FUSE Observations of O VI in High Velocity Clouds

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ABSTRACT

We have used moderate-resolution (FWHM \(\approx 25\) \(\text{km s}^{-1}\)) spectra of AGNs and QSOs observed by the Far Ultraviolet Spectroscopic Explorer to make the first definitive measurements of absorption by hot gas in high velocity clouds (HVCs) at large distances from the Galactic plane. Seven of the 11 sight lines studied exhibit high velocity \(|V_{\text{LSR}}| > 100\) \(\text{km s}^{-1}\) O VI \(\lambda 1031.93\) absorption with \(\log N(\text{O VI}) \approx 13.79–14.62\). High velocity O VI absorption is detected in the distant gas of H I HVC Complex C, the Magellanic Stream, several HVCs believed to be in the Local Group, and the outer Galaxy. The fraction of O VI in HVCs along the seven sight lines containing high velocity O VI averages \(\sim 30\%\), with a full range of \(\sim 10–70\%\). The O VI detections imply that hot \((T \sim 3 \times 10^5\) K\), collisionally-ionized gas is an important constituent of the HVCs since O VI is difficult to produce by photoionization unless the path lengths over which the absorption occurs are very large \((>100\) kpc\). The association of O VI with H I HVCs in many cases suggests that the O VI may be produced at interfaces or mixing layers between the H I clouds and hot, low density gas in the Galactic corona or Local Group. Alternatively, the O VI may originate within cooling regions of hot gas clouds as they are accreted onto the Galaxy.

Subject headings: Galaxy: halo – intergalactic medium – ISM: clouds – ISM: evolution – ISM: kinematics and dynamics – ultraviolet: ISM

1. Introduction

Since their discovery nearly 40 years ago, interstellar high velocity clouds (HVCs) have remained enigmatic. Their origins, fundamental physical properties, and distances are unknown in...
most cases (see review by Wakker & van Woerden 1997). Although HVCs are often described in terms of their HI 21 cm emission and their peculiar velocities\(^7\) with respect to the motions of the general interstellar medium, the traditional view of HVCs as completely neutral entities has given way to one that recognizes the importance of an ionized component to many of the clouds. Hα emission has been detected toward several large HVC complexes (Tufte, Reynolds, & Haffner 1998; Bland-Hawthorn et al. 1998; Weiner & Williams 1996), and recent absorption line observations with the Hubble Space Telescope have shown that some HVCs are almost fully ionized (Sembach et al. 1995, 1999).

Understanding the ionization of HVCs is a key step toward a more complete description of the high velocity gas. The large peculiar velocities of HVCs make them excellent candidates for studying hot gas within the clouds and their surrounding environments. A prime diagnostic of gas at temperatures \(T \sim 10^5 - 10^6\) K is the O VI \(\lambda\lambda1031.93,1037.62\) doublet, which can be observed in the spectra of distant QSOs and AGNs with the newly commissioned the Far Ultraviolet Spectroscopic Explorer (FUSE).

In this Letter we report the first detections of O VI absorption in several HVCs located in different regions of the sky. The directions considered are listed in Table 1, where we summarize sight line characteristics and basic measurements for the HVCs. The reader may find information about the overall extent and distribution of O VI in the Galactic halo in a companion paper (Savage et al. 2000). A description of the FUSE mission can be found in Moos et al. (2000).

### 2. Observations and Data Processing

The FUSE data for this investigation were obtained during the commissioning stage of the mission in late 1999. Each observation was obtained with the source centered in the \(30'' \times 30''\) aperture of the LiF1 spectrograph channel. Exposure times ranged from 13 ksec (Ton S210) to 55 ksec (Mrk 509) (see Savage et al. 2000). The time-tagged photon lists were processed through the standard FUSE calibration pipeline available at the Johns Hopkins University as of November 1999. The lists were screened for valid data with constraints imposed for earth limb angle avoidance and passage through the South Atlantic Anomaly. Corrections for detector backgrounds, Doppler shifts caused by spacecraft orbital motions, and geometrical distortions were applied (see Sahnow et al. 2000). No corrections were made for optical astigmatism aberrations or small spectral shifts introduced by thermal effects since the data were obtained prior to completion of in-orbit focusing activities. The primary effect of omitting these processing steps is to degrade the spectral resolution slightly.

