High-velocity O VI in and near the Milky Way

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Abstract. The Far Ultraviolet Spectroscopic Explorer (FUSE) has observed over three hundred fifty sightlines to extragalactic targets. About one hundred fifty of these are of sufficient quality to measure O VI absorption in and near the Milky Way. High-velocity O VI absorption is detected in about 80% of the sightlines, with the detection rate going up for sightlines with higher signal-to-noise ratios. O VI is almost always seen in directions with previously known H I HVCs, including HVCs complex C, complex A, complex WD, the Magellanic Stream, and the Outer Arm. Studies of several sightlines through complex C suggest that the O VI absorption is produced in conductive interfaces between the cool HVC and a hotter surrounding medium, most likely a corona around the Milky Way. The O VI detections associated with the Magellanic Stream imply that this hot corona has a radius of at least 50 kpc. About half of the detections of high-velocity O VI are in directions where no high-velocity H I was previously known. Some of these are probably associated with the Magellanic Stream, others may represent Local Group gas. Still others often show up as a distinct wing on the low-velocity absorption; these may either represent an outflow from the Milky Way associated with the Galactic Fountain, they may be extragalactic HVCs, or they may be tracing a wind from the Galactic Center. Distance limits to the high-velocity O VI are scarce, but at least one of the clouds appear to be more distant than 4 kpc.
1. Observations

The Far Ultraviolet Spectroscopic Explorer (FUSE) satellite has now measured OVI absorption in and near the Milky Way in hundred forty five sightlines to extragalactic objects. The OVI $\lambda\lambda$1031.926, 1037.617 doublet are the best lines to use for kinematical investigations of hot ($T > 10^5$ K) gas. Oxygen is the most abundant element heavier than helium, and the OVI lines have large oscillator strengths ($f_{1031}=0.133$, $f_{1037}=0.067$, Morton 1991). FUSE was launched in 1999, and contains four co-aligned spectrographs covering the 905–1187 Å spectral region. The optics in the two channels (side 1 and side 2) that record data above 1000 Å are coated with aluminum and lithium-fluoride (LiF), while the two channels registering the flux below 1000 Å are coated in silicon-carbide (SiC). Each LiF and SiC channel is further split into two segments, corresponding to two separate detectors (A and B). The OVI lines are covered by four channels, but a usefully high S/N ratio is only obtained in the LiF1A and LiF2B segments. Spectra are sampled on 0.0068 Å ($\sim 2$ km s$^{-1}$) pixels, but the resolution is about 15000 (20 km s$^{-1}$). FUSE data therefore always need to be heavily rebinned. The S/N ratio obtained in the LiF1A segment is usually a factor $\sim 1.5$ higher than that obtained in the LiF2B segment.

As of May 2004, 345 distant extra-galactic objects had been observed by FUSE. These include quasars, BL Lac objects, Seyfert galaxies, large H II regions in external galaxies, and starburst galaxies. This count excludes stars in the Magellanic Clouds, M 31 and M 33. The signal-to-noise (S/N) ratio of the observations ranges from 0 to a maximum of about 35. These S/N ratios are measured per 20 km s$^{-1}$ resolution element in the combined LiF1A+LiF2B data. There are 13 objects for which an S/N ratio >20 near OVI has been achieved, 40 objects with S/N=10 to 20, 35 with S/N=6 to 10, and 57 with S/N=3 to 6. This gives a total of 145 objects for which Galactic OVI absorption can be measured. For the remaining 210 extragalactic targets either the continuum near OVI is too complicated, or the S/N ratio is too low near OVI (though it is sometimes higher elsewhere in the spectrum). An earlier sample, consisting of 100 sightlines was described by Wakker et al. (2003).

In almost all sightlines OVI absorption is seen near velocities relative to the LSR of $|v_{\text{LSR}}|<100$ km s$^{-1}$. Just a few (low S/N) sightlines yield an upper limit (see Savage et al. 2003). In about 80% of the sightlines OVI is also seen at velocities $|v_{\text{LSR}}|$ larger than 100 km s$^{-1}$ (see Sembach et al. 2003). Figure 1 shows a representative set of spectra containing high-velocity OVI, while Fig. 2 shows both the H I and the O VI high-velocity sky.

