Exploring Hot Gas in the Galactic Halo and High Velocity Clouds

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Abstract. In the five years since its launch, the Far Ultraviolet Spectroscopic Explorer has given the astronomical community a marvelous glimpse into the realm of previously unexplored regions of the Milky Way and its surroundings. Absorption lines produced by gas along entire paths through the nearby universe have now been recorded in the spectra of distant QSOs and active galactic nuclei. Of the lines recorded, the O VI $\lambda\lambda$1031.926, 1037.617 doublet is the best tracer of highly ionized regions. Exciting discoveries include a definitive confirmation of the hot Galactic halo postulated by Lyman Spitzer nearly 50 years ago, the discovery of a hot, highly extended Galactic corona enveloping the Milky Way out to distances of several tens of kiloparsecs, and the discovery of an extensive network of highly ionized, high velocity clouds surrounding the Galaxy.

1. Introduction

It is a pleasure to be able to provide a review of FUSE O VI measurements in the Milky Way halo and high velocity cloud system. This work has been a major focus of the research efforts of many FUSE Team members over the past few years, and was the subject of much planning and preparation before launch. Before launch, we had high expectations for the detection of O VI absorption in the Galactic halo, and these came to fruition early in the mission.\(^1\) However, the large number of high-velocity clouds (HVCs) detected in O VI absorption came as a stunning surprise and was something that we had not expected prior to launch. If anything, it is probably fair to say that many of us believed that with the exception of a few highly ionized HVCs detected by HST/STIS, most of the high velocity gas was neutral, a view that has changed significantly since the FUSE observations.

\(^1\)The New York Times even reported the early Galactic halo results in an article entitled “Craft is Demystifying Milky Way’s Sizzling Halo of Gas” (J.N. Wilford, 13-Jan-2000).
2. The FUSE O VI Survey

We have conducted an extensive study of the O VI $\lambda\lambda 1032, 1038$ absorption in the vicinity of the Milky Way as measured by FUSE for 100 AGN/QSO sight lines and two distant halo star sight lines. This study was based on $\sim 4$ Msec of exposure time, pulling together data from many FUSE observing programs. We show portions of the FUSE spectra for two sight lines in Figure 1. The results of this survey have been published in a special issue of the Astrophysical Journal Supplement Series (May 2003, volume 146). The three papers in that issue include a description of the survey (Wakker et al. 2003), an investigation of the distribution and kinematics of O VI in the Galactic halo (Savage et al. 2003), and an analysis of the highly ionized high velocity gas in the vicinity of the Galaxy (Sembach et al. 2003). Rather than reference those papers repeatedly here, we simply draw upon the results therein and refer the reader to those papers for further details and background information.

![FUSE spectra for two objects in the FUSE high velocity O VI survey.](image)

Figure 1. Observations of two objects in the FUSE high velocity O VI survey. The data have a FWHM velocity resolution of $\sim 20$ km s$^{-1}$. Low velocity Milky Way halo absorption features and high velocity absorption features are present along both sight lines. Prominent interstellar lines, including the two lines of the O VI $\lambda\lambda 1031.92, 1037.61$ doublet, are identified above each spectrum at their rest wavelengths. H I and metal lines from intervening intergalactic clouds are marked in both panels. Unmarked absorption features are interstellar H$_2$ lines. Crossed circles mark the locations of terrestrial airglow emission lines of H I and O I.

Highlights of several investigations of individual HVCs in the FUSE survey are summarized in the papers by Fox et al. and Collins et al. in this volume. Brief descriptions of FUSE observations of O VI in the Milky Way disk and the Magellanic Clouds can be found in accompanying articles by Bowen et al. and Howk, respectively.
2.1. Velocities

With a few exceptions, we define O VI absorption in the survey as “high velocity” if it has $|v_{\text{LSR}}| \gtrsim 100$ km s$^{-1}$, while we attribute lower velocity gas to the thick disk and halo of the Milky Way. (For simplicity, we will use the term “halo” to denote both the thick disk and halo of the Milky Way.) The velocity distribution of the O VI features is shown in Figure 2.

![Figure 2](image)

Figure 2. Histograms of the O VI line centroids for the Galactic halo (unshaded) and high velocity gas (shaded). The bin size is 10 km s$^{-1}$.

