Probing Baryons in Galactic Halos and Gas Near Galaxies

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Abstract. We describe an extensive FUSE survey of highly ionized oxygen in the vicinity of the Milky Way that serves as an example of the type of study that would be desirable for other galactic systems. Understanding the origin of hot gas in the vicinity of galaxies and its relationship to the intergalactic medium presents a major observational challenge. Ultraviolet absorption-line spectroscopy is currently the most direct means for comprehensive investigations of the gas in galactic environments, but even with present (and near-term) facilities the number of background objects available to probe nearby galaxy halos and low-redshift cosmological structures is limited. Studying these structures over a range of impact parameters and angular separations would provide fundamental information about the baryonic content of the hot gas, its physical conditions, and its origins. A large space telescope optimized for high resolution spectroscopy in the 900–3200 Å wavelength region at a sensitivity sufficient to observe faint AGNs/QSOs at angular separations of $<1^\circ$ would be ideal for such studies.

1. Introduction

Understanding galaxy formation and evolution requires observational information about the hot, highly-ionized gas found in and near galaxies. A complete picture of the relationship between hot gas in galaxies and the intergalactic medium (IGM) does not yet exist because a variety of processes affect the heating and distribution of the interstellar gas in and around galaxies. Galaxy formation, accretion of satellite galaxies, tidal interactions, star-formation, galactic winds, and galaxy-IGM interactions may all contribute to the production of the hot gas observed in the IGM and extended galactic halos.

In this article, we outline a program we have begun with the Far Ultraviolet Spectroscopic Explorer (FUSE) to study the hot gas in the vicinity of the Milky Way. The study is described in detail in a series of three articles devoted to probing the highly ionized oxygen (OVI) absorption along complete paths through the Galactic halo and Local Group. The articles include a catalog of the spectra and basic observational information (Wakker et al. 2002), a study...
of the hot gas in the Milky Way halo (Savage et al. 2002b), and an investigation of the highly ionized high velocity gas in the vicinity of the Galaxy (Sembach et al. 2002). Here, we summarize the high velocity gas results and comment on their implications for understanding other types of highly ionized gas. This comprehensive study serves as a prime example of what can be learned if serious efforts are made to conduct large spectroscopic observing programs with existing space-based instrumentation. Similar types of studies conducted with future generations of instruments on the Hubble Space Telescope (HST) and other large space telescopes will enable us to explore the properties of gas in other groups of galaxies in much greater detail than is presently possible.

In Table 1 we list basic information for some of the best ultraviolet (UV) absorption-line diagnostics of hot gas. The table entries include the atom or ion, rest wavelength of the transition, cosmological redshift required to shift the line(s) to an observed wavelength of 1150 Å, the temperature at which the atom or ion peaks in abundance under conditions of collisional ionization equilibrium, the thermal width of the line at that temperature, and a logarithmic relative line strength that depends on the cosmic abundance of the element ($A$), the line strength ($f_\lambda$), and the peak ionization fraction ($\phi$) of the ion in collisionally ionized gas. Larger values of $Af_\lambda\phi$ indicate easier detectability.

| Species | $\lambda$ (Å) | $z(1150$ Å) | $T_{CIE}$ (K)$^a$ | $b_{th}$(km s$^{-1}$)$^b$ | log [$Af_\lambda\phi$]$^c$ |
|---------|----------------|-------------|---------------------|------------------------|-----------------|
| HI Lyα  | 1215.7         | —           | $< 10^5$            | 40.8$^d$               | $-2.06^d$       |
| HI Lyβ  | 1025.7         | 0.12        | $< 10^5$            | 40.8$^d$               | $-2.86^d$       |
| HI Lyγ  | 972.5          | 0.18        | $< 10^5$            | 40.8$^d$               | $-3.32^d$       |
| CIV     | 1548.2, 1550.8 | —           | $1.0 \times 10^5$  | 11.8                   | $-1.51, -1.81$  |
| NV      | 1238.8, 1242.8 | —           | $1.8 \times 10^5$  | 14.6                   | $-2.35, -2.65$  |
| OIV     | 787.7          | 0.46        | $1.6 \times 10^5$  | 12.9                   | $-1.36$         |
| O V     | 629.7          | 0.83        | $2.5 \times 10^5$  | 16.1                   | $-0.97$         |
| O VI    | 1031.9, 1037.6 | 0.11        | $2.8 \times 10^5$  | 17.1                   | $-1.65, -1.95$  |
| Ne VIII | 770.4, 780.3   | 0.48        | $5.6 \times 10^5$  | 21.5                   | $-2.36, -2.66$  |
| Mg X    | 609.8, 624.9   | 0.87        | $1.1 \times 10^6$  | 27.4                   | $-3.31, -3.61$  |

