HIGHLY-IONIZED GAS; PROBING ENERGETIC GALACTIC ENVIRONMENTS

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William F. Zech

J. Christopher Howk, Director

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Abstract

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We present Far Ultraviolet Spectroscopic Explorer (FUSE) and Space Telescope Imaging Spectrograph (STIS E140M) observations of the post-asymptotic giant branch star ZNG 1 in the globular cluster Messier 5 ($l = 3.9^{\circ}$, $b = +47.7^{\circ}$; $d = 7.5$ kpc, $z = +5.3$ kpc). High velocity absorption is seen in C IV, Si IV, O VI, and lower ionization species at LSR velocities of $\sim -140$ and $\sim -110$ km s$^{-1}$. We conclude that this gas is not circumstellar on the basis of photoionization models and path length arguments. Thus, the high velocity gas along the ZNG 1 sight line is the first evidence that highly-ionized HVCs can be found near the Galactic disk. We measure the metallicity of these HVCs to be $[\text{O}/\text{H}] = +0.22 \pm 0.10$, the highest of any known HVC. Given the clouds’ metallicity and distance constraints, we conclude that these HVCs have a Galactic origin. This sight line probes gas toward the inner Galaxy, and we discuss the possibility that these HVCs may be related to a Galactic nuclear wind or Galactic fountain circulation in the inner regions of the Milky Way.

Absorption from high ions (Si IV, C IV, and N V) is used to probe hot gas from the Milky Way to high-redshift primordial galaxies. However, only in our own Galaxy have they been observed with high enough spectral resolution to fully
resolve the line profiles. We present an homogeneous study of the high-resolution STIS E140H (1.5-2.7 km s\(^{-1}\) resolution) spectra of the interstellar Si IV, C IV, and N V absorption along 50 Galactic sight lines. These data are complemented by FUSE O VI for all but 5 stars. We are able to resolve narrow components in Si IV (\(\leq 6.5\) km s\(^{-1}\)) and C IV (\(\leq 10\) km s\(^{-1}\)) undetectable at lower resolution. We find that these narrow components are ubiquitous throughout the Galaxy and constitute a large part of the total number of components and almost half of the total column density. These narrow components imply temperatures where little C IV is expected, yet considerable amounts of C IV (and Si IV) is observed. We find that photoionization from OB stars can account for very few of the narrow components. The majority of the narrow components must have been photoionized by radiation from hot cooling gas, or the remains of a hot gas that has radiatively cooled.
Dedication

To my parents, grandparents, and sister.
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B.1 HD177989 (1) 
B.2 HD201345 (3) 
B.3 HD195965 (4) 
B.4 HD209339 (6) 
B.5 HD218915 (7) 
B.6 HD224151 (8) 
B.7 HD3827 (9) 
B.8 HD15137 (10) 
B.9 HD24534 (13) 
B.10 HD40005 (15)
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CHAPTER 1

INTRODUCTION

1.1 Introduction

This dissertation is composed of two studies. The first, Chapter 2, deals with highly-ionized high-velocity clouds (HVCs) located in the Milky Way. These highly-ionized HVCs have the distinction of being the first to be shown to originate from our Galaxy. The second part of this dissertation, Chapter 3, is a survey of the highly-ionized gas along 50 Galactic sight lines. Both of these studies share in common the analysis of the $10^4 - 10^6$ K gas that resides along the sight lines. This introduction is meant to familiarize the reader with a few basic characteristics of this gas and how we get information from it.

To probe gas that has a temperature of order $10^4 - 10^6$ K, we observe ions that exist in that temperature regime. The ions we focus on are Si IV, C IV, N V, and O VI, where this “spectroscopic notation” denotes an ion that has lost the number of electrons that is one less than the Roman numeral. The ionization energies required to create these ions are 33.5 eV, 47.9 eV, 77.5 eV, and 113.9 eV, respectively. A crude calculation reveals that these ions can be created in an ideal gas with a temperature of order $10^5$ K. Detailed computer simulations (e.g., Gnat & Sternberg 2007) show that these ions, if in collisional ionization equilibrium, peak in abundance at the temperatures 0.6, 1.0, 1.8, and 2.8 ($\times10^5$ K), respectively (Figure 1.1).
Figure 1.1. Collisional ionization equilibrium distributions of the ionic ratios of Si IV, C IV, N V, and O VI. These ions have ionization potentials of 33.5 eV, 47.9 eV, 77.5 eV, and 113.9 eV, and peak in abundance at temperatures 0.6, 1.0, 1.8, and 2.8 ($\times 10^5$ K), respectively.
We use absorption techniques to study these ions because they are sensitive to even very small amounts of material. Si IV absorbs photons with wavelengths at 1393.760 and 1402.773 Å, C IV at 1548.195 and 1550.770 Å, N V at 1238.821 and 1242.804 Å, and O VI at 1031.926 and 1037.617 Å. These wavelengths lie in the far-ultraviolet (FUV) region of the spectrum. To observe these ions requires space-based telescopes. The Space Telescope Imaging Spectrograph (STIS) onboard the Hubble Space Telescope (HST) covers the wavelength range that includes Si IV, C IV, and N V, and the Far Ultraviolet Spectroscopic Explorer (FUSE) covers the wavelength range that includes O VI. These two instruments provided the spectra for the research in this dissertation.

The ions observed (or more specifically, their absorbing wavelengths) determines the choice of astronomical target. What is required is an object that emits substantial radiation at these wavelengths. Thus, we want an object that has a blackbody curve that peaks in the far-ultraviolet. Quasars (QSOs) and active galactic nuclei (AGNs) are typical extragalactic targets of choice, and the young, hot O and B spectral type stars are typical Galactic targets. (Of course, we could choose to observe an O or B type star in another galaxy and they could also serve as extragalactic targets.) The next most important criterion for target selection is a well-behaved spectrum so that we can differentiate interstellar absorption from the underlying continuum. All the targets observed in this dissertation were O and B stars because they generally produce a smooth stellar wind that is easily modeled, peak in the FUV, and are bright enough to facilitate very high resolution spectroscopy.

The target for the first part of this dissertation was a high-temperature evolved post-asymptotic giant branch (PAGB) star located in a globular cluster that hap-
pened to show absorption at high velocities ($|v_{\text{LSR}}| > 90$ km s$^{-1}$). This turned out to be a great find, as it revealed the first highly-ionized HVCs to be shown to originate from within our Galaxy. All the other highly-ionized HVCs are observed toward extragalactic objects and are considered to have an extragalactic origin. The target selection criteria for the second part of this work was that the targets were Galactic spectral type O or B stars, that they were observed at the highest resolution available (using the STIS E140H setup), and that the wavelength range covered at least two of the ions Si IV, C IV, and N V (O VI is not covered with STIS). This second study constitutes a survey of 50 Galactic sight lines, probing various physical environments that contain ionized gas, at the highest resolution our current telescopes are capable of. The high resolution (1.5 to 2.7 km s$^{-1}$) allows us to decompose the absorption profiles into their individual cloud structures. We can then obtain the physical properties of each cloud along each sight line.

The physical properties of primary interest are column density, centroid velocity, temperature, metallicity, and distance. The column density of, e.g., Si IV, is the number of Si IV ions that occupy a column 1 cm$^2$ in cross section that extends to the target. This quantity can be used to compare with other sight lines, and also with theoretical calculations that model the physical mechanisms that give rise to the ionization. This, in turn, can help determine the ionization mechanisms of the ionized gas. The velocity structure of the gas can also help in determining the correct ionization model. The temperature of each cloud is derived from a property of the cloud’s absorption profile called a $b$-value (Doppler parameter). If we assume the absorption profile is Maxwellian, then the $b$-value is proportional to the standard deviation ($b = \sqrt{2}\sigma$) and the full width half max
(FWHM = $2\sqrt{\ln 2}b$), and is related to the most probable speed in a Maxwell-Boltzman distribution. This can then be translated to a temperature (or more accurately, an upper limit on temperature). The metallicity is the relative quantity of an element compared to hydrogen and its value is given relative to solar abundances. A direct measure of metallicity cannot always be obtained because a measure of the hydrogen content is required. Distance refers to the distance to the gas (not necessarily the target, although knowledge of the distance to the target helps to constrain the distance to the gas). This seems like the simplest of quantities, yet it remains the most elusive. Observing several stars of known distance in the direction of the gas and looking for a change in absorption is the best way to constrain the distance. For the ZNG 1 HVCs, distance and metallicity played a major role in the analysis.