The imprint of Galactic rotation can be seen in some of the absorption profiles in low latitude ($|b| < 30^\circ$) directions. At higher latitudes ($|b| \gtrsim 45^\circ$), outflows and inflows of gas in the halo are evident. The mean O VI velocities of the halo gas along high Galactic latitude sight lines range from $-46$ to $+82$ km s$^{-1}$ with a sample average of $0 \pm 21$ km s$^{-1}$. This result holds for both northern and southern Galactic latitudes, suggesting that the gas in both hemispheres is moving toward and away from the Galactic plane with approximately equal frequency.

The high velocity O VI features have velocity centroids ranging from $-372 \leq v_{\text{LSR}} \leq -90$ km s$^{-1}$ to $+93 \leq v_{\text{LSR}} \leq +385$ km s$^{-1}$. There are an additional six confirmed or very likely (> 90% confidence) detections and two tentative detections of O VI between $v_{\text{LSR}} = +500$ and $+1200$ km s$^{-1}$; these very high velocity features probably trace intergalactic gas beyond the Local Group. By definition, the high velocity O VI features have velocities incompatible with those of Galactic rotation.

2.2. Column Densities

For the 20 sight lines in the survey where both lines of the O VI doublet arising in the halo gas can be measured reliably, the O VI column density inferred from direct integration of the apparent column density profiles of the two lines is in good agreement in most cases. A few exceptions exist (see Table 2B in Savage et al. 2003), but in general the excellent agreement indicates that the more easily measured $\lambda 1031.926$ line provides a reliable estimate of the column density. Blending with other interstellar and intergalactic features is an important consideration for all sight lines; see Wakker et al. (2003) for details.
The Galactic halo O VI features in the survey have logarithmic column densities (cm$^{-2}$) of 13.85 to 14.78 with an average of $\langle \log N \rangle = 14.38 \pm 0.18$. If considered separately, the column density distributions differ slightly in the northern and southern Galactic skies for high Galactic latitudes ($|b| > 45^\circ$), with a northern column density enhancement of $\sim 0.25$ dex above that measured in the south.

The high velocity O VI features have logarithmic column densities of 13.06 to 14.59, with an average of $\langle \log N \rangle = 13.95 \pm 0.34$. Typically, the high velocity O VI accounts for 25-40% of the total O VI column density along sight lines for which both have been measured. The column density distributions for the Galactic halo and high velocity clouds are shown in the left panel of Figure 3.

![Figure 3.](image)

Figure 3. Histograms of the logarithmic O vi column densities and Doppler line widths for the Galactic thick disk/halo (dashed lines) and high velocity clouds (solid lines). The bin sizes are 0.10 dex and 10 km s$^{-1}$, respectively.

2.3. Line Widths

The line widths of the Galactic halo O VI features range from $\sim 30$ km s$^{-1}$ to $\sim 99$ km s$^{-1}$, with an average of $\langle b \rangle = 60 \pm 15$ km s$^{-1}$. The line widths of the high velocity O VI features range from $\sim 16$ km s$^{-1}$ to $\sim 81$ km s$^{-1}$, with an average of $\langle b \rangle = 40 \pm 14$ km s$^{-1}$. The lowest values of b in the high velocity gas are close to the thermal width of 17.1 km s$^{-1}$ expected for O VI at its peak ionization fraction temperature of $T = 2.8 \times 10^5$ K in collisional ionization equilibrium (Sutherland & Dopita 1993). The large b-values observed along many sight lines imply that non-thermal broadening mechanisms and multi-component velocity structure dominate the O VI line broadening in both the halo gas and in the high velocity clouds. The distributions of b-values for both types of gas are shown in the right panel of Figure 3.

3. O VI in the Galactic Thick Disk/Halo

3.1. Distribution

Strong O VI absorption arising in the low Galactic halo is measurable in 91 of the 102 sight lines in our survey. In those cases where it was not detected,
the upper limits on N(O\,VI) are generally higher than the smallest column density measured in the sample. Thus, the apparent absence of O\,VI along some sight lines is probably an artifact of the varying data quality within the sample. FUSE observations of halo stars within a few kiloparsecs of the Galactic plane reveal Galactic halo O\,VI absorption at a column density level consistent with approximately 40–50% of the halo absorption seen along complete halo paths (Zsargó et al. 2003).

