. Not only is the thick disk affected by in situ heating and upwellings from the thin disk beneath it, but it is also affected by inflows from above, as in the case of high velocity clouds (HVCs) colliding with the Galaxy (tripp et al. 2003), or if we consider the more extended halo, in the form of accretion from the intergalactic medium (e.g., Rasmussen et al. 2009).

Most of the volume within a few kiloparsecs of the midplane is filled with very hot gas having temperatures in excess of \( 10^6 \) K (see path length estimates in Shelton et al. 2007 or scale height estimates in Yao & Wang 2007). This gas is traced by O vii ions and O viii ions having collisional ionization equilibrium (CIE) temperatures, \( T_{\text{CIE}} \), of \( \sim 1 \times 10^6 \) K and \( \sim 3 \times 10^6 \) K, respectively. Somewhat cooler, but still hot, gas is traced by C iv ions (\( T_{\text{CIE}} \sim 1 \times 10^5 \) K) and O vi ions (\( T_{\text{CIE}} \sim 3 \times 10^5 \) K). It fills a lesser fraction of the space (see path lengths in Shelton et al. 2007) but accounts for more radiative energy loss than does the hotter gas. Because gas in this temperature regime cools rapidly, it must be replenished from a nearby reservoir of hotter gas. For this reason, a common convention of the hot interstellar medium (ISM) is one in which (1–3) \( \times 10^5 \) K gas resides in transition zones between hotter and cooler gas. Some authors (e.g., Savage & Wakker 2009) have begun to call the (1–3) \( \times 10^5 \) K material “transition temperature” gas. Here, for simplicity, however, we use the term “hot gas” for the entire \( \sim 1 \times 10^5 \) to \( \sim 3 \times 10^6 \) K regime.

The tracers of hot gas are observed by UV and X-ray instruments. Ultraviolet instruments are used to observe the strong resonance line transitions (\( 2S_{1/2} - 2P_{3/2} \) and \( 2S_{1/2} - 2P_{1/2} \)) of C iv and O vi. Owing to the excellent spectral resolution of recent UV instruments, interstellar C iv and O vi have been studied well via absorption line spectroscopy (Savage et al. 2003; Bowen et al. 2008; Savage & Wakker 2009). They have also been seen via emission spectroscopy, but along fewer sight lines (e.g., Shelton et al. 2001; Dixon & Sankrit 2008; Park et al. 2009). In contrast, X-ray instruments are used to observe Kα transitions of O vii and O viii. Due to the limited spectral resolution and/or throughput of current X-ray instruments, it is far easier to detect photons produced by interstellar O vii and O viiii ions than to identify O vii and O viii absorption profiles in the spectra of distant X-ray point sources. While some absorption column densities have been measured (e.g., Yao & Wang 2007; Bregman & Lloyd-Davies 2007), most of the O vii and O viii measurements are of emitted photons (e.g., Henley & Shelton 2010).

Column density and emission intensity measurements plumb different aspects of the interstellar gas. The column density depends only on the path length and the density of pertinent ions in the gas. The emission intensity, however, depends on two additional factors, the electron density and the emissivity, which is a function of temperature. Thus, high ions that are much...
Ultraviolet Spectroscopic Explorer with new measurements of the O iv absorption measurements are photoionized (Savage & Wakker 2009).

Here, we focus on the emission intensities from C iv, O vi, O vii, and O viii from a single region of the sky, ($\ell = 90^\circ$, $b \sim 40^\circ$), a region near, but not toward, the Draco molecular cloud complex (MBM 41 through 44; Magnani et al. 1985). This paper is organized as follows. In Section 2, we assemble measurements of C iv, O vi, O vii, and O viii. The C iv intensity measurements presented in Section 2.1 come from published observations made by FIMS/SPEAR. We complement these with new measurements of the O vi intensity, made from FUSE data (Section 2.2).

In Section 2.3, we deduce the extraplanar O vi column density in the Draco region from existing FUSE measurements. In Section 2.4, we present our O vii and O viii measurements, made from archival XMM-Newton observations of a direction 1° from our FUSE and FIMS/SPEAR direction. For each ion, we take care to remove the local contributions (from the Local Bubble and/or heliosphere) and compensate for interstellar absorption. The results are the second known foursome of intrinsic C iv, O vi, O vii, and O viii intensities for the region of the thick disk/halo that is above the thin disk and toward a single part of the sky, and the first such foursome for the northern Galactic hemisphere.

In Section 3, we use the O vi emission intensity and absorption column density to determine the density and pressure of the O vi-rich gas in the thick disk/halo above the thin disk. We then use the ratios of our C iv, O vi, O vii, and O viii intensities to test phenomenological models. These include a radiative cooling model, such as would be expected for accretion of intergalactic gas onto the galaxy, a point-injection model, such as would be expected for SN explosions, and a turbulent mixing model. We find that radiative cooling of very hot gas is not able to produce enough C iv and O vi photons per O vii or O viii photon. Bubbles formed from point injections of $5 \times 10^{50}$ erg have the opposite problem. Models of turbulent mixing between very hot gas and cooler gas do not provide O vii or O viii predictions, but can explain high ratios of C iv to O vi emission. We also present the ratio of C iv, O vi, O vii, and O viii intensities, so that they may be compared with other model predictions as they become available. In Section 4, we summarize our results, concluding that energy must have been injected into the halo in a way that heated some of the gas to $\sim 3 \times 10^6$ K while heating other gas to $(1-3) \times 10^5$ K.

2. DATA

2.1. The Halo C iv Intensity

As part of a survey program, the Draco region was observed by FIMS/SPEAR (Edelstein et al. 2006), which is sensitive to C iv resonance line doublet photons ($\lambda = 1548, 1551$ Å), between February and May of 2004. Park et al. (2009) presented measurements of the doublet’s intensity as a function of location within the Draco neighborhood in the form of a smoothed, pixelated map. The direction of interest, $\ell = 90^\circ$, $b = 39^\circ$, is located near the intersection of four O vi wide pixels in their map. For these four pixels, the average intensity is $\sim 5500$ in units of $\text{ph s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$, hereafter line units (LU), and the range of intensities is 700 LU. Because Park et al. (2009) reported a signal-to-noise ratio of $\geq 3.0$ for intensities over 5000 LU, we take $1\sigma$ to be 1/3 of the measured intensity and adopt $I = 5500 \pm 1830$ LU as the observed intensity in the doublet. This and later measurements are tabulated in Table 1. This value is very near to the average intensity reported by Park et al. (2009) for all off-cloud regions within their map: 5559 $\pm$ 1008 LU.