We primarily use two methods to extract the column densities, $b$-values, and centroid velocities from the spectral absorption; the apparent optical depth (AOD) method, and component fitting. We refer to the figures in Appendix B to illustrate the two methods. For both methods, we first model the continuum as it would be if no absorption were present. We accomplish this by fitting a polynomial to the spectrum surrounding the absorption feature (blue curve in the left-most panel). Once the continuum is determined, we divide the spectrum by the fitted continuum to obtain the normalized profile (second panel). Normalizing allows for an easier visual comparison between the absorption profiles by placing them on an equal footing. We measure the total column density (and the other mentioned properties) in the AOD method by integrating the area under the $N_a(v)$ profile (top third panel). We can choose various integration ranges to estimate the absorption in various parts of the profile, however, if a definite component (cloud)
structure is present in this area, component fitting is a more accurate method to obtain the properties of this component. Component fitting is the process where we model the individual clouds along the sight line. This is done by assuming the gas in each cloud follows a Maxwellian distribution. In this way, we can model each absorption feature (cloud) with a Gaussian curve and obtain the column density, \( b \)-value, and centroid velocity (right-most panel). Component fitting, however, requires fairly good resolution and signal-to-noise; the lower these values are, the less robust the component model will be. The AOD method can be used to obtain the integrated properties when no definite component structure is seen, and can also be used as a means to check the results of component fitting.

We have briefly covered the techniques employed in understanding the observed interstellar gas in this work. Understanding the energetic gas in the Milky Way is important because it drives the turbulence within the interstellar medium (ISM) and the energetic feedback in the Galaxy. This turbulence and feedback creates large-scale flows that redistribute metals in the Galaxy. This, in turn, determines the properties of subsequent generations of stars. In short, the hot gas plays a major role in the evolution of not only our Galaxy, but other galaxies as well. A further introduction to the roles of hot gas in the Galaxy will be presented in Chapters 2 and 3.
CHAPTER 2

THE FIRST HIGHLY-IONIZED HVCS FOUND IN THE MILKY WAY

2.1 Introduction

High-velocity clouds (HVCs) are identified because they are clearly inconsistent with participating in Galactic rotation. In practice, the cut-off for selecting HVCs is that they have LSR velocities $|v_{\text{LSR}}| \geq 90 \text{ km s}^{-1}$. While their origins are not fully understood, there is growing evidence that the HVCs are important components of the on-going exchange of matter between the Milky Way and the surrounding intergalactic medium (IGM) and, therefore, important to our understanding of the formation and evolution of galaxies (see, e.g., the recent reviews by Wakker & van Woerden 1997; Wakker et al. 1999; Wakker 2004; Benjamin 2004; Richter 2006). In this context, many models have been constructed for the HVCs. Oort (1970) first suggested the HVCs were gaseous relics left over from the formation of the Milky Way, and more recent models have elaborated on this model of HVCs as the building blocks of galaxies and the Local Group (Blitz et al. 1999). The discovery of disrupted stellar satellites in the halo of the Milky Way has led to suggestions that HVCs may be the gaseous remnants of such satellites accreted by the Galaxy (Ibata et al. 1994; Putman et al. 2004), and the Magellanic Stream has long been known as gas removed from the Magellanic Clouds (Putman et al. 2003). Various models (e.g., Bregman 1978, Houck & Bregman...
1990) have also discussed the HVCs in the context of the galactic fountain, in which gas is ejected from the Galactic disk by the combined effects of multiple, correlated supernova explosions (Shapiro & Field 1976; Norman & Ikeuchi 1989). These models have distinct predictions for the distances and metallicities of the HVCs. These are the two principal diagnostics for the origins of the HVCs.

Over the last decade, observations with the *Hubble Space Telescope* (*HST*), the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), and some ground-based instruments have provided measurements of the metallicities and distance brackets for some of the major neutral HVC complexes. The general picture that has emerged for these prominent neutral complexes (e.g., complexes A and C) is one in which they have an extragalactic origin given their low metallicities (e.g., complex C has a metallicity ∼15% solar; Collins et al. 2007, see van Woerden & Wakker 2004 for a summary) and distances from the sun bracketed to be within 5 ≲ d ≲ 12 kpc (e.g., Thom et al. 2006, 2007; Wakker et al. 2007, 2008; van Woerden et al. 1999). The Magellanic Stream is another example, thought to be at d ∼ 50 – 75 kpc with a metallicity ∼ 25% that of the sun (Gibson et al. 2000, Sembach et al. 2001).

Traditionally, HVCs were observed via optical or radio observations (e.g., Münch 1952; Münch & Zirin 1961, Wakker 1991). These clouds were therefore known as neutral entities. However, UV observations from *HST* and *FUSE* as well as ground-based Hα observations (Tufte et al. 2002, Putman et al. 2003), have revealed a significant ionized component of the neutral complexes. Furthermore, such data have also allowed the discovery of a new class of HVCs without H I emission, the highly-ionized HVCs (Sembach et al. 1999, 2003; Lehner et al. 2001, Lehner 2002; Collins et al. 2004, 2005; Ganguly et al. 2005; Fox et al.
These HVCs show absorption from the “high ions” O VI, N V, C IV, and Si IV; these ions require large energies for their production, and O VI, in particular, cannot be produced via photoionization within the Galaxy (e.g., Sembach et al. 2003), suggesting the presence of hot gas to provide for the ionization. Some of the highly-ionized high velocity absorption seen towards AGNs is associated with the outer layers of known H I HVC complexes based on their coincidental velocities and proximity on the sky (e.g., gas associated with the outer edges of complexes A, C, and the Magellanic Stream; Sembach et al. 2003, Fox et al. 2004, 2005). However, others have no H I 21-cm emission, and therefore are not part of large neutral complexes. They do, however, show H I and C III absorption counterparts, implying they have a multiphase structure (Fox et al. 2006 and references therein).

The origin of these highly-ionized HVCs are mostly unknown because neither their distances nor their metallicities are well known. Up to this work, there has been no report of highly-ionized HVCs observed in absorption against distant Milky Way stars (Zsargó et al. 2003), the only way to directly constrain the distances to HVCs. This, together with kinematic arguments (Nicastro et al. 2003), led Nicastro (2005) to conclude that these HVCs must be extragalactic since the highly-ionized HVCs are detected only toward AGNs and QSOs. However, early-type stars often have complicated spectra near the high ions, and absorption from a highly-ionized HVC could easily be lost in the complicated structure of the continuum, especially if the absorption is weak. The metallicities of highly-ionized HVCs are also difficult to determine. Since they are defined by their ionization state, the ionization corrections required to determine the metallicities are often large and extremely model dependent. For the majority of these clouds, the
distance and metallicity estimates rely on photoionization models based on an assumed ionizing spectrum (e.g., Sembach et al. 1999, Collins et al. 2004, 2005, Ganguly et al. 2005, and others). These studies have suggested the clouds are located in the distant reaches of the Milky Way (e.g., Collins et al. 2005, Fox et al. 2006) and have significantly sub-solar metallicites, typically $\sim 20\%$ solar with a range of $4\%$ to $40\%$ solar. Prior to the present work, there have only been three metallicity limits for highly-ionized HVCs using the columns of O I and H I (Fox et al. 2005, Ganguly et al. 2005), a comparison that does not require ionization corrections to derive the metallicity. These upper limits are mostly crude, consistent with both solar and sub-solar abundances.

In view of the uncertainties in their properties, the highly-ionized HVCs are consistent with both an extragalactic or Galactic origin. In particular, they may trace a hot Galactic fountain (Fox et al. 2006) or, in cases where the sight line passes near the Galactic center, a nuclear wind (Keeney et al. 2006). Galactic nuclear winds are observed in external galaxies across the electromagnetic spectrum (Martin 1999; Strickland 2002; Heckman 2002; Veilleux 2002), and there is evidence that the Milky Way also has a Galactic nuclear wind (Bland-Hawthorn & Cohen 2003). Analyses of X-ray observations toward the Galactic center have provided further evidence for an outflow from the central regions of the Galaxy (Almy et al. 2000; Sofue 2000; Yao & Wang 2007). Such a Galactic outflow/wind should be detectable via UV high-ion absorption not only in the spectra of QSOs but also in distant stars at high Galactic latitudes. Keeney et al. (2006) discussed the possibility that a wind from the Galactic center may give rise to highly-ionized HVC absorption seen in the spectra of two AGNs. The subsolar metallicities they attribute to these absorbers are at odds with a Galactic wind origin. However,
if, as they suggest, their photoionization models provide inappropriate metallicity estimates, there may yet be reason to believe these HVCs probe the expulsion (and perhaps subsequent return) of matter from the inner regions of the Milky Way.

