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# The FUSE Survey of O VI in and near the Milky Way

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**Abstract.** We summarize the results of the Far-Ultraviolet Spectroscopic Explorer (FUSE) program to study O VI in the Milky Way halo. Spectra of 100 extragalactic objects and two distant halo stars are analyzed to obtain measures of O VI absorption along paths through the Milky Way thick disk/halo and beyond. Strong O VI absorption over the velocity range from $-100$ to 100 km s$^{-1}$ reveals a widespread but highly irregular distribution of O VI, implying the existence of substantial amounts of hot gas with $T{\sim}3{\times}10^5$ K in the Milky Way thick disk/halo. The overall distribution of O VI can be described by a plane-parallel patchy absorbing layer with an average O VI mid-plane density of $n_o$(O VI) = $1.7{\times}10^{-8}$ cm$^{-3}$, an exponential scale height of $\sim$2.3 kpc, and a $\sim$0.25 dex excess of O VI in the northern Galactic polar region. Approximately 60 percent of the sky is covered by high velocity O VI with $|v_{\rm LSR}|{>}100$ km s$^{-1}$. This high velocity O VI traces a variety of phenomena in and near the Milky Way including outflowing material from the Milky Way, tidal interactions with the Magellanic Clouds, accretion of gas onto the Milky Way, and warm/hot gas interactions in a highly extended (>70 kpc) Galactic corona or with hot intergalactic gas in the Local Group.

## 1. Introduction

Absorption line observations of the highly ionized lithium-like atoms of O VI, N V, and C IV provide valuable information about gas in interstellar space with temperatures of $\sim 3{\times}10^5$ to $10^5$ K. Among these three species, O VI is especially important because of the large cosmic abundance of oxygen and the large energy (113.9 eV) required to convert O V into O VI. Studies of interstellar O VI have been hampered by the difficulties involved in making observations in the far-UV wavelength range of its resonance doublet at 1031.93 and 1037.62 Å. Instruments operating efficiently at wavelengths shortward of $\sim$1150 Å require reflecting optics with special coatings (such as LiF or SiC) and windowless detectors. Although the Copernicus satellite successfully observed interstellar O VI toward many stars in the Galactic disk (Jenkins 1978a,b), the studies were limited to stars with visual magnitudes $m_V{<}7$ and did not yield information about the extension of O VI away from the Galactic plane. However, the launch of the



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high throughput Far-Ultraviolet Spectroscopic Explorer (FUSE) satellite in 1999 (Moos et al. 2000; Sahnow et al. 2000) has made it possible to obtain far-UV high resolution spectra of a large number of extragalactic continuum sources. With these spectra it has been possible to obtain the first assessment of the distribution and kinematics of O VI in the Milky Way halo and beyond.

## 2. Observations and Reductions

The FUSE O VI catalog paper (Wakker et al. 2003) contains the full details of the FUSE observations and reductions of Galactic O VI absorption toward 100 extragalactic sources and two halo stars. The O VI $\lambda$1037.62 line is often confused by blending with C II* $\lambda$1037.02 and the $H_2$ (5-0) R(1) and P(1) lines at 1037.15 and 1038.16 Å. The O VI $\lambda$1031.93 line is usually relatively free of blending, since the $H_2$ (6-0) P(3) and R(4) lines are often relatively weak and are displaced in velocity by $-214$ and 125 km s$^{-1}$ from the rest O VI velocity.

Information about O VI in the Milky Way halo (see Savage et al. 2003) has mostly been derived from the relatively blend-free O VI $\lambda$1031.93 line. Examples of O VI $\lambda$1031.93 line profiles are shown in Wakker (this symposium volume). The continuum placement is generally quite reliable since most of the objects are AGNs, which usually have well-defined power-law continua. For O VI at $3\times10^5$ K (the temperature at which O VI peaks in abundance) the thermal Doppler contribution to the O VI line width corresponds to $b$=17.7 km s$^{-1}$ (FWHM=29.4 km s$^{-1}$), where $b$ is the standard Doppler spread parameter. The expected thermal width of the O VI line is comparable to the FUSE resolution of 20–25 km s$^{-1}$. Since the O VI lines are usually resolved, reliable column densities can be obtained using the apparent optical depth method (Savage & Sembach 1991). The O VI column densities, velocities and line widths can be found in Savage et al. (2003) and Sembach et al. (2003).