No observations of foreground C iv emission have been reported in the literature and little emission is expected from the Local Bubble or heliosphere. Therefore, we assume that the C iv-rich gas resides above the Local Bubble, and also above the Galaxy’s H i and/or dust-rich layer. The photons emitted in this region would be subject to extinction by intervening gas. The degree of obscuration determined from the H i column density from the Leiden–Argentine–Bonn (LAB) survey of neutral hydrogen (Kalberla et al. 2005) is roughly similar to that determined from the DIRBE-corrected IRAS data (Schlegel et al. 1998). The LAB survey found a column density of $N_{H i} = 1.52 \times 10^{20}$ cm$^{-2}$, which implies a loss of 20% of the intensity, based on the color excess to H i column density relation empirically determined by Diplas & Savage (1994) and the extinction relation calculated by Fitzpatrick (1999). The DIRBE-corrected IRAS 100 $\mu$m intensity is $I_{100} = 0.71$ MJy sr$^{-1}$, which implies a loss of 11%, based on the $I_{100}$ to color excess conversion used by Schlegel et al. (1998) and the extinction relation calculated by Fitzpatrick (1999). Thus, if all of the obscuring material lies between the source of the photons and the Earth, then the halo’s intrinsic intensity would be $6200 \pm 2070$ to $6880 \pm 2290$ LU, assuming the 11% and 20% loss rate, respectively. Here, we take the halo’s intrinsic C iv doublet intensity to be the average: 6540 $\pm$ 2180 LU. Note that throughout the paper, the unrounded measurement values are used in the calculations, but the rounded results are reported.

2.2. The Halo O vi Intensity

2.2.1. FUSE Observations and Data Reduction

We obtained two FUSE observations for this project. The first, observation ID E12401, was directed toward the Draco cloud, $\ell = 89^\circ$, $b = 38^\circ$.5. Beginning on 2005 November 30, six exposures were taken for a total of 5144 s. The FUSE spacecraft failed before the remainder of the observation could be completed. The second observation, observation ID E12402, was directed toward an unobscured region near the Draco cloud, $\ell = 90^\circ$, $b = 39^\circ$. Several exposures began on 2006 November 15 and the remainder began on 2007 March 14. The total exposure time was 79,912 s, of which 31,316 s were taken at night. The original intent of this program was to perform a cloud shadowing study. However, the on-cloud observation was too short to yield clear detections (see Section 2.2.2). Here, we focus on the off-cloud observation.

\begin{table}
\centering
\caption{Observed and Extraplanar Intensities of C iv, O vi, O vii, and O viii}
\begin{tabular}{|c|c|c|c|}
\hline
Ion  & $\ell$, $b$  & Observed Intensity & Intrinsic Extraplanar Intensity \\
     & (deg)        & ($\text{ph s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$) & ($\text{ph s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$) \\
\hline
C iv & 90/0, 39/6   & 5500 $\pm$ 1830 & 6540 $\pm$ 2180 \\
O vi & 90/0, 39/6   & 3500 $\pm$ 940  & 4770 $^{+1300}_{-1200}$ \\
O vii|O vii & 90/0, 38/4   & 6.8$^{+0.9}_{-0.6}$ & 6.4$^{+1.4}_{-1.5}$ \\
O viii| & 90/0, 38/4   & 1.0$^{+0.4}_{-0.3}$ & 1.0 $\pm$ 1.2 \\
\hline
\end{tabular}
\end{table}

Notes. The extraplanar O vi column density in this region is $N_{O vi} = (1.9 \pm 0.5) \times 10^{14}$ cm$^{-2}$. The C iv and O vi intensities are for the doublets.

The degree of obscuration determined from the H i column density from the Leiden–Argentine–Bonn (LAB) survey of neutral hydrogen (Kalberla et al. 2005) is roughly similar to that determined from the DIRBE-corrected IRAS data (Schlegel et al. 1998). The LAB survey found a column density of $N_{H i} = 1.52 \times 10^{20}$ cm$^{-2}$, which implies a loss of 20% of the intensity, based on the color excess to H i column density relation empirically determined by Diplas & Savage (1994) and the extinction relation calculated by Fitzpatrick (1999). The DIRBE-corrected IRAS 100 $\mu$m intensity is $I_{100} = 0.71$ MJy sr$^{-1}$, which implies a loss of 11%, based on the $I_{100}$ to color excess conversion used by Schlegel et al. (1998) and the extinction relation calculated by Fitzpatrick (1999). Thus, if all of the obscuring material lies between the source of the photons and the Earth, then the halo’s intrinsic intensity would be $6200 \pm 2070$ to $6880 \pm 2290$ LU, assuming the 11% and 20% loss rate, respectively. Here, we take the halo’s intrinsic C iv doublet intensity to be the average: 6540 $\pm$ 2180 LU. Note that throughout the paper, the unrounded measurement values are used in the calculations, but the rounded results are reported.
We examined the data taken through the largest aperture of the LiF1A channel, as this yields spectra with the greatest signal-to-noise ratio. Like other observations of diffuse emission, the data were taken in time-tag mode. Photon lists for each exposure were processed with version 3.2 of the CalFUSE pipeline. We used the extended source extraction window option, disabled the background subtraction feature, and set the pulse height limits to 2 and 25 for this processing.

Earlier analyses found that the wavelength scale must be re-calibrated by comparisons with emission lines of known wavelengths (Shelton et al. 2001). Because each exposure may have a different offset, the exposures were processed by CalFUSE and re-calibrated before being added. The wavelength offsets were found by aligning the observed Lyman β airglow feature in the LiF1A spectra with the theoretical Lyman β wavelength at zero velocity in the geocentric reference frame. After being corrected in this manner, the wavelength scale for each spectrum was converted to the heliospheric reference frame and the spectra added together.

2.2.2. O vi Intensity Measurements

Figure 1 shows the LiF1A spectrum in the 1027–1040 Å region. The O vi 1032 Å resonance line is apparent in both the night-only and the day+night spectra. The O vi 1032 Å resonance line is naturally dimmer and also easily obscured by the neighboring C iv 1037 Å feature. The bright peaks near 1027.5, 1028, and 1039 Å in the day+night spectrum are due to atmospheric hydrogen and oxygen. The 1031 Å feature that appears in the day+night spectrum, but not in the night-only spectrum, is thought to be the second-order diffraction line of atomic He i (Shelton et al. 2007).