In this work, we present new observations of a highly-ionized HVC that is located toward the inner Galaxy at a distance from the sun $d < 7.5$ kpc and height above the Galactic plane $z < 5.3$ kpc. This HVC is detected in the FUSE and Space Telescope Imaging Spectrograph (STIS) spectra of the post-asymptotic giant branch (PAGB) star ZNG 1 located in the globular cluster Messier 5 (NGC 5904, $d = 7.5$ kpc; see Figure 2.1). This is the first highly-ionized HVC for which the upper limit on the distance is known. This HVC was first reported by Dixon et al. (2004), but its origin (circumstellar or truly interstellar gas) was not fully explored in their work. Here we rule out the circumstellar origin and show the gas has a supersolar metallicity, which is consistent with an origin in the inner Galaxy. This is the first highly-ionized HVC unambiguously detected in the spectrum of a Galactic star, and this HVC has the highest measured metallicity of any yet studied.
Figure 2.1. An Aitoff all-sky projection showing the high-velocity clouds. The location of ZNG 1 is near the upper middle. Illustration courtesy of B.P. Wakker.
This chapter is structured as follows. We summarize the FUSE and STIS observations and our reduction of the data in § 2.2 and in § 2.3 we discuss the properties of the star and sight line. We present our measurements of the observed high velocity absorption in § 2.4 In § 2.5 we discuss the physical properties of the high velocity gas including the electron density, ionization fraction, and metallicity. We analyze the kinematics and ionization mechanisms involved with the gas along the ZNG 1 sight line in § 2.6. We use photoionization modeling and path length arguments to rule out the circumstellar hypothesis for the origin of the high velocity gas toward ZNG 1 in § 2.7. In § 2.8 we discuss our results in the context of a Galactic circulation/feedback and suggest further research to test this hypothesis, and we discuss the implications for other highly-ionized HVCs. We summarize our principal conclusions in § 2.9.

2.2 Observations and Reductions

The observations for this work were taken from STIS on board HST and FUSE. In the following subsections, we discuss the data reduction and handling procedures for the STIS and FUSE spectral data sets.

2.2.1 STIS

The STIS observations were made between July 8 and July 19, 2003 under the Guest Observer program 9410. Five visits were made with identifications O6N40401–402, and O6N40301–303 for a total exposure time of 12.8 ks. The STIS observations of ZNG 1 were taken in the ACCUM mode with the 0.2” × 0.2” aperture using the E140M echelle grating to disperse the light onto the far-ultraviolet Multi-Anode Microchannel-Array (MAMA) detector. The usable
wavelength coverage is from \(\sim 1150 \, \text{Å} \) to \(1710 \, \text{Å}\). The resolution of this mode is \(R \equiv \lambda/\Delta \lambda \sim 45,800\) corresponding to a velocity FWHM of \(\sim 6.5 \, \text{km s}^{-1}\) with a detector pixel size of \(3.22 \, \text{km s}^{-1}\). The STIS data were retrieved from the Multimission Archive at Space Telescope (MAST), and reduced with the CALSTIS (Version 2.14c; Dressel et al. 2007) pipeline in order to provide orbital Doppler shift adjustments, detector nonlinearity corrections, dark image subtraction, flat field division, background subtraction, wavelength zero-point calibration, and to convert the wavelengths into the heliocentric reference frame. The individual exposures were weighted by their inverse variance and combined into a single spectrum. For a description of the design and construction of STIS see Woodgate et al. (1998), and a summary of the STIS on-orbit performance is given by Kimble et al. (1998).

We applied a shift of \(\Delta \upsilon_{\text{LSR}} = \upsilon_{\text{LSR}} - \upsilon_{\text{helio}} = +13.25 \, \text{km s}^{-1}\) to the data to transform the heliocentric velocities provided by STIS to the local standard of rest (LSR) frame. This assumes a solar motion of \(+20 \, \text{km s}^{-1}\) in the direction \((\alpha, \delta)_{1900} = (18^h, +30^\circ) \) \([ (l, b) \approx (56^\circ, +23^\circ) ] \) (Kerr & Lynden-Bell 1986). For comparison, the Mihalas & Binney (1981) definition of the LSR gives a velocity shift of \(\Delta \upsilon_{\text{LSR}} = +11.76 \, \text{km s}^{-1}\). The velocity uncertainty of the STIS observations is \(\sim 1 \, \text{km s}^{-1}\) with occasional errors as large as \(\sim 3 \, \text{km s}^{-1}\) (see the Appendix of Tripp et al. 2005).

2.2.2 FUSE

The FUSE observations were made under programs A108 and D157 on July 15, 2000 and between April 11 – 13, 2003 for a total of four visits. The FUSE data sets are A1080303 and D1570301–303, and the total exposure time is 30.4
ks. The four FUSE observations of ZNG 1 were taken using the LWRS 30" × 30" apertures in the photon event (TTAG) mode. The wavelength range of the data is 905 Å to 1187 Å with a resolution of ∼ 20–25 km s$^{-1}$ and a binned output pixel size of 3.74 km s$^{-1}$. The data were reduced using the CalFUSE (Version 3.1.3) pipeline. The CalFUSE processing is described in Dixon et al. (2007), and the spectroscopic capabilities and early on-orbit performance of FUSE are described in Moos et al. (2000) and Sahnow et al. (2000), respectively.

Data were obtained from the SiC1, SiC2, LiF1, and LiF2 channels. For each FUSE segment, the intermediate data files produced by CalFUSE were shifted to a common wavelength scale and combined into a single file. Time segments exhibiting a low count rate, e.g., when the target fell near the edge of the spectrograph apertures, were excluded from further consideration. The detector and scattered-light background were scaled and subtracted by CalFUSE. The FUSE relative wavelength is accurate to roughly ±5 km s$^{-1}$ but can vary by 10 – 15 km s$^{-1}$ over small wavelength intervals. The absolute zero point of the wavelength scale for the individual absorption lines is uncertain and was determined using the well-calibrated STIS data. Where possible, transitions from the same species were compared (e.g., Fe II λλ1055, 1063 were aligned with Fe II λλ1608, 1611). Where this was not possible, we compared different ions with similar ionization potentials and similar absorption depths (e.g., Ar I λλ1055, 1066, with N I λλ1199, 1200). For the ion O VI we aligned and coadded the data from the LiF1A, LiF2B, SiC1A, and SiC2B channels. No ion was available to directly fix the velocity scale of O VI. However, the shifts for transitions throughout the LiF1A segment were all consistent, and we adopted their average to align O VI. Based on a comparison of the velocity centroids of the H$_2$ lines λλ1009, 1013, 1026, 1031 near O VI in FUSE, we
conclude that no additional velocity shift for O VI was needed.

2.3 The M5 ZNG 1 Sight Line

ZNG 1 is a post-asymptotic giant branch star in the globular cluster M5 (NGC 5904); the properties of the star and cluster are summarized in Table 2.1.1 ZNG 1 has a remarkably fast projected rotational velocity for a PAGB star (\( v \sin i = 170 \) km s\(^{-1}\)). One possible explanation may be that this star has been spun up by a merger with a binary companion. This star has very little hydrogen in its atmosphere, with a helium abundance of 99\% by number (W. V. Dixon 2007, unpublished). Its photospheric carbon and nitrogen abundances are 10 times solar by mass, suggesting products of helium burning were mixed to the surface while the star was on the AGB (Dixon et al. 2004). The sight line to this star shows high velocity absorption as first noted by Dixon et al. (2004). Over the velocity range \(-162 < v_{\text{LSR}} < -90\) km s\(^{-1}\), absorption from the ions H I, C II, C IV, N II, O I, O VI, Al II, Si II, Si III, Si IV, and Fe II is seen in our STIS and FUSE observations (see Figures 2.2, 2.3, and 2.4). The presence of strong Si IV, C IV, and O VI absorption at high velocities (\(|v| \gtrsim 100\) km s\(^{-1}\)) place these clouds in the category of highly-ionized HVCs recently discussed by Fox et al. (2005), Collins et al. (2004; 2005), and Ganguly et al. (2005). High velocity absorption is detected in multiple components with centroid LSR velocities at roughly \(-110\) km s\(^{-1}\) and \(-140\) km s\(^{-1}\) (\(-190\) km s\(^{-1}\) and \(-160\) km s\(^{-1}\) relative to the photosphere of ZNG 1). Our aim is to determine the origin of this observed multiphase high-velocity absorption.