The processed data have a nominal spectral resolution of 25 km s\(^{-1}\) (FWHM), with a relative

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\(^7\)Usually, clouds moving in excess of 100 km s\(^{-1}\) with respect to the Local Standard of Rest fall into the category of high velocity cloud.
wavelength dispersion solution accuracy of $\sim 6 \text{ km s}^{-1}$ (1$\sigma$). The zero point of the wavelength scale for each observation was determined by registering the $\text{H}_2$ (6–0) P(3) line at 1031.19 Å to the velocity of the peak $\text{H I}$ 21 cm emission for the sight line. In cases where no $\text{H}_2$ absorption is detected, we compared the velocities of the strong $\text{Si II}$ $\lambda$1020.70 and $\text{O I}$ $\lambda$1039.23 lines to those observed for lines of the same species at longer wavelengths.

Fully reduced FUSE LiF1A data covering the 1020–1045 Å spectral region are shown for PKS 2155-304 and Mrk 509 in Figure 1. Note the presence of negative high velocity $\text{O VI}$ 1031.93 Å absorption along both sight lines. $\text{O VI}$ $\lambda$1037.62 absorption is present in both spectra; however, the HVC components are blended with $\text{C II}$ $\lambda$1037.02. There is also weak, narrow $\text{C II}$ $\lambda$1036.34 absorption toward both objects near the velocities of the $\text{O VI}$ HVCs. Other figures showing the $\text{O VI}$ HVCs considered herein can be found in Savage et al. (2000), Oegerle et al. (2000), and Murphy et al. (2000a).

3. High Velocity $\text{O VI}$ Measurements

Continuum normalized intensity profiles for the $\text{O VI}$ HVC sight lines are presented in Figure 2. Equivalent widths and column densities were computed by direct integration of the $\text{O VI}$ $\lambda$1031.93 intensity and apparent column density profiles (Sembach & Savage 1992). $N_a (\text{O VI}) \ [\text{cm}^{-2}] = 2.748 \times 10^{12} \int \tau_a (v) \, dv$, where $\tau_a (v)$ is the measured optical depth of the 1031.93 Å line at velocity $v$ (in km s$^{-1}$) (Savage & Sembach 1991). We have assumed an oscillator strength $f = 0.133$ (Morton 1991). $N_a (\text{O VI})$ is a reasonable approximation to $N(\text{O VI})$ since the HVC lines are both weak and broad. The integration ranges lie beyond the velocities expected for $\text{O VI}$ absorption arising in the general environment of the thick disk and low halo ($|z| < 3 \text{ kpc}$) (see Savage et al. 2000). In Table 1 we list the fraction of total $\text{O VI}$ along each sight line in HVCs, $f_{HVC}$. On average, $f_{HVC} \sim 30\%$.

The $\text{H}_2$ (6–0) P(3) 1031.19 Å and R(4) 1032.35 Å lines occur at velocities of $-214 \text{ km s}^{-1}$ and $+123 \text{ km s}^{-1}$, respectively, relative to the $\text{O VI}$ $\lambda$1031.93 line. We have modeled the impact of these lines on the observed $\text{O VI}$ profiles by examining other $\text{H}_2$ (J = 3 or 4) lines in the (3–0) to (8–0) vibrational bands covered by the FUSE LiF1A spectra. Our estimates of the strengths and shapes of the P(3) 1031.19 Å and R(4) 1032.35 Å lines are shown as heavy solid lines in Figure 2. The values of $W_\lambda$ and log $N(\text{O VI})$ in Table 1 have had the illustrated $\text{H}_2$ contributions removed.