$^a$Temperature of maximum ionization fraction in collisional ionization equilibrium (Sutherland & Dopita 1993).
$^b$Thermal line width, $b = (2kT/m)^{1/2}$, at $T = T_{CIE}$ unless indicated otherwise.
$^c$Values of $f_\lambda$ are from Morton (1991) and Verner et al. (1994). Values of $A$ (abundance relative to hydrogen on a logarithmic scale where H = 12.00, C = 8.55, N = 7.97, O = 8.87, Ne = 8.07, and Mg = 7.59) are from Grevesse & Noels (1993) and Anders & Grevesse (1989). Values of $\phi$ are from Sutherland & Dopita (1993).
$^d$Value at $T = 10^5$ K.

The O VI $\lambda\lambda$1031.926, 1037.617 doublet lines are the best UV resonance lines to use for kinematical investigations of hot ($T \sim 10^5$ – $10^6$ K) gas in the low-redshift universe. Oxygen is the most abundant element heavier than helium, and the O VI lines have large oscillator strengths. Lower ionization UV lines observable at high spectral resolution are generally either much weaker than the
O VI lines (e.g., N V λ1238.821, 1242.804) or are better tracers of collisionally ionized gas at temperatures $T < 10^5$ K (e.g., C IV λ1548.195, 1550.770, C III λ1977.020, Si IV λ1393.755, 1402.770, Si III λ1206.500). This latter set of ions is also considerably more susceptible to photoionization than O VI.

X-ray spectroscopy of the interstellar or intergalactic gas in higher ionization lines (e.g., O VII, O VIII) is possible with XMM-Newton and the Chandra X-ray Observatory for a small number of sight lines toward AGNs and QSOs, but the spectral resolution ($R \equiv \lambda/\Delta \lambda < 1000$) is modest compared to that afforded by FUSE ($R \sim 15,000$). While the X-ray lines provide extremely useful information about the amount of gas at temperatures greater than $10^6$ K, the interpretation of where that gas is located, or how it is related to the $10^5 - 10^6$ K gas traced by O VI, is hampered at low redshift by the complexity of the hot ISM and IGM along the sight lines observed.

2. An Example: The Milky Way and its High Velocity Cloud System

We have conducted a study of the highly ionized high velocity gas in the vicinity of the Milky Way using an extensive set of FUSE data. We summarize the results for the sight lines toward 100 AGNs/QSOs and two distant halo stars in this section (see Sembach et al. 2002; Wakker et al. 2002). For the purposes of this study, gas with $|v_{LSR}| > \sim 100$ km s$^{-1}$ is typically identified as “high velocity”, while lower velocity gas is attributed to the Milky Way disk and halo. A sample spectrum from the survey is shown in Figure 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** A portion of the FUSE spectrum of PG 1116+215 in the 1015–1040 Å spectral region. Interstellar and intergalactic lines are indicated. The numbers under the top tick marks denote the rotational levels of the H$_2$ lines ($J = 0 - 2$ lines are prominent). The locations of high velocity O VI features are indicated below the spectrum.

2.1. Observational Results

We have identified approximately 85 individual high velocity O VI features along the 102 sight lines in our sample. A critical part of this identification process involved detailed consideration of the absorption produced by O VI and other species (primarily H$_2$) in the thick disk and halo of the Galaxy, as well as the absorption produced by low-redshift intergalactic absorption lines of HI and
ionized metal species. We searched for absorption in a velocity range of ±1200 km s\(^{-1}\) centered on the O VI \(\lambda 1031.926\) line. With few exceptions, the high velocity O VI absorption is confined to \(|v_{\text{LSR}}| \leq 400\) km s\(^{-1}\), indicating that the O VI features observed are either associated with the Milky Way or nearby clouds within the Local Group.

![All-sky projection of the high velocity O VI features in the LSR reference frame.](image)

Figure 2. All-sky projection of the high velocity O VI features in the LSR reference frame. The Galactic anti-center is at the center of the plot, and Galactic longitude increases to the left. This map does not include gas at velocities attributed to the thick disk/halo of the Galaxy (\(|v_{\text{LSR}}| > 100\) km s\(^{-1}\)). The velocities of the O VI features are gray-scale coded and displayed as filled regions of radius 12\(^{\circ}\). When two features are detected within 12\(^{\circ}\) of each other (either along the same sight line or along adjoining sight lines), the shaded area size is adjusted accordingly. Points with no shading indicate directions where no high velocity O VI is observed.