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1Table 2.1 sources: (1) Napiwotzki & Heber 1997; (2) Piotto 2002; (3) Harris 1996; (4) Dixon et al. 2004; (5) This work. Note: Abundances are quoted as mass fractions.
Figure 2.2. Normalized intensity profiles of the tracers of the low ions. The HVC region lies in the velocity range $-160 \text{ km s}^{-1}$ to $-90 \text{ km s}^{-1}$ with centroid velocities for C IV and Si IV at $-142 \text{ km s}^{-1}$ and $-111 \text{ km s}^{-1}$. Gas participating in the global rotation of the Galaxy is observed at $|v_{\text{LSR}}| \lesssim 30 \text{ km s}^{-1}$. The instrument from which the data were taken is identified in the lower right of each profile. FUSE has a resolution of $\sim 20 \text{ km s}^{-1}$ and STIS E140M has a resolution of 6.5 km s$^{-1}$. 
Figure 2.3. Same as Figure 2.2 but for the ions that are doubly or more ionized. The C II, N II, and Si II profiles are for comparison (although note that N II solely probes ionized gas).
Figure 2.4. Adopted continuum fits of the high ions are shown as the solid black curves. The fits to the continua for the C IV and Si IV lines were adopted from the component fitting software. The two vertical lines show the HVC region of interest. The P-Cygni profile with a terminal velocity of $\sim 900$ km s$^{-1}$ is clearly seen in the C IV, N V, and O VI lines. The plus signs represent the profiles and/or stellar wind features of the other line of the doublet. We do not use N V $\lambda 1238$ in our analysis due to the difficulty in determining the continuum. We show it here to demonstrate this difficulty and show the stellar wind profile.
<table>
<thead>
<tr>
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<th>Value</th>
<th>Reference</th>
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<tr>
<td>$v_{\text{LSR}}$</td>
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<td>3</td>
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<tr>
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</tr>
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</tr>
<tr>
<td>log $g$</td>
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<td>4</td>
</tr>
<tr>
<td>$v \sin i$</td>
<td>$170 \pm 20$ km s$^{-1}$</td>
<td>4</td>
</tr>
<tr>
<td>$v_{\text{LSR}}$</td>
<td>$+51 \pm 3$ km s$^{-1}$</td>
<td>5</td>
</tr>
<tr>
<td>log $L/L_\odot$</td>
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</tr>
<tr>
<td>$M/M_\odot$</td>
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</tr>
<tr>
<td>C abundance</td>
<td>$2.58 \pm 0.20%$</td>
<td>4</td>
</tr>
<tr>
<td>N abundance</td>
<td>$0.51 \pm 0.05%$</td>
<td>4</td>
</tr>
<tr>
<td>O abundance</td>
<td>$0.37 \pm 0.32%$</td>
<td>4</td>
</tr>
</tbody>
</table>
The sight line to M5 ZNG 1 probes a 7.5 kpc path toward the inner Galaxy. It passes through Radio Loop I (centered at roughly $l = 329.0^\circ, b = 17.5^\circ$ with a diameter of $\sim 116^\circ$, Berkhuijsen et al. 1971). The energy source for the Loop I superbubble is commonly thought to be stellar winds and/or supernovae in the Sco-Cen OB association located at a distance of $d \sim 170$ pc from the sun (Park et al. 2007; Wolleben 2007 and references therein).² It is a priori possible that the high velocity absorption toward ZNG 1 may be associated with material in Loop I.

Savage & Lehner (2006) analyzed the O VI in the sight lines to 39 white dwarfs, of which 3 lie in the direction of Loop I at low latitudes with distances close to 200 pc. No O VI is observed in any of these sight lines at high velocities. Sembach et al. (1997) observed the sight line toward HD 119608 ($l = 320.4^\circ, b = 43.1^\circ$) that passes through Loop I. In addition, they compiled archival IUE observations of $\sim 20$ sight lines passing through Loop I. Again, no high-ion absorption was detected at high velocities. The sight line to 3C 273 passes through Loop I which shows very strong C IV and O VI absorption with velocities between roughly $-100$ and $+100$ km s$^{-1}$ (Sembach et al. 2001, 1997); a high velocity wing feature is also seen, reaching as far as $+240$ km s$^{-1}$ (Sembach et al. 2001). Given that the sight lines which probe O VI in or near Loop I show no absorption at high negative velocities, it is unlikely that the high velocity gas toward ZNG 1 represents Loop I material. We note also that the [O/H] of the ISM within 800 pc is observed to be nearly solar (Cartledge et al. 2004). If the HVCs toward ZNG 1 were to represent Loop I material, one would expect the metallicity to more closely match that of

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²Loop I is typically associated with the Sco-Cen OB association; however, Bland-Hawthorn & Cohen (2003) and Yao & Wang (2007) argue that the North Polar Spur (NPS), which is usually thought to be a part of Loop I, is actually a limb brightened region associated with the outer walls of a bipolar Galactic nuclear wind.
the local neighborhood. The super-solar metallicity of the HVCs toward ZNG 1 (see §2.5.2), combined with the absence of HVCs with \( v_{\text{LSR}} \leq -100 \ \text{km s}^{-1} \), strongly suggest that they reside farther than the \( \sim 200 \ \text{pc} \) distance of Loop I.

The Leiden-Argentine-Bonn (LAB) Survey (Kalberla et al. 2005) provides us with a neutral hydrogen column density of \( N(\text{H I}) = 3.67 \times 10^{20} \ \text{cm}^{-2} \) for H I emission centered around \( v_{\text{LSR}} \approx 0 \ \text{km s}^{-1} \) in the direction of M5. A perusal of the survey reveals no H I emission at velocities \( |v_{\text{LSR}}| \gtrsim 30 \ \text{km s}^{-1} \) within 10° of ZNG 1 with a sensitivity of \( N(\text{H I}) \approx 3 \times 10^{18} \ \text{cm}^{-2} \) for an HVC FWHM \( \sim 20 \ \text{km s}^{-1} \). The high velocity gas seen toward ZNG 1 is not clearly associated with any known HVC complex (Wakker 2001). The closest HVC complex is complex L \( (\Delta \theta \sim 25° - 30°) \) which has a mean LSR velocity \( \sim -115 \ \text{km s}^{-1} \). Richter et al. (2005) find HVC absorption toward PKS 1448-232 \( (l = 335.°4, b = +31.°7, \ \Delta \theta \sim 27° \) from ZNG 1) with LSR velocities near \(-100, -130, \) and \(-150 \ \text{km s}^{-1} \) that are similar to those observed in the HVCs toward ZNG 1. Richter et al. attribute this absorption to complex L. The compact HVC CHVC 018.3–47.1–147 (de Heij et al. 2002) lies \( \sim 10° \) from ZNG 1 with an LSR velocity of \(-147 \ \text{km s}^{-1} \) (this is cloud 57 in Wakker & van Woerden 1991).

Zsargó et al. (2003) analyzed \textit{FUSE} spectra for 22 Galactic halo stars. They saw no clear evidence of high velocity O VI in any of the sight lines. Their sample included ZNG 1; however, they used earlier \textit{FUSE} data for this star with a S/N of about half of that of our data. ZNG 1 is the only known Galactic sight line to show highly-ionized interstellar HVCs.

Sembach et al. (2003), in their survey of high velocity O VI, analyzed highly-ionized high velocity gas along sight lines to 100 extragalactic objects and 2 halo

\footnote{The brightness-temperature sensitivity of the LAB survey is 0.07–0.09 K with a sensitivity of \( N(\text{H I}) \approx 2 \times 10^{17} \ \text{cm}^{-2} \) per 1.3 km s\(^{-1}\) resolution element.}
stars. Of the sight lines in their study, only Mrk 1383 \((l = 349.02, b = +55.01, \Delta \theta = 11.08\) from ZNG 1) lies within 30° of ZNG 1. Mrk 1383 shows no blueshifted high velocity absorption (Keeney et al. 2006; Sembach et al. 2003). Fox et al. (2006) analyzed the spectra of 66 extragalactic sight lines searching for highly-ionized HVCs. The sight line toward PG 1553+113 \((l = 21.09, b = +44.00, \Delta \theta = 13.01\) shows O VI absorption at blueshifted velocities between \(-170\) and \(-100 \text{ km s}^{-1}\) (e.g., see Figure 6 of Fox et al. 2006 and our § 8). Fox et al. (2006) reported a 3σ upper limit for the O VI absorption at negative LSR velocities \((-200 \text{ to } -100 \text{ km s}^{-1})\). The main difference between our analysis and theirs is the velocity range used to estimate the equivalent width and column density: Considering the velocity range \(v_{\text{LSR}} = -200 \text{ to } -100 \text{ km s}^{-1}\), the 3σ upper limit on the equivalent width is 40 mA. Between \(-170\) and \(-100 \text{ km s}^{-1}\), we measure \(W_{\lambda} = 39 \pm 11 \text{ mA} \) and \(\log N(\text{O VI}) = 13.57_{-0.13}^{+0.11}\), corresponding to a 3.5σ detection.

Given its evolutionary status, this star may be expected to have circumstellar material, perhaps even a (proto) planetary nebula (PN). Dixon et al. (2004) have summarized the prior observations of ZNG 1 and the search for a PN. Bohlin et al. (1983) suggested that an apparent N IV\(\lambda 1478\) emission feature in the \(IUE\) spectrum of ZNG 1 was a signature of a PN. However, using an analysis of the complete archival \(IUE\) data, de Boer (1985) argued the apparent N IV feature was not real; he did note the P-Cygni profile of the N V \(\lambda\lambda 1238,1242\) doublet, a sign of an outflowing wind from the star. This wind shows a terminal velocity of \(\sim 900 \text{ km s}^{-1}\) (e.g., see Figure 2.4 and Dixon et al. 2004). Napierwotzki & Heber (1997) set out to test the PN hypothesis by using \(HST\) to obtain a WFPC2 H\(\alpha\) image. The H\(\alpha\) image revealed no evidence for extended emission around the star from a PN. Any circumstellar H\(\alpha\) is constrained to lie within 0.2″ \((7 \times 10^{-3} \text{ pc})\) from
the star. We will present strong evidence against the possibility that the HVCs in this direction are associated with circumstellar material in § 2.7.