4. HVC Identifications

High velocity ($V_{\text{LSR}} < -100 \text{ km s}^{-1}$) $\text{O VI}$ is seen along 7 of the 11 extended sight lines toward AGNs and QSOs observed by FUSE. The HVCs have negative velocities, with the exception of a weak HVC detected toward Ton S180 (see Table 1). In many cases, the $\text{O VI}$ HVCs can be related to $\text{H I}$ HVCs located at large distances (>3 kpc) from the Galactic plane.
4.1. The C IV HVCs: Local Group Clouds

High velocity O VI absorption toward Mrk 509 and PKS 2155-304 occurs at velocities similar to those of some of the C IV HVCs studied by Sembach et al. (1999). The Mrk 509 C IV HVCs ($\langle V_{LSR} \rangle = -287, -228 \text{ km s}^{-1}$) are believed to be located in the Local Group outside the Milky Way based upon their ionization properties and the very low thermal pressures ($p/k \sim 2 \text{ cm}^{-3} \text{ K}$) inferred if the clouds are in photoionization equilibrium. They display strong C IV absorption, with little lower ionization absorption and no detectable H I 21 cm emission. Furthermore, they show no evidence of Hα emission (Sembach, Bland-Hawthorn, & Savage 2000). This ionization pattern is characteristic of gas clouds irradiated by extragalactic background radiation.

The O VI HVC absorption toward Mrk 509 is distributed in a broad component centered on $\langle V_{LSR} \rangle \approx -230 \text{ km s}^{-1}$, with FWHM $\approx 120 \text{ km s}^{-1}$. It exhibits a steep decline in strength at velocities where the C IV is strongest (i.e., in the $-287 \text{ km s}^{-1}$ component). Most of the O VI appears to be associated with the lower velocity C IV HVC at $-228 \text{ km s}^{-1}$. The ratio of C IV to O VI is $<1$ in this cloud and the HVCs observed toward PKS 2155-304. The observed amount of O VI is more than an order of magnitude higher than predicted by the standard photoionization model\(^8\) described by Sembach et al. (1999), which leads us to conclude that there are multiple ionization processes in these HVCs.

4.2. Complex C

Mrk 876 lies behind HVC Complex C, which is located more than 3.5 kpc from the Galactic plane (van Woerden et al. 1999). The low metallicity of Complex C, $[S/H] \sim -0.5$ to $-1.0$, indicates that it may be material falling onto the Milky Way rather than material ejected from the Galactic disk (Wakker et al. 1999; Gibson et al. 2000). In the direction of Mrk 876, Complex C has two distinct H I components centered on $V_{LSR} = -175$ and $-132 \text{ km s}^{-1}$ (Murphy et al. 2000a). The broad O VI absorption spans these neutral components and forms a smooth absorption trough (see Figure 2).

The presence of O VI at velocities similar to those of the neutral tracers of Complex C suggests that Complex C contains a substantial amount of ionized gas. For a gas in collisional ionization equilibrium at $T = 3 \times 10^5 \text{ K}$ with $Z \sim 0.1-0.3 \text{ Z}_\odot$, $N(\text{O VI}) = 1.5 \times 10^{14} \text{ cm}^{-2}$ translates into $N(\text{H}^+) \approx (3 - 9) \times 10^{18} \text{ cm}^{-2}$, or roughly 10–30% of the observed H I column density of $2.9 \times 10^{19} \text{ cm}^{-2}$.