## 3. Separating Low Velocity Thick O VI Disk Absorption from High Velocity Absorption

The lines of sight to the objects observed in the FUSE halo gas O VI program pass through Milky Way disk gas, thick disk/halo gas, intermediate-velocity clouds (IVCs), high-velocity clouds (HVCs), and may even sample intergalactic O VI in the Local Group of galaxies. At high Galactic latitude the dividing lines in velocity between high, intermediate, and low velocity are generally at $|v_{LSR}|$ = 90 and 30 km s$^{-1}$, although the effects of Galactic rotation must also be considered. The O VI absorption lines trace a complex set of processes and phenomena involving hot gas in the Milky Way disk, thick disk/halo, and beyond. We refer to O VI in the Milky Way disk-halo interface extending several kpc away from the Galactic plane as the "thick disk O VI".

The O VI profiles exhibit a diversity of strengths and kinematical behavior (see Fig. 1). Disk, and thick disk O VI are clearly detected within the general velocity range $-90$ to 90 km s$^{-1}$ toward 91 of the 102 survey objects. In addition, the absorption profiles reveal O VI at high velocities with $|v_{LSR}|$ ranging from $\sim$100 to 400 km s$^{-1}$ in $\sim$60% of the sight lines.

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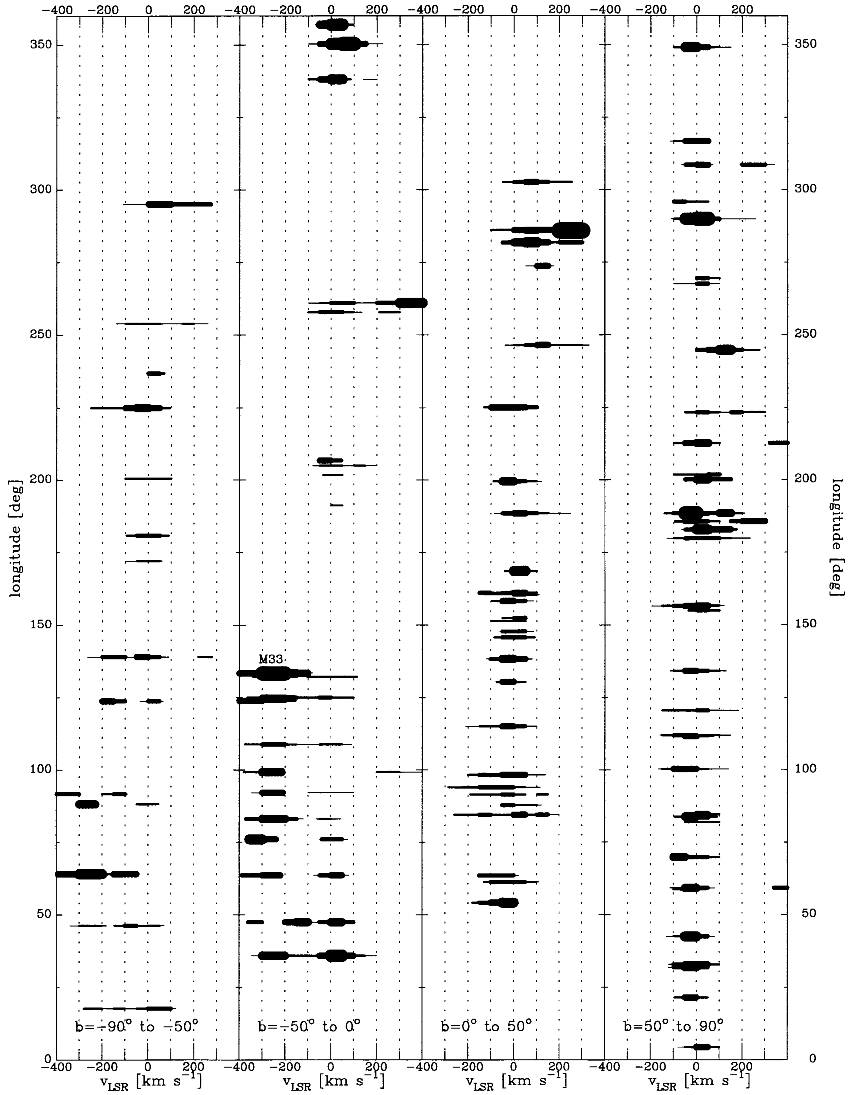