At Galactic coordinates \( l = 3.9^\circ, b = +47.7^\circ \), a distance of \( d = 7.5 \) kpc (Harris 1996), and a vertical distance above the Galactic plane of \( z = +5.3 \) kpc, ZNG 1 lies about 3.5 kpc from the rotation axis of the Galaxy. At this location, a Galactic bipolar wind, for which evidence has been accumulating recently, may play a role in this HVC material. Almy et al. (2000) analyzed ROSAT X-ray observations toward Loop I and the Galactic center and were able to show that a large fraction (45\% ± 9\%) of the X-ray emission originates beyond \( d \sim 2 \) kpc. They suggested that the most probable source for this emission was the Galactic X-ray “bulge.” Yao & Wang (2007) used a differential analysis of archival Chandra grating observations of the sight lines toward Mrk 421 \((l = 179.8^\circ, b = 65.0^\circ)\) and 3C 273 \((l = 290.0^\circ, b = 64.4^\circ)\) to obtain the net emission and absorption of the hot gas toward the Galactic center soft X-ray emission (seen toward 3C 273). They showed that the X-ray emitting gas toward 3C 273 originated beyond 200 pc and suggested the most likely source was a Galactic center outflow. If this X-ray emission indeed originates from the Galactic center, then the Galactic latitude of 3C 273 \((b = 65.0^\circ)\) suggests that an outflow can reach beyond the Galactic latitude of ZNG 1 \((b = 47.7^\circ)\). Based on the 408 MHz radio continuum and the ROSAT all-sky soft X-ray data, Sofue (2000) calculated the expected size of an outflow. His predictions for the outer boundary of an outflow encompass ZNG 1. Furthermore, ZNG 1 is located inside the outflow cones in the empirically-motivated models of Bland-Hawthorn & Cohen (2003). Keeney et al. (2006) have previously discussed a Galactic wind in the context of the highly-ionized HVCs toward Mrk 1383 and PKS 2005–489, attributing the HVCs to a Galactic center outflow. The sight line
toward ZNG 1 may intercept material associated with feedback-driven flows in the central regions of the Galaxy, either from a nuclear wind or from Galactic fountain-type flows from the inner Galaxy. We discuss this possibility in § 2.8.

2.4 Interstellar Absorption Line Measurements

We have measured column densities, equivalent widths, $b$-values, and signal-to-noise ratios for the ion profiles where significant absorption is seen in the HVC region. Where the absorption is absent and not contaminated, $3\sigma$ upper limits for the column densities and equivalent widths were calculated. We employed two principal methods in obtaining these values, the apparent optical depth (AOD) method as described by Savage & Sembach (1991) and a component fitting method as described by Fitzpatrick & Spitzer (1997), discussed in § 2.4.1 and § 2.4.2, respectively. We separately discuss our analysis of the H I Lyman series absorption in § 2.4.3.

2.4.1 AOD Measurements of the Metal Lines

Figures 2.2 and 2.3 show the normalized intensity profiles for the low and high ions, respectively. We normalized each absorption feature by fitting a low-order ($\leq 5$) Legendre polynomial to the adjacent continuum. The continuum of ZNG 1 for the most part was easily modeled, with the exception of the regions about Si IV and C IV. The C IV 1548, 1550 Å doublet lies in the presence of a stellar wind making the continuum placement more difficult. The Si IV 1393, 1402 Å lines each lie in a stellar feature with the added complication that the Si IV $\lambda$1402 line lies near the edge of a spectral order. The data from the spectral orders for the 1402 Å line were coadded, however, there was a feature near $-85$ km s$^{-1}$
which appeared in one order but not the other. For these high ions, we adopt continua determined through a component fitting analysis, the details of which are described in §2.4.2. Figure 2.4 shows the adopted continua for the ions C IV λλ1548, 1550, Si IV λλ1393, 1402, N V λλ1238, 1242 and O VI λ1031. While continuum placement near the O VI λ1031 line can sometimes be problematic in stars, here the continuum is well determined. We cannot use the O VI λ1037 line because it is always contaminated by C II, C II*, and H₂.

The strong line of O VI at 1031 Å can be contaminated by H₂ or HD lines from the Milky Way, and by Cl I at 1031 Å. The Cl I is at −122 km s⁻¹ with respect to O VI which is in the velocity region of our HVCs. We searched for absorption from Cl I λλ1004, 1003, which have similar strengths to the 1031 transition, and found none. Of the three molecular lines that can contaminate O VI, HD 6–0 R(0) λ1031, (6–0) P(3) λ1031, and R(4) λ1032, are at −4, −214 and +125 km s⁻¹ relative to O VI, respectively, and are not in the velocity region of our HVCs.

Table 2.2 gives our measured properties of the high-velocity interstellar absorption lines toward ZNG 1, including the equivalent widths, apparent column densities, signal-to-noise, and b-values. Table 2.3 gives the column densities and b-values for the two components seen in the high ions. We measured equivalent

---

![Table 2.2 note: Wavelengths and f-values are from Morton (2003). Upper limits are 3σ estimates; a b-value of 20 km s⁻¹ was assumed when no data were available. ∆v denotes the integration range. Where the range differs from −162 to −90 km s⁻¹ we have adjusted for nearby contaminating absorption. The quoted value is the signal to noise ratio per detector pixel. For STIS, the detector has a pixel size of 3.22 km s⁻¹ per pixel and FUSE, the detector has an output pixel size of 3.74 km s⁻¹ per pixel. a. The other members of these multiplets were blended with a stellar or interstellar features and are not included in this table. b. This measurement uses the coadded data from the LiF 1A, LiF 1B, SiC 1A, and SiC 2B FUSE segments. c. This line may be slightly contaminated by Si II λ1190.]

![Table 2.3 note: These results were obtained by the AOD method. The velocity range is [−162, −126] km s⁻¹ for component 1 and [−126, −90] km s⁻¹ for component 2. The b-value quoted here is defined as $b_a = [2f(v - \tau_a)^2N_a(v)dv/N_a]^{1/2}$ and integrated over the velocity range for each component. The b-values from O VI λ1031.926 LiF 1A were adopted in finding the upper limits for N V.]

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widths of interstellar features following Sembach & Savage (1992) including their
treatment of the uncertainties. We assumed statistical uncertainties for the FUSE
data were dominated by the effects of fixed pattern noise, while the uncertainties
for the STIS data were treated as statistical Poisson uncertainty. In addition, we
include an uncertainty in the placement of the continuum added in quadrature to
the statistical uncertainty following Sembach & Savage (1992).
### TABLE 2.2

**INTERSTELLAR ABSORPTION LINES TOWARDS M5-ZNG 1**

<table>
<thead>
<tr>
<th>Species</th>
<th>λ</th>
<th>log λf</th>
<th>Wλ</th>
<th>log N_a</th>
<th>∆v</th>
<th>b_a</th>
<th>S/N</th>
<th>Instrument</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>[Å]</td>
<td>[mÅ]</td>
<td>[cm^{-2}]</td>
<td>[km s^{-1}]</td>
<td>[km s^{-1}]</td>
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<tr>
<td>C II</td>
<td>1334.532</td>
<td>2.234</td>
<td>177 ± 2</td>
<td>&gt; 14.27</td>
<td>−162, −90</td>
<td>17.9 ± 0.2</td>
<td>31</td>
<td>STIS</td>
</tr>
<tr>
<td>C II</td>
<td>1036.337</td>
<td>2.088</td>
<td>131 ± 5</td>
<td>&gt; 14.26</td>
<td>−162, −90</td>
<td>22.3 ± 0.7</td>
<td>16</td>
<td>FUSE/LiF 1A</td>
</tr>
<tr>
<td>C II*</td>
<td>1335.708</td>
<td>2.186</td>
<td>&lt; 5</td>
<td>&lt; 12.44</td>
<td>−162, −90</td>
<td>... 42</td>
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<td></td>
</tr>
<tr>
<td>C IV</td>
<td>1548.195</td>
<td>2.468</td>
<td>144 ± 6</td>
<td>13.70 ± 0.04</td>
<td>−162, −90</td>
<td>24.4 ± 1.0</td>
<td>12</td>
<td>STIS</td>
</tr>
<tr>
<td>C IV</td>
<td>1550.770</td>
<td>2.167</td>
<td>92 ± 6</td>
<td>13.74 ± 0.03</td>
<td>−162, −90</td>
<td>24.7 ± 1.3</td>
<td>14</td>
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</tr>
<tr>
<td>N I*</td>
<td>1199.550</td>
<td>2.199</td>
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<td>&lt; 12.82</td>
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<td>... 17</td>
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<td></td>
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<tr>
<td>N II</td>
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</tr>
<tr>
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<td>&lt; 14.19</td>
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<tr>
<td>N II**</td>
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<td>&lt; 13.41</td>
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<td>FUSE/SiC 1A</td>
<td></td>
</tr>
<tr>
<td>N V</td>
<td>1242.804</td>
<td>1.985</td>
<td>&lt; 8</td>
<td>&lt; 12.84</td>
<td>−162, −90</td>
<td>... 27</td>
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<td></td>
</tr>
<tr>
<td>O I</td>
<td>1302.168</td>
<td>1.796</td>
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<td>13.38 ± 0.08</td>
<td>−162, −85</td>
<td>20.8 ± 5.0</td>
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<td>STIS</td>
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TABLE 2.2