Here, we focus on the O vi 1032 Å line in the off-cloud data. We measure its strength, both by the method of searching for significant excesses in counts that was employed in Shelton et al. (2001) and later papers (method 1) and by a modified version of the method of fitting with a Gaussian function that has been convolved with a 106 km s$^{-1}$ top-hat function that was employed in Dixon et al. (2001) and later papers (method 2). The modification is to add a second top-hat-convolved Gaussian to model the second-order He i airglow feature that appears at 1031 Å in the daytime data. See Figure 2 for the fitting results. Both methods cleanly separate the O vi 1032 Å feature from the daytime 1031 Å feature. Table 2 presents the intensity measurements. We average the measurements, yielding an observed intensity in the O vi 1032 Å line of 2340 ± 630 LU.

To place the O vi 1032 Å intensity along our off-cloud sight line into context, we compare it with O vi 1032 Å intensities measured for other high-latitude lines of sight. Using archival FUSE data, Dixon et al. (2006) and Dixon & Sankrit (2008) have searched for diffuse O vi photons along roughly 300 lines of sight. Here, we consider the 54 sight lines in their sample (plus E12402) with Galactic latitudes of |$b$| > 20° and orbital-night exposure times exceeding 18 ks. This sample is complete in the sense that any emission brighter than 2000 LU would have been detected in an 18 ks night-time exposure. Within this sample, 63% have statistically significant (i.e., >2σ) intensities of O vi 1032 Å photons, the greatest of which is 5500 LU. If null detections are treated as having zero flux and a 1σ error, then the median and mean intensities in the 1032 Å line are 2100 and 1800 LU, respectively, while the standard deviation about the mean is 1620 LU. Our off-cloud sight line, with an observed 1032 Å intensity of 2340 ± 630 LU, lies within 1σ of the mean, so it is not at all unusual.

Our measurements of the weaker O vi 1038 Å feature were not as sound as our measurements of the stronger 1032 Å feature. The 1038 Å feature sits to the right of the 1037 C iv line and to the left of the O1 airglow feature, making it impossible
The wavelength scale is accurate to 1031.49 Å in our heliocentric rest-frame spectra. We searched the observation of a weak intermediate \(\text{O}_{\text{vi}}\) feature. Assuming this ratio, the doublet intensity \(\pm 210\) for a good measurement, we take the local contribution from the only other \(\text{O}_{\text{vi}}\) cloud shadow observation, that toward \(\ell = 278:6, b = -45:3\) where a cloud lies 230 ± 30 pc from Earth. That cloud observation yielded upper limits on the \(\text{O}_{\text{vi}}\) 1032 Å and 1038 Å line intensities. The tightest upper limit is that on the 1032 Å line in the day+night data. Multiplying it by 1.5 in order to account for the 1038 Å contribution yields a limit on the doublet intensity of \(30\pm340\) LU (Shelton 2003).

The unrounded values were made available by the author. Subtracting them from our unrounded doublet intensity yields \(3480_{-1000}^{+940}\) LU.

If the non-local photons originated above even part of the Galaxy’s \(\text{H}1\) layer, then the intrinsic intensity would be greater than \(3480_{-1000}^{+940}\) LU. Here, we make the assumption that the \(\text{O}_{\text{vi}}\)-rich gas resides above the full extent of the Galaxy’s \(\text{H}1\) and/or dust-rich layer. As with the \(\text{C}_{\text{iv}}\) intensity, we estimate the degree of obscuration of the halo \(\text{O}_{\text{vi}}\) emission using the LAB \(\text{H}1\) column density (Kalberla et al. 2005) and the DIRBE-corrected IRAS 100 \(\mu\)m intensity (Schlegel et al. 1998). Using the same input values and conversion relations that we used in Section 2.1, we find that the LAB \(\text{H}1\) column density and the 100 \(\mu\)m intensity imply \(\text{O}_{\text{vi}}\) losses of 30% and 20%, respectively. Thus, if all of the obscuring material lies between the source of the photons and the Local Bubble, then the halo’s intrinsic intensity would be \(4320_{-1240}^{+170}\) to \(5220_{-1510}^{+1420}\) LU. Here, we take the halo’s intrinsic \(\text{O}_{\text{vi}}\) doublet intensity to be the average: \(4770_{-1380}^{+1300}\) LU, which is also listed in Table 1.

The optical thickness of the on-cloud line of sight is much larger (\(\tau_{100} = 3.48\) MJy sr\(^{-1}\), implying a loss of 70% of the incoming photons). If the gas above the cloud produces the same doublet intensity as that derived above for the off-cloud line of sight, then only \(1440_{-120}^{+390}\) LU would survive passage through the cloud and reach the detector. Of this, \(960_{-260}^{+260}\) LU would be in the \(\text{O}_{\text{vi}}\) 1032 Å line. This intensity is within our observational upper limits.

### 2.3. An Estimate of the Halo’s \(\text{O}_{\text{vi}}\) Column Density

We estimate the line-of-sight \(\text{O}_{\text{vi}}\) column density in nearly the same manner as Shelton et al. (2007), namely, by averaging the column densities on the four nearest directions for which they are measured and calculating the uncertainty from the typical scatter in measured values. The difference between our method and that of Shelton et al. (2007) is that we also include the measurement error; see below. We

### 2.2.3. Intrinsic Halo \(\text{O}_{\text{vi}}\) Intensity

For optically thin plasmas, the 1038 Å line is half as strong as the 1032 Å line. Assuming this ratio, the doublet intensity becomes \(3500 \pm 940\) LU (Table 1). The observed intensity is due to photons emitted in the halo but attenuated by intervening material plus photons emitted locally, by the Local Bubble if it exists. When the observations were planned, it was intended to use the on-cloud measurement to estimate the foreground intensity. However, because the exposure time was too short for a good measurement, we take the local contribution from the only other \(\text{O}_{\text{vi}}\) cloud shadow observation, that toward \(\ell = 278:6, b = -45:3\) where a cloud lies 230 ± 30 pc from Earth.