The distribution of Galactic halo O\,VI is patchy, which suggests that the O\,VI may be distributed in filamentary or small-scale structures. The O\,VI regions must have a large covering factor to account for the common occurrence of O\,VI absorption in halo directions, but need not have a large volume filling factor. Variations of a factor of three in N(O\,VI) have been seen across the face of the LMC at angular scales of $\sim 1^\circ$ (Howk et al. 2002a). These variations are comparable to those seen over much larger angular separations in the FUSE survey. Smaller variations have been seen toward both the LMC and SMC at smaller angular separations (Howk et al. 2002b; Hoopes et al. 2002). Measurements of O\,VI in the direction of the globular cluster NGC\,6752 (Lehner & Howk 2004) show no variations in N(O\,VI) or the O\,VI velocity distribution on angular scales $\Delta \theta = 2^\circ 2 - 8^\circ 9$ (or 2.5–10.1 pc). The constancy of the O\,VI absorption in this direction suggests that there may be a characteristic size of $\gtrsim 10$ parsecs for the O\,VI regions, but similar checks for several other directions need to be conducted before such a conclusion can be generalized to the entire Galactic halo.

Nearby regions of hot gas do not appear to contribute significantly to the O\,VI variations. There is no obvious enhancement in N(O\,VI) in the directions of Radio Loops I-IV, with the possible exception of the 3C 273 sight line, which passes through a region of enhanced soft X-ray emission in the North Polar Spur region (see Sembach et al. 2001 and Figure 9 of Savage et al. 2003). Similarly, the Local Bubble contains only a small amount of O\,VI (typically, log $N \lesssim 13.0$; Oegerle et al. 2004) and contributes at most $\sim 10\%$ of the O\,VI column along the extended paths probed in the AGN/QSO survey.

It is possible to estimate the extension of the O\,VI gas distribution away from the Galactic plane by examining the column density perpendicular to the plane ($N \sin |b|$) as a function of distance of the background source from the plane ($z$). Figure 5 shows this distribution for the survey sight lines as well as sight lines toward the Magellanic Clouds and stars in the Galactic disk. The solid curves on the plot show the predicted relation between $N_\perp = N \sin |b|$ and $z$ for a smooth, exponentially distributed gas layer with a mid-plane density $n_0(O\,VI) = 1.7 \times 10^{-8}$ cm$^{-3}$ and scale heights of 1, 2.5, and 10 kpc. The north-south column density difference mentioned in §2.2 is evident in this plot. The simplest model for the gas is one with an exponential scale height of 2.3 kiloparsecs with log $N_\perp = 14.09$ and a 0.25 dex enhancement in $N_\perp$ at high positive Galactic latitudes. This distribution is roughly consistent with those for other high ionization species such as Si\,IV, C\,IV, and N\,V ($h \sim 3 - 5$ kpc; Savage, Sembach, & Lu 1997). A careful comparison of the O\,VI and other high ions along many individual sight lines is needed to fully assess the relative kinematics and distributions of these species (see, e.g., Zsargó et al. 2003 and Indebetouw & Shull 2004).
3.2. Relationship to Other Gas Tracers

The distribution and total amount of O VI generally does not correlate well with other tracers of ionized interstellar gas, such as soft x-ray emission from gas with $T \sim 10^6$ K or Hα emission from the warm ($T \sim 10^4$ K) ionized ISM. Similarly, N(O VI) does not track the total intensity of HI 21 cm emission. However, it is common for O VI to be found at velocities similar to those of HI and lower ionization species, such as C II-III-IV and Si II-III-IV. This result suggests that the O VI arises in distinct regions that are kinematically coupled to the lower ionization gas, such as interfaces between warm and hot gas.

3.3. Production of the Hot Gas

In the Milky Way, it is difficult to convert O V into O VI through photoionization. The ambient interstellar radiation field and the starlight from all but the hottest He-poor stars lack the 114 eV photons necessary for this conversion. Furthermore, photoionization by the extragalactic ultraviolet background is also inefficient at producing O VI in the local universe; path lengths of hundreds of kiloparsecs are required to reproduce the observed O VI columns (see Figure 20 in Sembach et al. 2003). As a result, the vast majority of the O VI observed along extended paths through the Galactic halo must be created by collisional processes. O VI is an excellent tracer of collisionally ionized gas at temperatures of $(1 - 5) \times 10^5$ K.