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\(^8\)Their photoionization model uses an AGN/QSO spectral energy distribution with a mean intensity at the Lyman limit $J_0 = 1 \times 10^{-23} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$ (Haardt & Madau 1996).
4.3. Magellanic Stream

Three of the 7 sight lines exhibiting high velocity O VI lie in the general direction of the Magellanic Stream. Ton S210 and Ton S180 lie about $10^\circ$ off the Stream near Complex MSII. No high velocity 21 cm emission from the Stream is detected toward either object; however 21 cm emission is detected toward Ton S210 at $-196 \text{ km s}^{-1}$ with a width of $26 \text{ km s}^{-1}$ (Murphy, Sembach, & Lockman 2000b). The H I and O VI HVCs toward Ton S210 are distinct from the nearby Stream material, which has velocities $V_{LSR} \gtrsim -100 \text{ km s}^{-1}$ in this direction. A sensitive H I map of this region indicates that the 21 cm emission is isolated (M. Putman, private communication) and resembles the compact H I HVCs believed to be located in the Local Group (Braun & Burton 1999; but see also Charlton et al. 2000 and Zwaan & Briggs 2000).

In the direction of NGC 7469, the high velocity O VI absorption is related to Magellanic Stream material seen in H I 21 cm emission near $-350 \text{ km s}^{-1}$ (Murphy et al. 2000b). Ionized Stream gas has been detected previously through its Hα emission (Weiner & Williams 1996). Most of that emission could be explained by photoionization by starlight (Bland-Hawthorn & Maloney 1999). However, the presence of O VI in the Stream toward NGC 7469 indicates that hot gas must be present since the low gas densities required to produce the observed amounts of O VI solely by photoionization requires very large path lengths ($l \gtrsim 100 - 200 \text{ kpc} > d_{MS}$).

4.4. Outer Galaxy

Most of the O VI absorption toward H 1821+643 can be attributed to the thick disk and outer Galactic warp (Oegerle et al. 2000; Savage et al. 2000). The broad, shallow absorption between $-300$ and $-175 \text{ km s}^{-1}$ is probably tracing gas in the most distant portions of the outer Galaxy. The limiting velocity of co-rotating interstellar gas in this direction is roughly $-200 \text{ km s}^{-1}$. Savage, Sembach, & Lu (1995) noted a very weak C IV feature with $N(\text{C IV}) = (1.2 \pm 0.3) \times 10^{13} \text{ cm}^{-2}$ near $-213 \text{ km s}^{-1}$. The velocity of the LSR with respect to the velocity centroid of the Local Group ($l \approx 105^\circ$, $b \approx -8^\circ$) is $\approx -300 \text{ km s}^{-1}$ (see Mihalas & Binney 1982), so the projection of this relative velocity onto the H 1821+643 sight line is $\approx -220 \text{ km s}^{-1}$, similar to that of the high velocity O VI.

5. Discussion

O VI is difficult to produce by photoionization (114 eV photons are required). The gas density must be so low that path lengths exceeding the distance to the Magellanic Stream are necessary to account for the observed quantities of O VI in the HVCs. See Sembach et al. (1999) for a discussion of the photoionization models.

Many of the O VI HVCs contain cooler material (e.g., Mrk 876, NGC 7469), or are in close proximity to H I HVCs at similar velocities (e.g., Mrk 509, PKS 2155-304, Ton S210). To produce
O VI by shocks requires a shock speed of $\approx 170 \text{ km s}^{-1}$ (Hartigan, Raymond, & Hartmann 1987). The observed velocity gradients of the neutral gas in Complex C (van Woerden, Schwarz, & Hulsbosch 1985) and the Magellanic Stream (Mathewson & Ford 1984; Putman & Gibson 1999) are much smaller than this, so it seems unlikely that cloud-cloud collisions are responsible for the O VI.

One possibility for the production of the O VI observed in the HVCs is that the clouds are moving through a pervasive, hot ($T \sim 10^6 \text{ K}$), low density ($n_H \lesssim 10^{-4} - 10^{-5} \text{ cm}^{-3}$) Galactic halo or Local Group medium. The existence of such gas has been considered in various contexts (see Fabian 1991; Weiner & Williams 1996; Blitz & Robishaw 2000; Murali 2000). The O VI HVCs have velocities comparable to the adiabatic sound speed ($\sim 150 \text{ km s}^{-1}$) for a hot, low density medium. Thus, strong shocks are probably not responsible for the O VI production. Rather, in such a scenario, the O VI would occur in the conductive interfaces or turbulently mixed regions of ionized gas between the hot medium and the Magellanic Stream or other cooler gas detected in 21 cm emission or ultraviolet absorption.