### Table 2

| Direction | Night-only Method 1 (ph \(\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) | Night-only Method 2 (ph \(\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) | Day+Night Method 1 (ph \(\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) | Day+Night Method 2 (ph \(\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| Off-cloud  | 1970 ± 600      | 2240 ± 660      | 2140 ± 470      | 2990 ± 790      |
| On-cloud   | 0 ± 690         | −240 ± 1600     | 0 ± 1030        |                 |

Notes. For the on-cloud data, method 1 was unable to fit the continuum for the night-only data. Method 2 calculated the 3\(\sigma\) upper limit. For comparison with the other values, the 3\(\sigma\) upper limits found by method 2 were converted into a “measurement \(\pm 3\sigma\)” form by dividing by 3.

### Table 3

| Emission Line | Velocity with Respect to the Local Standard of Rest |
|---------------|---------------------------------------------------|
| \(\text{O}_{\text{vi}}\) 1032 Å | \(-12\pm7\) (km s\(^{-1}\)) | \(2\pm17\) (km s\(^{-1}\)) | \(-9\pm11\) (km s\(^{-1}\)) | \(-3\pm14\) (km s\(^{-1}\)) |

| Emission Line | Night-only Method 1 (km s\(^{-1}\)) | Night-only Method 2 (km s\(^{-1}\)) | Day+Night Method 1 (km s\(^{-1}\)) | Day+Night Method 2 (km s\(^{-1}\)) |
|---------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| \(\text{O}_{\text{vi}}\) 1032 Å | \(-12\pm7\) | \(2\pm17\) | \(-9\pm11\) | \(-3\pm14\) |

to determine the background continuum accurately. For this reason, we present neither day+night nor night-only 1038 Å measurements.

We do, however, present measurements from our search for a second \(\text{O}_{\text{vi}}\) 1032 Å feature. This search was motivated by the observation of a weak intermediate/high velocity (\(V_{\text{LSR}} = -112\) km s\(^{-1}\)) feature in the LAB survey of galactic \(\text{H}1\). If infalling gas at this LSR velocity was accompanied by \(\text{O}_{\text{vi}}\), then the stronger line in its doublet would appear at a wavelength of 1031.49 Å in our heliocentric rest-frame spectra. We searched for such a feature in a 0.36 Å wide window (corresponding to the width of the LWRS aperture) in the night-only data. We did not search for the feature in the day+night data, because it would have overlapped with the second-order \(\text{He}\_1\) feature. Using method 1, we found a statistically insignificant excess intensity of 210 ± 480 LU.

We examined the on-cloud data, as well. These spectra were of very poor quality, because of the short observation time (5144 s of day+night data, including 2056 s of night-only data.) Neither method 1 nor method 2 could find emission features around 1032 or 1038 Å. We were able to use method 1 to determine and subtract the continuum and then measure the residual intensity within the wavelength range where the 1032 Å feature was expected to be found, based on the location of the 1032 Å feature in the off-cloud spectra taken from the day+night data. This method yielded a measured intensity of \(-243 \pm 1604\) LU, where the negative sign indicates that this region of the spectrum has fewer counts than the fitted continuum. Method 2 yielded 3\(\sigma\) upper limits of 3090 and 2060 LU from the day+night and night-only data, respectively. In both cases, the uncertainties are too large to constrain our conceptions of the ISM.

In order to determine the velocities using method 1, the heliocentric spectra were refit using a Gaussian for the feature in question and a low-order polynomial for the continuum. Method 2 also yielded velocity estimates. In both cases, the reference frames of the analyzed spectra were heliospheric. The resulting velocities have been converted to the LSR reference frame by the addition of 16.73 km s\(^{-1}\). (See Table 3 for the measurement results.) The wavelength scale is accurate to \(\sim 10\) km s\(^{-1}\) (Shelton et al. 2001).
obtain the column density measurements from the Savage et al. (2003) catalog of ∼100 sight lines, which excludes high velocity O vi and is based on the Wakker et al. (2003) data analysis. Their four sight lines nearest to our off-cloud sight line are those toward PG 1626+554 (log \( N = 14.25 \pm 0.09 \pm 0.08 \)) where the first uncertainty is the combined statistical and continuum placement 1σ error in the log of the column density; the second is the 1σ systematic error, which, in this case, is not necessarily correlated from one observation to the next), Mrk 487 (log \( N = 14.25 \pm 0.11 \pm 0.04 \)), Mrk 290 (log \( N = 14.21 \pm 0.12 \pm 0.05 \)), and Mrk 876 (log \( N = 14.43 \pm 0.02 \pm 0.05 \)). The average Milky Way O vi column density on these four lines of sight is \( 1.97^{+0.21}_{-0.17} \times 10^{14} \) cm\(^{-2}\).

The average angular separation between these sight lines and our own is 7.3 and the maximum is <10°. The average deviation in the mean column density for pairs of sight lines having ∼7° of separation in the Savage et al. (2003) catalog (their Figure 11) is 24%. Following the logic of Shelton et al. (2007), the rms deviation between the mean of the parent population and the mean of a sample of four observations drawn randomly from the parent population should be \( \sqrt{\pi}/4 \) times as large as the average deviation between two sight lines, thus 11%, and the intrinsic fluctuation between column densities along different directions should be a factor \( \sqrt{\pi}/2 \) times the average deviation between two sight lines, thus 21%. Combining these terms in quadrature yields 24%. This is larger than the average statistical plus continuum placement error and the average systematic error obtained from the four individual column density measurements. Here, we add the three sources of uncertainty in quadrature in order to obtain an estimate of the uncertainty in the estimated column density for our direction. The column density and combined error are \( 1.97^{+0.53}_{-0.57} \times 10^{14} \) cm\(^{-2}\).

The column density of local material must be subtracted from the line-of-sight column density. The Savage & Lehner (2006) survey of O vi toward nearby white dwarfs includes nine sight lines that are within 20° of our off-cloud direction. Ions of O vi were not detected on four of these sight lines. In those cases, Savage & Lehner (2006) listed 2σ upper limits. We treat these cases as if the 1σ upper limits were half of the 2σ upper limits and the detected values were 0, so that we can find the average for the nine sight lines. The resulting average column density of O vi is \( 1.5^{+0.5}_{-0.4} \times 10^{8} \) cm\(^{-3}\). Although there are reports (i.e., Barstow et al. 2009) claiming that only a few of the previous O vi detections for nearby sight lines can be shown to be interstellar, as opposed to photospheric or ambiguous (generally due to the similarities between the observed velocities and the velocities of photospheric lines in the spectra), a culled data set is not yet available. Thus, we use the Savage & Lehner (2006) data set.