Continued

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<tr>
<th>Species</th>
<th>$\lambda$</th>
<th>$\log \lambda f$</th>
<th>$W_{\lambda}$</th>
<th>$\log N_a$</th>
<th>$\Delta v$</th>
<th>$b_a$</th>
<th>S/N</th>
<th>Instrument</th>
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<td></td>
<td>[Å]</td>
<td>[mÅ]</td>
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<td>[km s$^{-1}$]</td>
<td>[km s$^{-1}$]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>O VI</td>
<td>1031.926</td>
<td>2.136</td>
<td>33 ± 3</td>
<td>13.46 ± 0.04</td>
<td>−162, −90</td>
<td>25.6 ± 2.3</td>
<td>23</td>
<td>FUSE$^b$</td>
</tr>
<tr>
<td>Al II</td>
<td>1670.787</td>
<td>3.463</td>
<td>50 ± 8</td>
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<td>−162, −90</td>
<td>20.4 ± 3.6</td>
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<tr>
<td>Si II</td>
<td>1190.416</td>
<td>2.541</td>
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<td>&gt; 13.27</td>
<td>−162, −110</td>
<td>14.8 ± 0.7</td>
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<tr>
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<td>1193.290</td>
<td>2.842</td>
<td>86 ± 4</td>
<td>&gt; 13.23</td>
<td>−162, −100</td>
<td>15.7 ± 0.7</td>
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<tr>
<td>Si II</td>
<td>1260.422</td>
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<td>&gt; 13.15</td>
<td>−162, −90</td>
<td>17.3 ± 0.4</td>
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<tr>
<td>Si II</td>
<td>1304.370</td>
<td>2.052</td>
<td>36 ± 2</td>
<td>13.49 ± 0.03</td>
<td>−162, −90</td>
<td>18.1 ± 1.4</td>
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</tr>
<tr>
<td>Si II</td>
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<td>2.307</td>
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<td>−162, −90</td>
<td>19.2 ± 1.3</td>
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<tr>
<td>Si III</td>
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<td>3.293</td>
<td>197 ± 3</td>
<td>&gt; 13.30</td>
<td>−162, −85</td>
<td>22.0 ± 0.3</td>
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<tr>
<td>Si IV</td>
<td>1393.755</td>
<td>2.854</td>
<td>50 ± 3</td>
<td>12.81 ± 0.02</td>
<td>−162, −90</td>
<td>23.3 ± 1.0</td>
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<tr>
<td>Si IV</td>
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<td>2.552</td>
<td>30 ± 3</td>
<td>12.86 ± 0.04</td>
<td>−162, −90</td>
<td>21.8 ± 1.8</td>
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<tr>
<td>S II</td>
<td>1253.811</td>
<td>1.135</td>
<td>&lt; 8</td>
<td>&lt; 13.67</td>
<td>−162, −90</td>
<td>⋮</td>
<td>28</td>
<td>STIS</td>
</tr>
<tr>
<td>Species</td>
<td>$\lambda$</td>
<td>$\log \lambda_f$</td>
<td>$W_\lambda$</td>
<td>$\log N_a$</td>
<td>$\Delta v$</td>
<td>$b_a$</td>
<td>S/N</td>
<td>Instrument</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
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<td>---------</td>
<td>---------</td>
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<td>-----------</td>
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<tr>
<td>S II</td>
<td>1259.519</td>
<td>1.311</td>
<td>&lt; 6</td>
<td>&lt; 13.39</td>
<td>$-162, -90$</td>
<td>· · ·</td>
<td>36</td>
<td>STIS</td>
</tr>
<tr>
<td>S III</td>
<td>1190.208</td>
<td>1.421</td>
<td>$12 \pm 3^c$</td>
<td>$13.67 \pm 0.10^c$</td>
<td>$-162, -105$</td>
<td>$18.8 \pm 4.2$</td>
<td>18</td>
<td>STIS</td>
</tr>
<tr>
<td>Fe II</td>
<td>1144.938</td>
<td>1.978</td>
<td>$14 \pm 5$</td>
<td>$13.19 \pm 0.13$</td>
<td>$-162, -90$</td>
<td>$24.7 \pm 8.2$</td>
<td>15</td>
<td>FUSE/LiF 1B</td>
</tr>
<tr>
<td>Fe II</td>
<td>1144.938</td>
<td>1.978</td>
<td>$13 \pm 5$</td>
<td>$13.15 \pm 0.14$</td>
<td>$-162, -90$</td>
<td>· · ·</td>
<td>16</td>
<td>FUSE/LiF 2A</td>
</tr>
<tr>
<td>Fe II</td>
<td>1608.451</td>
<td>1.968</td>
<td>$14 \pm 6$</td>
<td>$13.07 \pm 0.02$</td>
<td>$-162, -90$</td>
<td>· · ·</td>
<td>16</td>
<td>STIS</td>
</tr>
</tbody>
</table>
The column densities quoted here are derived from the apparent optical depth \( \tau_a(v) \). The apparent optical depth is an instrumentally-blurred version of the true optical depth of an absorption feature and is given by

\[
\tau_a(v) = -\ln \left[ \frac{I(v)}{I_c(v)} \right],
\]

(2.1)

where \( I_c(v) \) is the estimated continuum intensity and \( I(v) \) is the observed intensity of the line as a function of velocity. The apparent column density per unit velocity, \( N_a(v) \) [atoms cm\(^{-2}\) (km s\(^{-1}\))\(^{-1}\)], is related to the apparent optical depth by

\[
N_a(v) = \frac{m_e c \tau_a(v)}{\pi e^2 \frac{f \lambda}{f \lambda}} = 3.768 \times 10^{14} \frac{\tau_a(v)}{f \lambda},
\]

(2.2)

where \( \lambda \) is the wavelength in Å, and \( f \) is the atomic oscillator strength. We adopt rest wavelengths and \( f \)-values from Morton (2003). Resolved saturated structure is not seen in any of the profiles, but if present, would be clearly identifiable. Unresolved saturated structure can be identified by comparing the \( N_a(v) \) profiles for different transitions of the same species; a smaller apparent column density in the stronger transition suggests saturation. In regions of the profiles for which unresolved saturated structure is not significant, the integrated apparent column density, \( N_a \), is equivalent to the true column density, \( N \). For cases where unresolved saturated structure becomes significant, the apparent column density is a lower limit to the true value. The integrated values of \( v_a, b_a, \) and \( \log N_a \) are obtained from

\[
v_a = \int v N_a(v) dv / N_a, \quad b_a = [2 \int (v - \tau_a)^2 N_a(v) dv / N_a]^{1/2}, \quad N_a = \int N_a(v) dv,
\]

where the integration is performed over the absorption region noted in Table 2.2.

According to Savage & Sembach (1991), the AOD method is adequate for
### TABLE 2.3

HIGH ION COMPONENT INTEGRATIONS

<table>
<thead>
<tr>
<th>Species</th>
<th>$\lambda$ [Å]</th>
<th>$\log N_a$ [cm$^{-2}$]</th>
<th>$b_a$ [km s$^{-1}$]</th>
<th>$\log N_a$ [cm$^{-2}$]</th>
<th>$b_a$ [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td>1548.195</td>
<td>13.25 ± 0.05</td>
<td>11.0 ± 1.1</td>
<td>13.50 ± 0.02</td>
<td>12.2 ± 0.5</td>
</tr>
<tr>
<td>C IV</td>
<td>1550.770</td>
<td>13.35 ± 0.05</td>
<td>12.2 ± 1.3</td>
<td>13.53 ± 0.04</td>
<td>12.2 ± 0.8</td>
</tr>
<tr>
<td>N V</td>
<td>1242.804</td>
<td>&lt; 12.73</td>
<td>⋯</td>
<td>&lt; 12.75</td>
<td>⋯</td>
</tr>
<tr>
<td>O VI</td>
<td>1031.926</td>
<td>12.92 ± 0.08</td>
<td>14.4 ± 2.4</td>
<td>13.34 ± 0.03</td>
<td>15.6 ± 0.8</td>
</tr>
<tr>
<td>Si IV</td>
<td>1393.755</td>
<td>12.58 ± 0.03</td>
<td>7.8 ± 1.1</td>
<td>12.44 ± 0.04</td>
<td>11.6 ± 1.0</td>
</tr>
<tr>
<td>Si IV</td>
<td>1402.770</td>
<td>12.65 ± 0.05</td>
<td>7.8 ± 2.1</td>
<td>12.47 ± 0.08</td>
<td>9.9 ± 2.0</td>
</tr>
</tbody>
</table>
data with \( b_{\text{line}} \sim (0.25-0.50) b_{\text{instr}} \), where \( b_{\text{line}} \) is the intrinsic \( b \)-value of the line and \( b_{\text{instr}} \) is the \( b \)-value of the instrument. Since \( b \equiv \text{FWHM}/1.667 \), for STIS E140M, \( b_{\text{instr}} \simeq 4 \text{ km s}^{-1} \) and for \( FUSE \), \( b_{\text{instr}} \approx 12 \text{ km s}^{-1} \). Since there is no tracer of cold gas in the HVCs along this line of sight, such as C II* or C I it is very unlikely that there is any absorption line with \( b \ll 1 \text{ km s}^{-1} \).