2. High-velocity O VI with high-velocity H I

In most cases where the sightlines intersect an HVC seen in 21-cm H I emission, a distinct OVI absorption component is seen at the same velocities. This is the case for twelve sightlines through HVC complex C, two through complex WD, and seven through the Magellanic Stream. Only complex A is not always detected in both H I and O VI: just three (weak O VI) complex A components are found in nine sightlines.
Figure 1. Sample of 12 sightlines showing the different kinds of high-velocity O VI detected by FUSE. The high-velocity components are identified by the labels below the plots: C=complex C, WB=complex WB, WD=complex WD, MS=Magellanic Stream, MSe=MS extension, LG=possible Local Group, EP=extreme-positive velocity, Scl=Sculptor group. The continua include a model for the H$_2$ absorption lines at 1031.191 and 1032.356 Å, and in one case (NGC 7469) HD at 1031.912 Å.
Figure 2. Comparison of high-velocity H I and O VI. The continuous grey scale shows H I LSR velocities from the Hulsbosch & Wakker (1988) survey. Filled circles indicate the sightlines with detected high-velocity O VI. Smaller open circles are for sightlines without high-velocity O VI.
Fox et al. (2004, and elsewhere in this proceedings) analyzed several of the better complex C sightlines, and compared O VI, C IV, N V, and H I with model predictions for the ionic ratios and kinematics. They concluded that the O VI most likely originates in a conductive interface (or possibly in a turbulent mixing layer) between the cool gas seen in 21-cm emission and a hotter (10^6 K or more) surrounding medium. This result thus provides strong evidence for the existence of a hot, highly-extended gaseous corona. Since the distance of complex C is still unknown (though it is >6 kpc, and is thought to be 10–20 kpc, see Wakker 2001), the size of this corona is not constrained by the complex C results. The fact that O VI is rarely seen associated with complex A might imply that the hot gas lies at z<5 kpc (for the z-height of complex A, see van Woerden et al. 1999). However, the fact that in directions through the Magellanic Stream high-velocity O VI is always seen in association with Stream H I would argue that the hot corona is larger than 50 kpc in diameter. Of course, it is quite possible (likely even) that the hot corona is patchy.

3. High-velocity O VI without high-velocity H I

One of the more interesting discoveries coming out of the FUSE survey of Galactic O VI were the many absorption components in directions without high-velocity H I seen in 21-cm emission. Fifteen of these are probably associated with the Magellanic Stream, as they lie within about 5 degrees from the Stream as seen in H I. Five positive-velocity wings are found at galactic longitudes within 30° of the Galactic Center, and these could possibly originate in a Galactic Wind. The more mysterious discoveries are the 18 detections with velocities of ∼−150 km s$^{-1}$ at galactic longitude $l=30^\circ$ to $140^\circ$, and galactic latitude $b<−10^\circ$, and the 18 detections with velocities between +100 and +250 km s$^{-1}$ at $l=175^\circ$ to $330^\circ$, $b>38^\circ$, often in the form of a “wing” to the low-velocity absorption.

The detections at southern latitudes with velocities of about −150 km s$^{-1}$ lie in the same part of the sky as the Magellanic Stream. But in 21-cm emission the Stream has velocities of −300 to −450 km s$^{-1}$, and an O VI absorption component is seen at those velocities. (see Fig. 2). The tidal models do not predict any gas at lower velocities in this part of the sky (e.g. Gardiner & Noguchi 1996). On the other hand, several Local Group galaxies with negative velocities are located here, including M 31, M 33, and several dwarf irregulars (NGC 6822, DDO 210, WLM, Pegasus, IC 10), which have velocities ranging from −53 to −237 km s$^{-1}$. Sembach et al. (2003) thus suggested that the high-velocity O VI might be associated with Local Group gas. However, more analysis of the physical conditions in the O VI gas is going to be necessary before this conclusion can be made firm.

The high-positive-velocity O VI lies on the opposite side of the sky. Again, gas in the Magellanic Stream generally would have high positive velocities in this part of the sky, but the Stream is not seen in 21-cm emission in the directions of the background targets, nor are such velocities expected from the tidal model. There seem to be two explanations: the high-positive-velocity O VI may represent the outflowing Galactic Fountain, or it may represent samples of distant gas clouds that even might be the counterpart of the negative-velocity
Figure 3. Apparent column density profiles as a function of LSR velocity for the O VI $\lambda$1031.926 line for Mrk 421, BD+38°2182 and HD 93521. The Mrk 421 profile has been binned to 5 pixels (10 km s$^{-1}$), while the profiles for the stars were binned to 2 pixels (4 km s$^{-1}$). Note the large breadth of the O VI profile for the extragalactic line of sight compared to the halo star lines of sight. The lower panels compares the O VI and C III absorption for Mrk 421. The C III profile has been scaled by a factor 10. The vertical solid line at 60 km s$^{-1}$ is where the C III transitions from very strong to weak.
Local Group gas seen in the southern sky. Again, more work is needed (and in progress) before these absorptions can be given a definitive interpretation.

4. The distance of the O VI HVCs

The distance to the gas producing the high-velocity O VI absorption is still very uncertain. For cases where H I and O VI are seen at the same velocity it is possible to constrain the distance in the usual manner (using detections and non-detections against stellar targets with known distances, see Wakker 2001). For the O VI associated with the Magellanic Stream a distance of 50 to 150 kpc is implied by the tidal models of the Stream. For the possible Local Group gas, and for the positive-velocity wings, however, no such secondary information is available. For these absorbers there are two possible ways to constrain the distance. First, if many other ions are seen to be associated with the O VI absorption, one can analyze the physical conditions in the cloud, combining the ionic column densities with photoionization models, such as those provided by CLOUDY (Ferland et al. 1998); this gives constraints on the cloud’s size. Second, one can search for the presence or absence of high-velocity O VI absorption in the spectra of distant stars. So far, only one such comparison has been published (Savage et al. 2004), shown in Fig. 3. The absorption toward the QSO Mrk 421 shows a clear positive-velocity wing, extending from +65 to +165 km s$^{-1}$. No such wing is seen in the spectrum of the star BD+38 2182, just 4$^{\circ}$ away, at a distance of 4.0 kpc. This clearly indicates that the high positive velocity O VI gas is distant.

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