We estimate the maximum extent of the Local Bubble from a survey of the Local Cavity’s wall, in this case the Na i and Ca ii survey of Welsh et al. (2010). In Figures 14 and 17 of that paper, the Local Cavity extends 75 pc in the direction of our observation. Taking this and the average volume density yields an estimate of the Local Bubble’s column density of O vi of \( 3.4^{+2.8}_{-1.0} \times 10^{12} \) cm\(^{-2}\). This is so small compared with the full column density through the Galactic disk and halo that approximations are inconsequential. Subtracting this value from the full column density yields a halo O vi column density of \( N_{O\,\text{vi}} = (1.9 \pm 0.5) \times 10^{14} \) cm\(^{-2}\). Again, the unrounded measurement values are used in the calculations, but the rounded results are reported.

### Table 4

| Obs. ID     | Obs. Date   | \( \ell \) | \( b \) | \( I_{\text{O\,vi}} \) (LU) | \( I_{\text{O\,viii}} \) (LU) |
|-------------|-------------|-------------|--------|----------------------------|----------------------------|
| 00049540401 | 2003 Aug 19 | 86.567      | 40.932 | 11.6^{+0.8}_{-0.7}         | 3.7^{+0.5}_{-0.4}          |
| 0200750601  | 2005 Sep 7  | 90.029      | 38.406 | 6.8^{+1.0}_{-0.6}          | 1.0^{+0.4}_{-0.3}          |
| 0302310101  | 2004 Sep 29 | 86.462      | 41.115 | 15.3^{+0.3}_{-1.8}         | 2.2^{+0.7}_{-0.5}          |

**Notes.** For these measurements, the extragalactic background component was removed. During the estimation of its strength, the background was assumed to have been partially absorbed by Galactic material, whose H I column density was measured by the LAB survey.

### 2.4. The Halo O vi and O viii Intensities

#### 2.4.1. Intensity Measurements from XMM-Newton Observations

There are 33 archival XMM-Newton observations within 5° of our FUSE points that have at least some EPIC–MOS exposure. All but three of the observations were badly affected by soft proton contamination. We have processed the data from these three observations using the method described in Henley & Shelton (2010). We removed times affected by soft proton flares, and also times when the solar wind proton flux exceeded \( 2 \times 10^{8} \) cm\(^{-2}\) s\(^{-1}\) (the latter step was to reduce contamination from solar wind charge exchange (SWCX) X-rays; see Section 2.4.2). We extracted spectra from the blank sky regions of the EPIC–MOS chips and measured the intensities in the O vii Kα triplet (569–574 eV) and O viii Kα line, accounting for the effects of residual soft proton contamination and the extragalactic background (the spectrum of which we assumed to be \( 10.5(E/\text{keV})^{-1.46} \) ph cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) (Chen et al. 1997). For the portions of observation 0200750601 (\( \ell = 90.0; b = 38.4 \)) not affected by soft proton flares, the solar wind proton flux exceeded our standard filtering threshold of \( 2 \times 10^{8} \) cm\(^{-2}\) s\(^{-1}\). However, the proton flux was not unusually large, and did not exceed \( 2.8 \times 10^{8} \) cm\(^{-2}\) s\(^{-1}\). We therefore did not carry out proton flux filtering on this observation. The X-ray intensity measurements are listed in Table 4.

#### 2.4.2. SWCX Abatement

The measured O vii and O viii intensities differ from one sight line to the next by factors of \( \lesssim 2 \) and \( \lesssim 4 \), respectively, in spite of the fact that the ROSAT 3/4 keV map of this region shows a relatively uniform surface brightness. The variation found between the three XMM-Newton observations is not due to absorbing material along the lines of sight, as the obscuration toward \( \ell = 90.0; b = 38.4 \) is insufficient to explain the relative dimness of its O vii measurement. The variation is probably due to flares of contamination by SWCX X-rays. Such X-rays were generated after solar wind ions charge exchanged with neutral gas in the heliosphere and Earth’s extended atmosphere (Robertson & Cravens 2003; Koutroumpa et al. 2006). Observational work has shown that SWCX contamination can vary significantly as a function of time (Snowden et al. 2004; Fujimoto et al. 2007; Henley & Shelton 2008; Carter & Sembay 2010), even during periods having modest solar wind proton fluxes (Henley & Shelton 2010). The intensity variation that we found among the three Draco pointings, which were observed during different years (see Table 4), is within the range of the variation seen among multiple XMM-Newton observations of the same direction in the Henley & Shelton (2010) catalog and is probably due to...
variability in the SWCX X-ray intensity. With this in mind, we take the observation having the minimum oxygen intensities and adopt these measurements. Nonetheless, this observation ($\ell = 90^0.0, b = 38^0.4$, having $I_{0 \text{viii}} \sim 7$ LU and $I_{0 \text{vii}} \sim 1.0$ LU), is subject to low-level, slowly varying SWCX. Note that the pointing direction is only $1^0.2$ from our FUSE and FIMS/SPEAR direction and that the O vii and O viii intensities are not unusual compared with those seen along $b \gtrsim 30^0$ directions in the Henley & Shelton (2010) XMM-Newton catalog.

### 2.4.3. The Intrinsic Halo O vii and O viii Intensities

Low-level SWCX contamination is not the only contribution to the observed spectra. SWCX X-rays, together with Local Bubble X-rays, if they exist, form a foreground component, $I_{fg}$, which is not subject to interstellar extinction. The emission from the Galactic halo, $I_h$, is subject to extinction having an optical depth of $\tau$ and combines with the foreground component as $I_{obs} = I_h + I_h \exp(-\tau)$ to produce the observed intensity, $I_{obs}$. The foreground component can be estimated from shadowing observations of nearby clouds (see Table 4 in Gupta et al. (2009) and SWCX models (see Table 4 in Koutroumpa et al. (2007)) for cases not subject to strong SWCX flares. Here, we use the foreground component to be $I_{fg,\text{Ovii}} = 1.5 \pm 1.0$ LU and $I_{fg,\text{Oviii}} = 0 \pm 1.0$ LU. The optical depth was estimated in three different ways: by using the weighted average of the H i column densities on nearby pointings in the LAB survey (Kalberla et al. 2005), using relations in Snowden et al. (2000) to convert the $10 \mu$m intensity from the DIRBE-corrected IRAS maps (Schlegel et al. 1998) to $N_{HI}$, and using relations in Güver & Özel (2009) to convert the reddening ($E(B - V)$) obtained from the DIRBE-corrected IRAS maps to $N_{HI}$. In each case, the absorption cross sections of Balucinska-Church & McCammon (1992) were then used. Table 5 lists the data from these surveys and the intrinsic O vii and O viii intensities calculated by solving for $I_h$ in $I_{obs} = I_h + I_h \exp(-\tau)$. Here, we adopt the average values: $I_{h,\text{Ovii}} = 6.4^{+1.4}_{-1.5}$ LU and $I_{h,\text{Oviii}} = 1.0 \pm 1.2$ LU.