The high velocity O VI features have velocity centroids ranging from \(-372 < v_{\text{LSR}} < -90\) km s\(^{-1}\) to \(+93 < v_{\text{LSR}} < +385\) km s\(^{-1}\). There are an additional 6 confirmed or very likely (> 90% confidence) detections and 2 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. We plot the sky distribution of the high velocity O VI in Figure 2, where we code the velocities of the features by shading circular regions around the sight lines for which high velocity O VI is detected.

Most of the high velocity O VI features have velocities incompatible with those of Galactic rotation (by definition). 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. While this reduction is expected if the O VI is associated with gas in a highly extended Galactic corona or in the Local Group, it does not provide sufficient proof by itself of an extragalactic location for the high velocity gas. Additional information, such as the gas metallicity or ionization state, is needed to constrain the cloud locations.
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 \( b \) are close to the thermal width of 17.1 km s\(^{-1}\) expected for O VI at \( T = 2.8 \times 10^5 \) K, while higher values of \( b \) require additional non-thermal broadening mechanisms or gas temperatures significantly larger than \( 2.8 \times 10^5 \) K.

The high velocity O VI features have logarithmic column densities of 13.06 to 14.59, with an average of \( \langle \log N \rangle = 13.95 \pm 0.34 \) and a median of 13.97. We show the distribution of the high velocity O VI column densities on the sky in Figure 3. The average high velocity O VI column density is a factor of 2.7 times lower than the typical low velocity O VI column density found for the same sight lines through the thick disk/halo of the Galaxy (see Savage et al. 2002b).

![Figure 3](image)

Figure 3. All-sky projection of the high velocity O VI column densities observed in our FUSE survey. The logarithmic column density is coded according to symbol size (see legend), with the symbol split in half if two features are present. Triangles indicate upper limits. Note that large column densities of high velocity O VI (\( \log N > 14 \)) are found in many regions of the sky.

We detect high velocity O VI \( \lambda 1031.926 \) absorption with total values of \( W_\lambda > 30 \) mÅ at \( \geq 3\sigma \) confidence 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 \( W_\lambda > 100 \) mÅ, and 27 have \( W_\lambda > 150 \) mÅ. Converting these O VI equivalent width detection frequencies into estimates of \( N(H^+) \) 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 \( N(H^+) \geq 8 \times 10^{17} \) cm\(^{-2}\) if the high velocity gas has a metallicity similar to that of the Magellanic Stream \( (Z \sim 0.2 - 0.3) \). This detection frequency of hot H\(^+\) associated with the high velocity O VI appears to be larger than the value of \( \sim 37\% \) found for high velocity warm gas with \( N(HI) \sim 10^{18} \) cm\(^{-2}\) traced through 21 cm emission (Lockman et al. 2002).

Some of the high velocity O VI is associated with well-known HI high velocity clouds (HVCs; see Wakker & van Woerden 1997 for a review). These include
the Magellanic Stream, possibly Complex A, Complex C, the Outer Arm, and several smaller HI clouds. Some of the high velocity O VI features have no counterpart in HI 21 cm emission. These include discrete high velocity features as well as broad positive-velocity O VI absorption wings that blend with lower velocity O VI absorption in the Galactic thick disk/halo. The discrete features may typify clouds located in the Local Group. The broad, high velocity O VI absorption wings are concentrated mainly in the northern Galactic hemisphere and may trace either tidal debris or thick disk/halo gas that has been accelerated to high velocities by star-formation activity in the Galactic disk.

2.2. Interpretation

High velocity O VI is both widespread and common along complete paths through the Galactic halo. The high velocity O VI traces numerous phenomena, including tidal interactions with the Magellanic Clouds (via the Magellanic Stream), accretion of low-metallicity gas (e.g., Complex C), highly ionized clouds (e.g., the Mrk 509 HVCs), and the outflow of hot gas from the Galactic disk (e.g., the broad positive velocity absorption features). Distinguishing between all of the possible phenomena occurring at large distances from the Galactic plane is absolutely essential for understanding the role of HVCs in Galactic evolution.

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 \( (T > 10^6 \text{ K}) \) Galactic corona or Local Group medium. Sources of the high velocity material might include infalling or tidally disturbed galaxies. Since viscous processes affect the gas but not the stars in interacting systems, tracing the original source of the high velocity gas may prove difficult. A hot, highly extended \( (R > 70 \text{ kpc}) \) 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. \( N \)-body simulations of the tidal evolution and structure of the Magellanic Stream favor a low-density medium \( (n < 10^{-4} \text{ cm}^{-2}) \) for imparting weak drag forces to deflect some of the Stream gas and providing a possible explanation for the absence of stars in the Stream (Gardiner 1999). Moore & Davis (1994) also postulated a hot, low-density corona to provide ram pressure stripping of some of the Magellanic Cloud gas. 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, some viscous or turbulent stripping of the cooler gas likely occurs.