A variety of processes have been suggested as possible high ion production mechanisms (turbulent mixing, conduction, radiative cooling, shocks, etc).
is not possible to describe all of these here. For reviews, see the discussions in Fox et al. (2004) and Sembach, Tripp, & Savage (1997). A combination of models involving radiatively cooling gas, turbulent mixing, and the cooling of superbubbles in the Galactic halo may be necessary to explain all of the O VI data. If the origin of the O VI is dominated by cooling gas in a Galactic fountain flow, Savage et al. (2003) estimate that a mass flow rate of \(1.4 M_\odot \text{yr}^{-1}\) to each side of the Galactic plane with an average density of \(10^{-3} \text{cm}^{-3}\) is required to explain the average value of \(N_\perp(\text{O VI}) = 1.2 \times 10^{14} \text{cm}^{-2}\) measured for the southern Galactic hemisphere.

4. High Velocity O VI

4.1. Sky Covering Fraction

Sembach et al. (2003) have identified 84 individual high velocity O VI features along 102 sight lines observed by FUSE. With few exceptions, the high velocity O VI absorption is confined to \(100 \leq |v_{\text{LSR}}| \leq 400 \text{ km s}^{-1}\), indicating that the identified O VI features are either associated with the Milky Way or are nearby clouds within the Local Group.

We detect high velocity O VI \(\lambda 1031.926\) absorption with total equivalent widths \(W_\lambda > 30 \text{ mÅ} (3\sigma)\) along 59 of the 102 sight lines surveyed. For the highest quality sub-sample of the dataset, the high velocity detection frequency increases to 22 of 26 sight lines. Forty of the 59 sight lines have high velocity O VI \(\lambda 1031.926\) absorption with \(W_\lambda > 100 \text{ mÅ}\), and 27 have total equivalent widths \(W_\lambda > 150 \text{ mÅ}\). Converting these O VI equivalent width detection frequencies into estimates of \(N(\text{H}^+)\) in the hot gas indicates that \(\sim 60\%\) of the sky (and perhaps as much as \(\sim 85\%\)) is covered by hot ionized hydrogen at a level of

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N(\text{H}^+) \gtrsim 10^{18} \left( \frac{f_{\text{O VI}} < 0.2}{0.2} \right) \left( \frac{Z}{Z_\odot} \right) \text{cm}^{-2},
\]

where \(f_{\text{O VI}}\) is the fraction of oxygen in the form of O VI, and \(Z/Z_\odot\) is the gas metallicity relative to the Sun. This \(\text{H}^+\) detection frequency is larger than the value of \(\sim 37\%\) found for warm, high velocity neutral gas with \(N(\text{H I}) \sim 10^{18} \text{cm}^{-2}\) traced through 21 cm emission (Lockman et al. 2002).

4.2. Distribution

Figure 4 shows the locations of the high velocity O VI features on the sky, with squares indicating positive velocity features and circles indicating negative velocity features. The magnitude of the LSR velocity (without sign) is given inside each square or circle for the dominant high velocity O VI feature along each sight line. For sight lines with multiple high velocity features, we have plotted the information for the feature with the greatest O VI column density. Solid dots indicate directions where no high velocity O VI was detected.

There is often good correspondence between high velocity H I 21 cm emission and high velocity O VI absorption. When high velocity H I 21 cm emission is detectable in a particular direction, high velocity O VI absorption is usually detected if a suitable extragalactic continuum source is bright enough for FUSE to observe. O VI is present in the Magellanic Stream, which passes through the
south Galactic pole and extends up to $b \sim -30^\circ$, with positive velocities for $l \gtrsim 180^\circ$ and negative velocities for $l \lesssim 180^\circ$. O VI is present in high velocity cloud Complex C, which covers a large portion of the northern Galactic sky between $l = 30^\circ$ and $l = 150^\circ$ and has velocities of roughly $-100$ to $-170$ km s$^{-1}$.

The segregation of positive and negative velocities in Figure 4 is striking, indicating that the clouds and the underlying (rotating) disk of the Galaxy have very different kinematics. A similar velocity pattern is seen for high velocity H I 21 cm emission and has sometimes been used to argue for a Local Group location for the high velocity clouds (see Blitz et al. 1999). The kinematics of the high velocity O VI clouds are consistent with a distant location, but do not necessarily require an extended Local Group distribution as proposed by Nicastro et al. (2003). The dispersion about the mean of the high velocity O VI centroids decreases when the velocities are converted from the Local Standard of Rest (LSR) into the Galactic Standard of Rest (GSR) and the Local Group Standard of Rest (LGSR) reference frames with various assumptions about the distances of the clouds and their transverse motions. While this reduction is expected if the O VI is associated with gas in a highly extended Galactic corona, it does not provide sufficient proof by itself of an extended extragalactic distribution for the high velocity gas because the correction to the LGSR reference frame requires proper knowledge of the total space velocities of the clouds. Only one component of motion - the velocity toward the Sun - is observed. Additional information, such as the gas metallicity, ionization state, or parallax resulting from transverse motion across the line of sight, is needed to constrain whether the clouds are located near the Galaxy or are farther away in the Local Group.