### 3. DISCUSSION

The ratio of $I_{0 \text{vii}}$ to $N_{0 \text{vii}}$ allows us to estimate the electron density ($n_e$) and thermal pressure ($P_h$) of the O vii-rich gas in the halo. The calculation method is the same as that used in Shelton et al. (2001) and Dixon et al. (2001), but is used here with the intrinsic intensity and column density of the O vii ions located above the disk. It yields $n_e = 0.011 \pm 0.004$ K cm$^{-3} P_h/k = 6500^{+2500}_{-2600}$ K cm$^{-3}$, where $k$ is Boltzmann’s constant. This pressure estimate and that found for the southern off-filament direction (7000–10,000 K cm$^{-3}$; Shelton et al. 2007) are the only pressure estimates for extraplanar O vii-rich gas in which the local contributions to the observed quantities were subtracted before the pressure was calculated. In addition, several estimates have been made without the subtraction of the relatively small local contributions to the O vii intensity and column density (i.e., Shelton et al. 2001: $P_h/k \sim 5300$ to 14,000 K cm$^{-3}$, with the range reflecting the uncertainty in the location of the H i gas; Dixon et al. 2001: $P_h/k \sim 20,000$ K cm$^{-3}$ for $T = 10^{5.5}$ K gas; Shelton 2002: $P_h/k \sim 3700$ to 4900 K cm$^{-3}$, depending upon the location of the H i gas; Dixon & Sankrit 2008: $P_h/kg \sim 5300$ to 7400 K cm$^{-3}$ for the Fairall nine direction and 3000–3600 K cm$^{-3}$ for the NGC 625 direction, with the ranges reflecting the uncertainties in the locations of the H i gas). The thick-disk/halo O vii-rich gas is expected to reside between heights of $|z| \sim 160$ pc (the height of the shadowing cloud that was used in the observation of local O vii photons and discussed in Section 2.2.3) and $\sim 2300$ pc (the scale height of O vii ions; Savage et al. 2003) and has a much larger thermal pressure than had been estimated for this region based on observations and the assumption of hydrostatic equilibrium ($P_h/k < 2200$ K cm$^{-3}$; Ferriere 1998). The discrepancy could be due to a lack of hydrostatic balance, as would occur if disruptive events occurred too frequently for the thick disk to re-lax. The discrepancy could also be due to the assumption that the gas is at its CIE temperature. The calculated pressure is proportional to temperature divided by a function of temperature and has a minimum of $P_h/k = 3300 \pm 1300$ K cm$^{-3} at T = 9.6 \times 10^5$ K. Alternatively, the discrepancy for our direction can be reduced by relaxing our assumption that the obscuring material along the sight line resides below the extraplanar O vii. If, instead, it lies above, then the extraplanar O vii’s intensity would be $3480^{+940}_{-38}$ LU (from Section 2.4.3, implying a thermal pressure of $P_h/k = 4700^{+3940}_{-1300}$ K cm$^{-3}$.

The ratios of the intrinsic extraplanar intensities of C iv, O vii, O vii, and O viii are useful tests for halo models. Here, we use them to test several models, beginning with a model in which gas is heated to a high temperature and then allowed to cool radiatively. This model is plausible, given that its predictions have been found consistent with the ratios of O vii, O vii, and O viii column densities observed for the PKS 2155–304 sight line by Heckman et al. (2002). An application of the radiative cooling model involves gas that was accreted from intergalactic space. Although Henley et al. (2010) show that an extended hot halo of accreted gas ($r \sim 10s$ of kpc) may be too faint to account for the X-ray emission seen in the XMM-Newton band (including the O vii and O viii lines), the model X-ray luminosities used by Henley et al. (2010) excluded emission from near the disk. If accreted material near the disk contributes to the observed O vii and O viii emission then the model is not ruled out. Here, we predict theoretical intensity ratios and compare with our observations.

Lei et al. (2009) presented a simple model in which radiative cooling of hot, shocked intergalactic gas results in a temperature-stratified layer of accreted gas. In such a model, the intensities in the C iv, O vii, O vii, and O viii lines can be calculated from

$$I = \left( \frac{k}{4\pi} \right) \left( \frac{3}{2} s \right) \left( \frac{1}{A} \right) \int n_e \epsilon(T) \frac{n_{hi} A}{N(T)} dT,$$

where $n_h$ and $n_{pi}$ are the volume densities of hydrogens and positive ions, respectively, $s$ is 0 for isochorically cooling gas
(Lei et al. 2009) and 1 for isobarically cooling gas (Edgar & Chevalier 1986), \( \frac{1}{A} \frac{dN}{A dT} \) is the unknown rate at which particles are accreted per unit cross sectional area, \( \epsilon(T) \) is the emission coefficient, and \( \Lambda_n(T) \) is the cooling function for radiatively cooling gas. Following Sutherland & Dopita (1993), \( \Lambda_n \) has units of erg cm\(^{-3}\) s\(^{-1}\) and is defined such that the energy loss per unit volume per unit time equals \( n_e n_H \Lambda_n(T) \), where \( n_e \) is the volume density of electrons. We take \( \Lambda_n(T) \) from Table 6 in Sutherland & Dopita (1993), which approximates the ionization levels of the gas as those in CIE plasma. Solar abundances from Anders & Grevesse (1989) are used. We take the emission coefficients from the Xspec databases for the Raymond & Smith and APEC models for radiation from optically thin thermal plasmas in collisional ionization equilibrium. The elemental abundances, which are assumed to be solar from Anders & Grevesse (1989), and the fraction of atoms in the relevant ionization stage are factored into these coefficients. The emission coefficients have units of erg cm\(^{-3}\) s\(^{-1}\) and are defined such that the energy loss per unit volume per unit time is \( \epsilon(T) n_e n_H \). Because \( \Lambda_n(T) \) and \( \epsilon(T) \) are tabulated at discrete values of \( T \), we approximate the intensity integral with a sum.