An alternative explanation for the O VI observed at high velocities may be that the clouds and any associated HI fragments are simply 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 pass through the \( T = 10^5 – 10^6 \text{ K} \) temperature regime. Estimates of the number density of these structures are consistent with the observed IGM O VI detection rate (Tripp, Savage & Jenkins 2000; Fang & Bryan 2001; Savage et al. 2002a). This situation is in many ways analogous to the coronal model described above.
because only about 30% of the hot gas is detectable in O VI absorption, while the remaining ∼70% is too hot to observe (Davé et al. 2001).

The tenuous hot Galactic corona or Local Group gas may manifest itself through X-ray absorption-line observations of higher ionization species than O VI. For example, the amount of O VII in the hot gas is given by $N(\text{O VII}) = (\text{O/H})_{\odot} Z f_{\text{O VII}} n L$, where $Z$ is the metallicity of the gas, $f$ is the ionization fraction, and $L$ is the path length. At $T \sim 10^6$ K, $f_{\text{O VII}} \approx 1$ (Sutherland & Dopita 1993). For $n = 10^{-4}$ cm$^{-3}$, $N(\text{O VII}) \sim 2 \times 10^{16} Z (L/100$ kpc) (cm$^{-2}$).

Preliminary results (Fang et al. 2002; Nicastro et al. 2002) demonstrate that O VII absorption is detectable near zero velocity at a level consistent with the presence of a large, nearby reservoir of hot gas. A firm association of the X-ray absorption with a hot Galactic corona or Local Group medium will require additional observations since the ionization mechanism and location of the higher ionization gas traced by O VII are still uncertain (see Heckman et al. 2002).

3. Looking Forward: The Need for a Large Space Telescope

Studying the basic physical properties of gas in the vicinity of galaxies is essential for understanding how galaxies evolve over time and quantifying the relationship between galaxies, the IGM, and large-scale cosmic structures. Key quantities to be determined include the elemental abundances, ionization state, and physical properties ($n$, $T$, size) of the gas. We have made a start at examining the properties of gas in the Milky Way and Local Group, but extending these studies to other groups of galaxies is required if we are to incorporate the local results into broader descriptions of galaxy evolution and the formation of the "cosmic web" of hot gas expected in the local universe. To make accurate assessments of the kinematics and column densities of a wide range of ionization stages requires high spectral resolution ($R \sim 20,000 – 50,000$), broad UV wavelength coverage (preferably 900–3200 Å so that both zero and low-redshift systems could be observed in C III and O VI), and excellent sensitivity.

Current ultraviolet spectrographs (e.g., FUSE and STIS) are limited to observing QSOs with $m_B < 16$. At this magnitude, the number of QSOs per square degree is $\ll 1$, and it is difficult to observe individual stars in galaxies other than the Milky Way and Magellanic Clouds. The Cosmic Origins Spectrograph (COS), which is scheduled for installation in HST in 2004, will have about an order of magnitude greater sensitivity than STIS at far-UV wavelengths. QSOs with $m_B \approx 17 – 18$ should be observable in reasonable integration times. However, even at this greater sensitivity, the number of QSOs per square degree is still limited. A large space telescope with a diameter of 4 meters (or better still, 8 meters) equipped with a high efficiency spectrograph and detector could easily improve upon the COS sensitivity by a factor of 10 or more and dramatically increase the number of background sources available for spectroscopic studies. At $m_B \approx 20$, the average separation between QSOs is only $\sim 7'$ (see Shull et al. 1999), and there are numerous possibilities for studying multiple sight lines through low-redshift galactic halos, groups, and clusters of galaxies. Furthermore, at these sensitivities lightly reddened B supergiants could be observed out to distances of $\sim 2$ Mpc, making it possible to study the gaseous content of Local Group galaxies such as M31 or M33 in unprecedented detail.
A 4 m to 8 m space telescope optimized for point source spectroscopy would provide an opportunity for an entirely new approach to studying the gaseous halos of galaxies and intragroup gas. Instead of our current methodology of blindly finding low-redshift absorption-line systems spectroscopically and then trying to identify (image) the galaxies responsible for the absorption, one could target specific, well-studied galactic systems for spectroscopic investigations of their gaseous content. A similar pro-active approach may prove fruitful for studying the filamentary structures of the ionized IGM once they are identified through their OVI or X-ray emissions by future observatories such as SPIDR or Constellation-X.

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