Figure 1. Overall kinematical behavior of the O VI bearing gas in the Milky Way Halo and beyond. The horizontal bars display the LSR velocity ranges of the O VI absorption. The width of each bar is a measure of the column density in the velocity range of the bar. The observations are grouped according to Galactic longitude and latitude. O VI absorption associated with the thick disk of the Milky Way is mostly confined to the velocity range from $-90$ to $90$ km s$^{-1}$. Note that the high velocity O VI absorption appears in $\sim$60% of the objects. This high velocity O VI absorption is mostly at positive velocities for longitudes between 180 and 360 degrees and at negative velocities for longitudes between 0 and 180 degrees.

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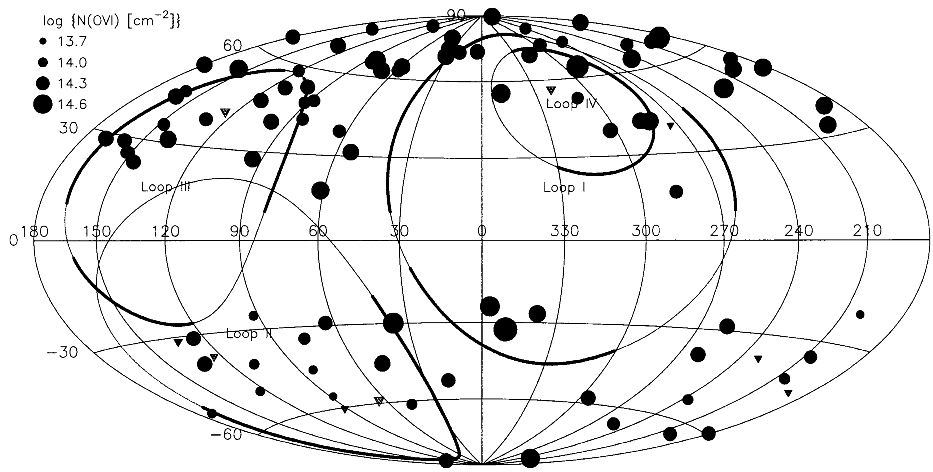


Figure 2. Values of log N(O VI) for the thick disk of the Milky Way are represented as circles displayed in this Aitoff projection of the sky with the Galactic center at the center of the figure and Galactic longitude increasing to the left. The circle size is proportional to log N(O VI) according to the code shown. Upper limits to log N(O VI) are denoted with triangles with a size proportional to the limit. The thick disk O VI has an irregular distribution with a ∼0.25 dex excess of O VI at the higher northern Galactic latitudes. The positions of four non-thermal radio loops are displayed in the diagram.

## 4. Properties of the Thick Disk O VI Absorption

The relatively strong O VI absorption associated with the thick disk of Galactic O VI has log N(O VI) between 13.85 and 14.78. The equivalent column density perpendicular to the Galactic plane, log [N(O VI)sin$|b|$], ranges from 13.45 to 14.68. The distribution of O VI on the sky is quite irregular (see Fig. 2).