When \( \tau_a \ll 1 \), unresolved saturation should not be problematic as long as \( b \) is not much smaller than \( 1 \text{ km s}^{-1} \). For stronger lines, unresolved saturated structure can be identified by comparing the lines of the same species with different \( f\lambda \). Following Savage & Sembach (1991), the difference in \( f\lambda \) must be a factor of 2 (or 0.3 dex) or more to be able to detect the effects of unresolved saturation. If some moderate saturation exists, we can correct for it using the procedure described in Savage & Sembach (1991). For various cases of blending and line broadening, they found a tight relation between the difference of the true column density and the apparent column density of the weak line against the difference of the strong line and weak line apparent column densities. The needed correction to the apparent column density of the weak line for a given difference between the strong- and weak-line apparent column densities are summarized in their Table 4.

For the C IV and Si IV doublets, the weak lines of the doublet give systematically larger \( N_a \), suggesting that these lines suffer from small saturation (less than 0.02–0.05 dex), although as we argued above, the continua near these lines is complicated and errors in the continuum placement will have a greater effect on the weak lines. For O VI, because the intrinsic broadening is large, this line is unlikely to be affected by saturation (see Wakker et al. 2003). Because the peak apparent optical depth for the O I, S III, and Fe II lines are \( \lesssim 0.16 \), these lines are also unlikely to be saturated. For Si II, 5 transitions are available: the
strong lines at 1190, 1193, and 1260 Å show some saturation effects. The apparent column density of Si II λ1304 (weakest line) is 0.06 dex larger than the one of Si II λ1526, although within 1σ their apparent column densities overlap. Nonetheless, this is an indication of weak saturation (the continuum placement near these lines is straightforward), and we therefore correct for it in our adopted column density by increasing the column density of Si II λ1304 by 0.06 dex (see Table 4 in Savage & Sembach 1991). For Al II, we note that the peak apparent optical depth is smaller than for Si II λ1304 (0.5 compared to 0.7) and therefore the saturation correction is likely smaller than the error quoted in Table 2.2 (these two ions very likely probe the same gas given their similar ionization potentials). Finally, for C II, Si III, N II, only strong transitions are available and are likely all saturated. We therefore only quote lower limits for these ions.

For lines which showed no significant absorption, we adopt 3σ upper limits for the equivalent width. We follow Wakker et al. (1996) and calculate the limit on the equivalent width by

\[
\sigma(W)_{m\lambda} = 6.5 \times 10^{-3} \frac{\lambda(\AA)}{S/N} \sqrt{h b},
\]

where \( \lambda \) is the rest wavelength, \( S/N \) is the signal to noise ratio, \( h \) is the velocity dispersion per pixel for the spectrograph (3.22 km s\(^{-1}\) for STIS E140M and 3.74 km s\(^{-1}\) for FUSE), and \( b \) is the estimated \( b \)-value in km s\(^{-1}\). From this, the 3σ upper limits on the column density are calculated assuming that the lines fall on the linear part of the curve of growth,

\[
\sigma(N) = 1.13 \times 10^{17} \frac{\sigma(W)}{f\lambda^2(\AA)} [\text{cm}^{-2}].
\]
(Savage & Sembach 1996). Here $f$ is the oscillator strength, and $\sigma(W)$ is in mÅ.

Our adopted total column densities (i.e. that include all the absorption between $-162$ and $-90$ km s$^{-1}$) are summarized in Table 2.4. Note that for C IV and Si IV, we adopt the results from the profile fitting described in the next section, while the measurement for $N$(H I) is described in §2.4.3.

2.4.2 Component Fitting of the High Ions

The high ions C IV and Si IV are prominent in both HVC components toward ZNG 1. Since there may be overlap between the absorbing regions, we utilize the method of component fitting that allows us to separate the distinct velocity components. We employ software (described in Fitzpatrick & Spitzer 1997) in which we construct a model for the absorption wherein each profile is composed of multiple Maxwellian “clouds” or components. The best-fit values describing the gas are determined by comparing the model profiles convolved with an instrumental line-spread function (LSF) with the data. The three parameters $N_i$, $b_i$, and $v_i$ for each component, $i$, are input as an initial guesses and subsequently varied to minimize $\chi^2$. The fitting process enables us to find the best fit of the component structure using the data from one or more transitions of the same ionic species simultaneously.

We applied this component-fitting procedure to the C IV and Si IV doublets. In addition to fitting the profiles, we used the code to simultaneously determine the best fit continuum about each line (see Fitzpatrick & Spitzer 1997). The continuum for each of the four lines was modeled with a fourth-order Legendre polynomial. The continua determined this way are shown as solid lines in Fig-
### Table 2.4

**Adopted Total Interstellar Column Densities**

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<tr>
<th>Species</th>
<th>log $N$</th>
<th>Method</th>
</tr>
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<td>H I</td>
<td>16.50 ± 0.06</td>
<td>FIT, COG</td>
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<tr>
<td>C II</td>
<td>&gt; 14.27</td>
<td>AOD</td>
</tr>
<tr>
<td>C II*</td>
<td>&lt; 12.44</td>
<td>3σ</td>
</tr>
<tr>
<td>C IV</td>
<td>13.71 ± 0.07</td>
<td>FIT</td>
</tr>
<tr>
<td>N I</td>
<td>&lt; 12.82</td>
<td>3σ</td>
</tr>
<tr>
<td>N II</td>
<td>&gt; 14.07</td>
<td>AOD</td>
</tr>
<tr>
<td>N II**</td>
<td>&lt; 13.41</td>
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<tr>
<td>N V</td>
<td>&lt; 12.84</td>
<td>3σ</td>
</tr>
<tr>
<td>O I</td>
<td>13.38 ± 0.08</td>
<td>AOD</td>
</tr>
<tr>
<td>O VI</td>
<td>13.46 ± 0.04</td>
<td>AOD</td>
</tr>
<tr>
<td>Al II</td>
<td>12.11 ± 0.07</td>
<td>AOD</td>
</tr>
<tr>
<td>Si II</td>
<td>13.55 ± 0.03</td>
<td>AOD</td>
</tr>
<tr>
<td>Si III</td>
<td>&gt; 13.30</td>
<td>AOD</td>
</tr>
<tr>
<td>Si IV</td>
<td>12.86 ± 0.03</td>
<td>FIT</td>
</tr>
<tr>
<td>S II</td>
<td>&lt; 13.39</td>
<td>3σ</td>
</tr>
<tr>
<td>S III</td>
<td>13.67 ± 0.10</td>
<td>AOD</td>
</tr>
<tr>
<td>Fe II</td>
<td>13.07 ± 0.02</td>
<td>AOD</td>
</tr>
</tbody>
</table>
The Si IV and C IV ions were fit separately, i.e., we did not assume a common component structure for both ions a priori. The profile fits are shown as solid lines in Figure 2.5. Examination of the component models reveals a close agreement between the velocity centroids of C IV and Si IV in the HVC region. We call the component at $\sim -142$ km s$^{-1}$ component 1, and the component at $\sim -111$ km s$^{-1}$ component 2. In the low-velocity region of the C IV profiles, we allowed the software to determine, freely, components at $v_{\text{LSR}} \sim -79$ km s$^{-1}$ and $\sim -24$ km s$^{-1}$ to account for overlap of this low velocity material with the HVCs. Similarly, for Si IV we included components at $v_{\text{LSR}} \sim -24$ km s$^{-1}$ and $\sim -18$ km s$^{-1}$.

The results of the component fitting for C IV and Si IV are given in Table 2.5. The temperature, $T$, is determined by assuming only thermal broadening. This gives $T \lesssim A(60.6)b^2$ where $A$ is the atomic weight of the ion, and $b$, the Doppler parameter in km s$^{-1}$, is obtained from the fit. The temperatures of the gas are likely to be less than these values due to non-thermal motions. These results are discussed in more detail in § 2.6 in the context of kinematics and ionization.