Alternatively, some of the O VI may be produced within cooling regions of hot gas structures associated with the assembly of the Milky Way. Much of the baryonic content of the low redshift universe is expected to be at temperatures of $10^5 - 10^7 \text{ K}$ in the vicinity of galaxies and groups of galaxies (Cen & Ostriker 1999). As the hot gas flows onto galaxies, portions of it should cool as the density increases. Complex C may represent a relatively advanced stage of such an accretion, while the HVCs toward Mrk 509 and PKS 2155-304 would represent an earlier evolutionary stage. FUSE data for a large number of AGN/QSO sight lines should help to distinguish between these various possibilities for the production of the O VI HVCs.

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Table 1. O VI High Velocity Cloud Sight Lines

| Object       | Type   | V (mag) | l (°) | b (°) | W_λ(1031.9) (mA) | log N^a (cm^{-2}) | f_{HVC}^b | Velocity (km s^{-1}) | HVC^c | ID |
|--------------|--------|---------|-------|-------|------------------|-------------------|------------|----------------------|-------|----|
| Mrk 509      | Syft1  | 13.1    | 36.0  | -29.9 | 243±14           | 14.44±0.04        | 0.35       | -380 to -95          | 1     |    |
| PKS 2155-304 | BL Lac | 13.1    | 17.7  | -52.3 | 107±10           | 14.00±0.04        | 0.33       | -300 to -80          | 1     |    |
| Mrk 876      | Syft1  | 15.5    | 98.3  | +40.4 | 146±14           | 14.18±0.06        | 0.39       | -215 to -100         | 2     |    |
| Ton S180     | Syft1  | 14.3    | 139.0 | -85.1 | 156±21           | 14.29±0.07        | 0.37       | -250 to -75          | · · · |    |
| Ton S210     | QSO    | 15.2    | 225.0 | -83.2 | 44±14            | 13.79±0.11        | 0.12       | +225 to +310         | · · · |    |
| NGC 7469     | Syft1  | 13.0    | 83.1  | -45.5 | 289±23           | 14.62±0.07        | 0.74       | -400 to -100         | 4     |    |
| H1821+643    | QSO    | 14.2    | 94.0  | -27.4 | 87±20            | 14.00±0.06        | 0.21       | -330 to -175         | 5     |    |

^a Column density derived by integrating the O VI 1031.926 Å line over the velocity range listed. The value is corrected for the (6–0) H$_2$ P(3) 1031.19Å absorption shown in Figure 2. An additional uncertainty of $\sim \pm 0.04$ dex (not listed) is appropriate for those observations where H$_2$ absorption has been removed.

^b Ratio of N(O VI) in the high velocity gas within the velocity range listed compared to total N(O VI) along the sight line. See Savage et al. (2000) for values of N(O VI) outside the listed velocity range.

^c HVC Association: 1 = C IV-HVCs detected by Sembach et al. (1999); 2 = Complex C; 3 = Compact H I-HVC, possibly in the Local Group; 4 = Magellanic Stream; 5 = Distant outer Galaxy.
Fig. 1.— FUSE LiF1A data for the 1020–1045 Å spectral regions of PKS 2155-304 and Mrk 509. Ticks above the Mrk 509 spectrum indicate the locations of prominent H$_2$ lines in the (5–0) and (6–0) vibrational bands. Note the presence of O VI HVCs toward both objects.
Fig. 2.— Normalized intensity versus LSR velocity for the O VI $\lambda1031.93$ line along the 7 sight lines containing O VI HVCs. The heavy solid line overplotted on each spectrum is a model of the H$_2$ absorption in the (6–0) $P(3)$ $\lambda1031.19$ and $R(4)$ $\lambda1032.35$ lines.