The large O VI column densities measured along extragalactic sight lines imply that a substantial amount of O VI is situated in the Galactic thick disk at large distances away from the plane of the Galaxy. The scale height of Galactic O VI can be estimated from the behavior of log [N(O VI)sin$|b|$] versus log $|z(\mathrm{kpc})|$ measured toward stars in the Galaxy and toward the extragalactic objects of the FUSE O VI survey. In fitting the observations, the use of a mid-plane density of $1.7\times10^{-8}$ cm$^{-3}$ appears well justified since the value represents an average extending over ∼220 stars in the combined Copernicus Satellite and FUSE disk star sample (Jenkins et al. 2001). The observations are not well fitted by a symmetric plane parallel model for the distribution of O VI extending away from the Galactic plane. The simplest model that improves the fit is a superposition of a plane-parallel patchy absorbing layer with an exponential scale height of ∼2.3 kpc, a mid-plane density of $1.7\times10^{-8}$ cm$^{-3}$, and a ∼0.25 dex excess of O VI at the higher northern Galactic latitudes.

The kinematic properties of the O VI absorption provide useful information about the various physical processes controlling the distribution of gas at $T{\sim}3{\times}10^5$ K in the Galactic halo. Two simple measures of the kinematics of the O VI absorption are the average LSR velocity, and the velocity dispersion of the absorption as measured by the Doppler-spread parameter $b$. At high latitudes, where the effects of Galactic rotation are small, the values of $v_{\rm obs}$ exhibit a large spread in velocity with an average of 0 km s$^{-1}$ and a standard deviation of 22 km s$^{-1}$. It is interesting that the O VI at high latitudes in each Galactic hemisphere is moving with positive and negative velocity with nearly equal frequency. For the full sample, $b$(min)=30 km s$^{-1}$, $b$(max)=99 km s$^{-1}$, $b$(median)=59 km s$^{-1}$, $b$(average)=61 km s$^{-1}$, and the standard deviation on $b$ is 15 km s$^{-1}$. The O VI absorption lines are much wider than the absorption expected from thermal Doppler broadening alone since gas at $T{\sim}3{\times}10^5$ K, the temperature at which O VI is expected to peak in abundance, has $b$(O VI)=17.7 km s$^{-1}$. Inflow, outflow, Galactic rotation, and turbulence therefore also affect the profiles.

The relationship between the column density of O VI and other ISM tracers was studied for H I, H$\alpha$, soft X-ray emission, and non-thermal radio emission. In all cases the amount of O VI is poorly related to the amount of these other ISM tracers. The correspondence between the X-ray sky brightness and N(O VI) is poor. This is not too surprising given the 0.25 KeV diffuse X-ray background is a complex superposition of a non-uniform local bubble component and halo and extragalactic background components experiencing attenuation due to photoelectric absorption occurring in cooler foreground gas.

## 5. Origin of O VI and Other Highly Ionized Species in the Thick Galactic Disk

The FUSE O VI survey observations reported here provide important new insights into the distribution and kinematics of highly ionized gas in the Milky Way halo. The observations confirm the basic validity of Spitzer's (1956) prediction that the ISM of the Galaxy contains a hot gas phase that extends well away from the Galactic plane. Theories for the origin of highly ionized gas in the Milky Way halo must explain the distribution, ionization, kinematics, and support of the gas. For reviews of the models see Spitzer (1990), McKee (1993), and Savage (1995). The ionization of Si IV and C IV is likely either from electron collisions in a hot gas, photoionization, or some combination of both processes. With their high ionization threshold, O VI and N V are more likely to be produced by collisional ionization in hot gas. However, non-equilibrium ionization effects will probably be important because collisionally ionized gas cools very rapidly in the temperature range $(1\text{–}5){\times}10^5$ K. Such transition temperature gas might occur within the cooling gas of a "Galactic fountain" (Shapiro & Field 1976; Edgar & Chevalier 1986; Shapiro & Benjamin 1991), in the conductively heated interface region between the hot and cool interstellar gas (Ballet, Arnaud, & Rothenflug 1986), in radiatively cooling SN bubbles (Slavin & Cox 1992, 1993) or in turbulent mixing layers (TMLs) where hot gas and warm gas are mixed by turbulence to produce gas with non-equilibrium ionization characteristics (Begelman & Fabian 1990; Slavin, Shull, & Begelman 1993). The heating and ionization of the gas could also occur through magnetic reconnection processes (Raymond 1992; Zimmer, Lesch, & Birk 1997).