Not knowing the value of 10\(^{26} \) from the Raymond & Smith coefficients and 10\(^{26} \) from the APEC coefficients. Another possible source of extraplanar O\( \text{VI} \), O\( \text{VII} \), and O\( \text{VIII} \) is hot gas that has welled up from the Galactic disk. In the hydrodynamical simulations of Joung & Mac Low (2006), SN explosions stir the ISM and drive hot gas into the thick disk. These simulations, which modeled 80 Myr of ISM evolution, were extended to 155 Myr for Henley et al. (2010). (Note that these times include the time taken for the initial conditions to be eradicated.) From them and the Raymond & Smith spectral code, Henley et al. (2010) created synthetic spectra. The synthetic spectra from time periods after 140 Myr were found to be at least as bright in 0.4-2.0 keV photons as the spectra extracted from XMM-Newton observations after removing the local contribution. Thus, such upwelled hot gas is a probable source of O\( \text{VII} \) and O\( \text{VIII} \). However, model I\( \text{CIV} : \text{IOVI} : \text{IOVII} : \text{IOVIII} \) ratios are not yet available for comparison with our observations.

Furthermore, there have been reports of enhanced X-ray intensities associated with HVCs (Hirth et al. 1985; Kerp et al. 1999; Bregman et al. 2009). Our line of sight passes near the intermediate and high velocity material associated with the Draco Nebula and Complex C, crosses some fast moving material (see Section 2.2.2), and hypothetically could encounter material left behind by an HVC, given that simulated HVCs shed material (Heitsch & Putman 2009). Although intensity predictions from simulations are not yet available, we can assume that several known physical processes may be active. Supersonic collisions between HVCs and thick disk/halo gas would heat the gas. The clouds may experience turbulent mixing and evaporation if they are passing through a hot ambient medium. Radiative cooling will also operate.

Slavin et al. (1993) analytically calculated the C\( \text{IV} \) and O\( \text{VI} \) intensities resulting from model turbulent mixing layers. The I\( \text{CIV} : \text{IOVI} \) ratios from their predictions ranged from 1.7 to 16, depending upon the assumed conditions. The low end of the predicted I\( \text{CIV} : \text{IOVI} \) ratio is within the \( \sigma \) error bars of the observationally determined ratio and is from models having mixed gas temperatures of \( T = 10^5 \) K. Kwak & Shelton (2010) hydrodynamically simulated mixing layers and calculated the quantities of C\( \text{IV} \), N\( \text{V} \), and O\( \text{VI} \) ions in a time-dependent manner of 1800 K cm\(^{-3}\) (Shelton 2006). These large injections of energy engender shocks that heat and ionize the gas. Although the early post-shock temperatures are above \( 3 \times 10^6 \) K, the expanding spherical shock fronts weaken with time, reducing the post-shock temperature. As this happens, the gas inside the bubble cools by adiabatic expansion. Later, it cools primarily by radiative cooling. Each of these processes skews the temperature distribution in favor of C\( \text{IV} \) and O\( \text{VI} \)-rich gas rather than O\( \text{VII} \) and O\( \text{VIII} \)-rich gas. When averaged over time and space, the resulting bubbles have ratios of median intensities of I\( \text{CIV} : \text{IOVI} : \text{IOVII} : \text{IOVIII} = 0.39 : 1.0 : 3.4 \times 10^{-4} : 3.7 \times 10^{-5} \) (assuming Anders & Grevesse 1989 abundances). These ratios were calculated from a Monte Carlo simulation that included the luminosity of individual supernova remnant (SNR) bubbles as a function of time, variation in ISM conditions and therefore SNR characteristics as a function of height above the plane, and the likelihood that a sight line would pass through any given SNR, based the SNR’s size, height above the midplane, and the height distribution of progenitor stars. They, therefore, represent the all high-latitude sky average, which is serendipitous as our observed intensities are also near the average of those observed across the high-latitude sky. In contrast with the accreting gas model, the impulsive injection model predicts too little emission from O\( \text{VII} \) and O\( \text{VIII} \) per photon emitted by O\( \text{VI} \).
(i.e., not assuming CIE). Subsequently, they calculated the ratio of the C iv photon intensity to the O vi photon intensity for their primary model, Model A, and for a similar model with 10 times as much thermal pressure after 50 Myr of evolution, finding it to be 2.4 and 4.9, respectively (K. Kwak 2010, private communication). Not only are the ratios of C iv to O vi intensity larger in turbulent mixing layer models than in radiative cooling and SNR models, but the ratios of C iv to O vi column densities are also larger (Slavin et al. 1993; Esquivel et al. 2006; Kwak & Shelton 2010). None of these papers predict the intensities of O vii and O viii and such values would depend strongly upon the assumed depth of the hot reservoir. However, we can assume that the greater the number of mixing layers, the greater the $I_{O\text{vi}} : I_{O\text{vii}}$ and $I_{O\text{vii}} : I_{O\text{viii}}$ ratios will be.

In the foregoing analyses, we have ignored scattering of UV background photons by interstellar C iv and O vii ions because we expect the scattered intensities to be small. Shelton et al. (2001) estimated the intensity of photons scattered by O vi ions, finding it to be much less than (i.e., 6% of) the intensity produced by line emission for their Case 3b, which is similar to our case in that it assumed that most of the O vi photons originated in the halo and that there is some line-of-sight obscuration. By similar logic, we expect that scattering by O vii ions has negligibly affected our observations. To examine the magnitude of scattering by C iv ions in comparison with that by O vi ions, we use Equation (14) from Shelton et al. (2001) for the scattered intensity, $I_{scat} = \frac{2}{3} I_{abs} F(t_{\infty})$. The background continuum specific intensity, $I_{abs}$, near 1550 Å is $4.1 \times 10^{-21}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$ (Bowyer 1991), which is only $1/10$ of the intensity near 1030 Å, $4.4 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$ (Mathis et al. 1983) and assumed in the Shelton et al. (2001) analysis. If the line profile is thermally broadened and the gas is in CIE, then the velocity spread parameter, b, of C iv is 2/3 of that of O vi. Its wavelength, $\lambda$, is obviously larger. We expect the column density of C iv ions to be around 60% of that of O vi ions, given the ensemble statistics reported in Savage & Wakker (2009). Thus, the optical depth of scatterers, $\tau$, will be smaller, and $F$, which is a function of $\tau$, will be smaller for C iv than for O vi. The variable a is related to absorption by intervening dust and is 6% larger at 1550 Å than at 1030 Å. As a result of these factors, the intensity scattered by C iv ions is even smaller than that scattered by O vi ions.