4.3. Positive Velocity Absorption Wings

Twenty-one of the sight lines in the FUSE survey exhibit broad, weak absorption wings at high positive velocities. These wings extend asymmetrically from
low velocities, representative of those of Galactic halo gas, out to much higher velocities. In most cases, the integrated O VI column densities in the broad wings are much less than N(O VI) in the lower velocity absorption. Of the 21 sight lines with broad wings, 17 are in the northern Galactic hemisphere.

Some of the wings may be associated with outflows of hot gas from the Galactic disk, as has been suggested for the positive velocity wing in the direction of 3C 273 (Sembach et al. 2001). Toward Mrk 421, there is no corresponding wing of absorption in two nearby halo stars, implying that the wing arises in gas at distances of more than 3.5 kiloparsecs from the Galactic plane (Savage et al. 2005). This result may hold more generally as well, since no such wings are observed toward a larger sample of halo stars spread across the sky (Zsargó et al. 2003). Some of the wing gas could be tidal debris from past encounters between the Milky Way and Magellanic Clouds or other dwarf galaxies. A thorough study of the O VI wing absorption features and their relationship (or lack thereof) to lower ionization absorption may help to reveal their origin.

4.4. Origin of the High Velocity O VI

One possible explanation for some of the high velocity O VI is that transition temperature gas arises at the boundaries between cool/warm clouds of gas and a very hot (T > 10^6 K) Galactic corona or Local Group medium. Sources of the high velocity material might include infalling or tidally disturbed galaxies. A hot, highly extended (R > 70 kpc) corona or Local Group medium might be left over from the formation of the Milky Way or Local Group, or may be the result of continuous accretion of smaller galaxies over time. Hydrodynamical simulations of clouds moving through a hot, low-density medium show that weak bow shocks develop on the leading edges of the clouds as the gas is compressed and heated (Quilis & Moore 2001). Even if the clouds are not moving at supersonic speeds relative to the ambient medium, turbulent stripping of the cooler gas should result in mixing with the hotter coronal gas. O VI would be produced in the transition temperature gas resulting from the mixing. This mechanism for producing O VI has been suggested for Complex C (Fox et al. 2004) as well as smaller isolated high velocity clouds (e.g., Ganguly et al. 2005). Additional evidence for a hot Galactic corona through which the high velocity clouds must pass comes from the detection of O VII X-ray absorption lines near zero velocity (e.g., Nicastro et al. 2002; Fang, Sembach, & Canizares 2003; Rasmussen et al. 2003; Futamoto et al. 2004; McKernan, Yaqoob, & Reynolds 2004).

Alternatively, the O VI high velocity clouds and any associated H I or lower ionization material may be condensations within large gas structures falling onto the Galaxy. Cosmological structure formation models predict large numbers of cooling fragments embedded in dark matter, and some of these structures should be observable in O VI absorption as the gas cools through the T = 10^5 − 10^6 K temperature regime (Davé et al. 2001).

Some of the high velocity O VI clouds may be extragalactic clouds, based on what we currently know about their ionization properties (see, for example, Sembach et al. 1999). However, claims that essentially all of the O VI HVCs are extragalactic entities associated with an extended Local Group filament based on kinematical arguments alone are untenable. Such arguments fail to consider the selection biases inherent in the O VI sample, the presence of neutral (H I)
and lower ionization (Si IV, C IV) gas associated with some of the O VI HVCs, and the known “nearby” locations for at least two of the primary high velocity complexes in the sample — the Magellanic Stream is circumgalactic tidal debris, and Complex C is interacting with the Galactic corona (see Fox et al. 2004; Collins, Shull, & Giroux 2003). Furthermore, the O vii X-ray absorption measures used to support an extragalactic location have not yet been convincingly tied to either the O VI HVCs or to an external Local Group location. The O vii absorption may well have a significant Galactic component in some directions (see Fang et al. 2003). The Local Group filament interpretation (Nicastro et al. 2003) may be suitable for some of the observed high velocity O VI features, but it clearly fails in other cases (e.g., the Magellanic Stream or the PKS 2155-304 HVCs – see Sembach et al. 2003 and Collins, Shull, & Giroux 2004).

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