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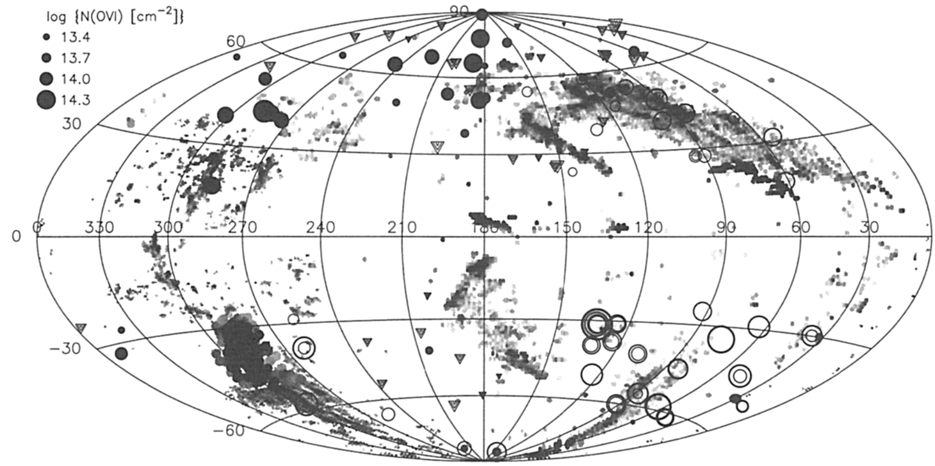


Figure 3. Values of log N(O VI) for high velocity O VI are represented as circles displayed in this Aitoff projection of the sky with the Galactic anti-center at the center of the figure and Galactic longitude increasing to the left. The circle size is proportional to log N(O VI) according to the code shown. Open circles are for negative high velocity O VI filled circles are for positive high velocity O VI. Upper limits to log N(O VI) are denoted with triangles with a size proportional to the limit. The grey scale gives the column density distribution of high velocity H I (adapted from Wakker et al. 2003).

## 6. **High Velocity** O VI

We have identified 85 individual high velocity O VI features along the 102 lines of sight in our sample. Based on the frequency of occurrence of high velocity O VI toward the 102 objects, we estimate that approximately 60% of the high latitude sky is covered with high velocity O VI. The observed limiting column densities and the assumption of a metallicity of 0.25 solar implies that 60% of the high latitude sky is covered with hot ionized hydrogen with $N(H^+)>10^{18}$ cm$^{-2}$. The sky covering factor of high velocity hot ionized hydrogen exceeds that for neutral high velocity hydrogen. The full details of the survey are discussed in Sembach et al. (2003). The velocity extents of the high velocity O VI features are indicated in Fig. 1. The logarithmic column densities of O VI range from 13.06 to 14.59 with a median of 13.97. The average high velocity O VI column density is 2.7 times smaller than for the typical low velocity O VI for sight lines through the thick disk/halo. The distribution on the sky of objects with high velocity O VI absorption is shown in Fig. 3 where each circle indicates a detection of high velocity O VI with the circle size proportional to logN(O VI). Triangles denote upper limits. In Fig. 3 we also display the high velocity H I sky with the gray-scale proportional to the H I column density in gas with absolute LSR velocity exceeding 100 km s$^{-1}$. Wakker (this symposium volume) discusses the different types of highly ionized HVCs detected in the FUSE survey and their possible origins. The high velocity O VI traces gas from the tidal interactions with

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the Magellanic Clouds, the accretion of gas by the Galaxy, outflowing material from the Galactic disk, warm/hot gas interactions in a highly extended Galactic corona, and intergalactic gas in the local group. The high velocity sky in O VI is as rich and complex as the H I high velocity sky.

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