4. SUMMARY AND CONCLUSIONS

In this paper, we discuss measurements of the C iv, O vi, O vii, and O viii intensities. The O vi, O vii, and O viii data are newly presented here, while the C iv intensity is taken from Park et al. (2009). Each of the measured intensities was taken from $\ell = 90^\circ$, $b \sim 40^\circ$, a region that is near to but not toward the Draco cloud, and is fairly typical of high-latitude values.

We have subtracted the contributions made by local diffuse gas and compensated for the absorption loss due to intervening material, in order to obtain the intrinsic intensities of photons that originated above the plane. While this region is often called the halo, especially when discussing the diffuse X-ray background, most of the observed ions reside in the thick disk. We find a high pressure $p_{hi}/k = 6500^{+2500}_{-2600}$ K cm$^{-3}$, see Section 3 for the O vii-rich gas in this region. It is consistent with the measurement of extraplanar O vi made in the southern Galactic hemisphere and is greater than expected from static models of the thick disk. Such a high pressure could result from the thick disk being disturbed on a faster timescale than the relaxation timescale. In addition, if the true temperature of the gas is much less than the CIE temperature, then the true pressure may be somewhat less than that derived from our measurements.

Each of our ions traces hot gas, although they sample different, sometimes overlapping temperature subregimes (C iv traces $\sim 1 \times 10^5$ K gas, O vi traces $\sim 3 \times 10^5$ K gas, O vii traces $1 \times 10^6$ K gas, and O viii traces $\sim 3 \times 10^6$ K gas if the gas is in collisional ionization equilibrium). The hot gas in these subregimes is thought to be causally and sometimes physically related. One relationship occurs through radiative cooling, because gas that was heated to a few million degrees will cool through the other subregimes if left undisturbed. Another relationship occurs through energy transfer, either by thermal conduction or by mixing. If very hot gas abuts significantly cooler gas, then a C iv and/or O vii-rich zone develops between the hotter (O vii and/or O viii-rich) gas and the cooler gas.

The ratio of intensities provides a diagnostic of the heating mechanism. Mechanisms that heat gas to several times $10^5$ K favor C iv and O vi, while mechanisms that heat the gas to higher temperatures boost the relative O vii and O viii intensities. It should be noted that atomic physics favors the resonance lines of lithium-like ions (i.e., O vi 1032, 1038 Å and C iv 1548, 1551 Å emission) over the Kr lines of helium-like and hydrogen-like ions (i.e., the O vii “triplet” between 561 and 574 eV and the O viii 653 eV line), if all other factors, such as abundance, are equivalent. Therefore, when we indicate that heating the gas to very high temperatures favors O vii and O viii emission, we mean that $I_{O\text{vii}}/I_{O\text{vi}}$ and $I_{O\text{viii}}/I_{O\text{vii}}$ are greater than in other models. We do not mean to imply that our O vii and O viii intensities are brighter than our O vi intensity, because they are not.

The O vii intensity is the reference point for all of our comparisons. Our intrinsic, halo O vii intensity is $4770^{+1300}_{-1200}$ K (see Section 2.4.3) and the $I_{CIV} : I_{O\text{vi}} : I_{O\text{vii}} : I_{O\text{viii}}$ ratios are $1.4^{+0.6}_{-0.6} : 1.0 : (1.3 \pm 0.5) \times 10^{-3} : 2.2^{+2.6}_{-2.3} \times 10^{-4}$ (see Section 3). For the moment, we ignore C iv, which we will return to later. The $I_{O\text{vi}} : I_{O\text{vii}} : I_{O\text{viii}}$ ratios lie between the extremes formed by two models, one of which is relatively preferential to O vii and O viii while the other is relatively preferential to C iv and O vi. The first model is fairly simple. It heats gas to a high temperature ($10^6$ K), then allows it to cool radiatively. This model, which may correspond to halo gas resulting from a smooth accretion of intergalactic gas, produces ratios of $0.13 : 1.00 : 0.037 : 0.031$ (assuming Raymond & Smith coefficients; the ratios found from APEC coefficients are also presented in Section 3). The second model was made from simulations of the bubbles blown by sporadic and isolated injections of energy. The particular model employed was for bubbles blown by SN explosions. The model ratios take into account the different numbers of photons produced at different stages of the bubble’s life, including the short-lived early period when the shock-front heats the gas to temperatures well above $3 \times 10^5$ K, the longer-lived stage when the shock-front heats the gas to a few times $10^5$ K, and the final much longer period when the SNR bubble radiatively cools. Thus, this model includes the effects of injecting energy to create a wide range of gas temperatures, in addition to radiative cooling. It produces ratios of $0.39 : 1.0 : 3.4 \times 10^{-4} : 3.7 \times 10^{-5}$ (see Section 3). The observed $I_{O\text{vii}} : I_{O\text{vii}} : I_{O\text{viii}}$ ratios are between the two comparison models.

We can conclude that in addition to some very hot gas ($T_{CIE} \sim 3 \times 10^5$ K), a broad temperature profile is needed. Not only could a broad temperature profile result from SN bubbles,
but it may also result from mixing or thermal conduction between very hot gas and cooler gas, injections of moderately hot fountain gas into the “halo,” or other phenomena.

Interestingly, neither model produced more C IV photons than O VI photons, yet the observations show that C IV is at least as intense as O VI in both the Draco region and the southern filament region (see Shelton et al. 2007). Adjusting the C:O abundance ratio cannot solve this problem, as it would require raising it from 0.4 (Anders & Grevesse 1989) to 1.6, which is unrealistic. Instead, the large $I_{C IV} : I_{O VI}$ ratio indicates that there exists a strong mechanism for producing C IV photons. Turbulent mixing between hot and cool gas is one such mechanism.

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Note that substantial $I_{C IV} : I_{O VI}$ ratios were also reported in Table 1 of Welsh et al. (2007). Their $I_{O VI}$ and $I_{C IV}$ were measured from FIMS/SPEAR observations directed in the north galactic polar region and supplemented by an additional measurement of the north ecliptic pole made by Korpela et al. (2006). The extreme range in $I_{C IV} : I_{O VI}$ from the various fields in which they detected both C IV and O VI photons is 0.37 ± 0.13 to 1.0 ± 0.11.