Since there is a good agreement in the velocity structure between the C IV and Si IV ions in the HVC region, we looked for the same velocity structure in O VI (note that N V is not detected). Although we were able to fit the HVC region of O VI $\lambda$ 1031 with one component ($v_{\text{LSR}} = -101.2 \pm 2.8$ km s$^{-1}$, $b = 35.3 \pm 11.5$ km s$^{-1}$, $\log N = 13.62 \pm 0.04$ cm$^{-2}$), we were unable to satisfactorily obtain a two-component fit likely due to both the cruder FUSE resolution and an intrinsically
Figure 2.5. The normalized profiles of the ions C IV and Si IV along with the best-fit component model (solid black line). The centroid for component 1 is $-142 \text{ km s}^{-1}$ and for component 2 is $-111 \text{ km s}^{-1}$. The vertical dotted lines represent the centroids derived for each ion.
TABLE 2.5

RESULTS OF COMPONENT FITTING OF HIGH ION PROFILES

<table>
<thead>
<tr>
<th>Species</th>
<th>(V_{\text{LSR}}) [km s(^{-1})]</th>
<th>(\log N_a) [cm(^{-2})]</th>
<th>(b) [km s(^{-1})]</th>
<th>(T) [10(^5) K]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Component 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C IV</td>
<td>(-142.1 \pm 0.9)</td>
<td>(13.25 \pm 0.06)</td>
<td>(7.1 \pm 1.8)</td>
<td>(&lt; 0.4 \pm 0.2)</td>
</tr>
<tr>
<td>Si IV</td>
<td>(-141.5 \pm 0.4)</td>
<td>(12.63 \pm 0.03)</td>
<td>(6.3 \pm 0.8)</td>
<td>(&lt; 0.7 \pm 0.2)</td>
</tr>
<tr>
<td><strong>Component 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C IV</td>
<td>(-111.3 \pm 1.4)</td>
<td>(13.53 \pm 0.07)</td>
<td>(12.8 \pm 2.7)</td>
<td>(&lt; 1.2 \pm 0.5)</td>
</tr>
<tr>
<td>Si IV</td>
<td>(-111.2 \pm 0.9)</td>
<td>(12.47 \pm 0.05)</td>
<td>(10.6 \pm 1.8)</td>
<td>(&lt; 1.9 \pm 0.6)</td>
</tr>
</tbody>
</table>

different velocity distribution of O VI. We discuss the velocity structure of O VI along with the other ions in § 2.6.

2.4.3 H I Column Density Measurements

To estimate the H I column density of the HVC, we used the Lyman series from 926 down to 918 Å, where the HVC absorption is separated from the stronger H I absorption at higher velocities. In Figure 2.5, we show the H I profiles of the transitions considered in our measurements from the SiC2A detector. Higher wavelength transitions were not used because all the components were blended (i.e., the Galactic component is so strong that it covers the weaker absorption at lower velocities). The continuum shown in Figure 2.6 for each transitions was estimated over a large range of velocities in order to reproduce the overall stellar
TABLE 2.6

H I EQUIVALENT WIDTHS FOR THE HVC

<table>
<thead>
<tr>
<th>λ [Å]</th>
<th>f \times 10^{-3}</th>
<th>W_λ [mÅ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>926.2257</td>
<td>3.18</td>
<td>195.8 ± 12.5</td>
</tr>
<tr>
<td>923.1504</td>
<td>2.22</td>
<td>176.5 ± 20.4</td>
</tr>
<tr>
<td>920.9631</td>
<td>1.61</td>
<td>160.5 ± 15.5</td>
</tr>
<tr>
<td>919.3514</td>
<td>1.20</td>
<td>131.0 ± 11.0</td>
</tr>
<tr>
<td>918.1294</td>
<td>9.21 \times 10^{-4}</td>
<td>123.8 ± 12.1</td>
</tr>
</tbody>
</table>

continuum. The same procedure for the continuum placement was employed for the SiC1B detector segment.

To estimate the column densities, a curve-of-growth (COG) method and a profile fitting method were used. The COG method used the minimization of the $\chi^2$ error derivation approach summarized by Savage et al. (1990). In Table 2.6, we summarize the averaged equivalent width measurements estimated in the SiC2A and SiC1B profiles. The 1σ errors include continuum and statistical errors. The darkened part of the spectra in Figure 2.6 shows the typical integration range where the equivalent width was measured. The result from the single-component COG is shown in Figure 2.7, where $b = 21.3^{+2.7}_{-2.4}$ km s$^{-1}$ and log $N$(H I) = 16.47$^{+0.11}_{-0.08}$.

For the profile fitting, we assume a Gaussian instrumental line spread function.

---

*Table 2.6 note: The equivalent widths represent the average of the SiC2A and SiC1B measurements. We adopt the f-values from Morton (2003).*
Figure 2.6. \textit{FUSE} SiC 2A spectra of the H I transitions used to estimate the HVC H I column density (filled absorption at $\sim-140$ km s$^{-1}$). The solid thick lines shows our model for the continuum. The data are binned by 4.2 km s$^{-1}$ per pixels, the \textit{FUSE} resolution at these wavelengths is $\sim25$ km s$^{-1}$ (FWHM).
Figure 2.7. Best fit single-component COG for the HVC absorption produced (HI with $b = 21.3^{+2.7}_{-2.4}$ km s$^{-1}$ and log $N$(HI) = $16.47^{+0.11}_{-0.08}$). The equivalent widths represent the averages of measurements from the FUSE SiC1B and SiC2A.
with a FWHM = 25 km s$^{-1}$. We simultaneously fit all the H I transitions summarized in Table 2.6 for both segments, SiC 2A and SiC 1B. In Figure 2.8, we show an example of this process, where we fitted the absorption with one HVC component and one low velocity component. The result of the fit gives for the HVC component $v = -135.0 \pm 0.8$ km s$^{-1}$, $b = 21.5 \pm 0.5$ km s$^{-1}$, and $\log N = 16.48 \pm 0.02$, which is consistent with the COG result although with much smaller errors. However, the absorption in both the local and HVC shows multiple components. Considering the O I $\lambda$1302 profile (which is the best proxy for the H I profiles), the HVC has at least two components, at $-140$ km s$^{-1}$ and $-125$ km s$^{-1}$. Considering the S II profile, the local absorption reveals at least two components. Importantly, the singly-ionized species systematically show intermediate-velocity absorption at $-59$ km s$^{-1}$, and from our profile fitting trials (see below), its strength and broadening can affect the total column density of the HVC. In the N I absorption profile, this component is not observed. In the O I $\lambda$1302 profile, the $-59$ km s$^{-1}$ component is blended with P II $\lambda$1301. Unfortunately, P II $\lambda$1152 has an apparent optical depth near unity; thus the 0.3 dex larger column density measured in P II $\lambda$1301 relative to P II $\lambda$1152 is consistent with some saturation in the latter transition or with contamination of the P II $\lambda$1301 by intermediate velocity absorption from O I $\lambda$1302. Therefore, it is not clear how much O I absorption there is at $-59$ km s$^{-1}$, if any. The O I profiles in the FUSE bandpass provide no additional information. There is likely some H I absorption at $-59$ km s$^{-1}$, but since the singly-ionized species trace both neutral and ionized gas, it is not clear how strong and broad the H I absorption is in this region.

To test the robustness of the previous fit with 2 components, we modeled the H I lines using several combinations of parameters, including fits with 5 compo-
Figure 2.8. Normalized H I profiles against the LSR velocities. The left-hand side shows data from SiC 2A, the right-hand side shows data from SiC 1B. The black solid line shows the fit to the H I transitions where the velocity centroid of each component is depicted by the dashed line. The grey dotted lines show an example of a fit with 4 components, where the velocities are $-140, -125, -59, -7.9$ km s$^{-1}$ as suggested by the metal lines. In the two-component fit, the total H I column density for the HVC is 16.48 dex, while in the four-component fit, it is 16.58 dex. Note that the excess absorption in the H I $\lambda\lambda 918, 919$ lines is due to contamination from other absorption lines.
nents centered at $-140, -125, -59, -6, +12$ km $s^{-1}$ and 4 components (removing the $+12$ km $s^{-1}$ component), where all the parameters were allowed to vary (except the velocity at $-59$ km $s^{-1}$) or where some parameters were fixed (for example, $b$ and $v$ in the $-59$ km $s^{-1}$ component). We show in Figure 2.8 an example of a four-component fit where the all the parameters were allowed to vary except for the velocity centroids of the HVC and intermediate-velocity cloud. The result of our robustness trial is that the total H I column density in the HVC ranges from 16.44 to 16.60 dex depending on the assumptions. The reduced-$\chi^2$ is within 10% in all our profile fitting trials. Our fitting results give a mean H I column density of $\log N$(H I) = 16.52 ± 0.08. Since the COG and fit methods explore different $\chi^2$ parameters, we adopt a weighted average of the COG and profile fitting results. Our adopted weighted-average (total) H I column density of the HVC is $\log N$(H I) = 16.50 ± 0.06.

We note that the single-component fit to the H I provides a firm upper limit to the temperature of component 1: $T \leq (2.80 \pm 0.13) \times 10^4$ K. Because this single component is known to be a combination of multiple absorbing regions, the non-thermal broadening is significant. The H I-bearing gas making up component 1 is thus quite cool.

2.5 Physical Conditions and Chemical Abundances in the HVC

2.5.1 Electron Density

We make use of the C II $\lambda 1334$ and C II$^*$ $\lambda 1335$ lines to calculate an upper limit to the electron density. The C II$^*$ line arises out of the $^2P_{3/2}$ upper fine structure level, which has an energy $E_{12} \sim 8 \times 10^{-3}$ eV above the $^2P_{1/2}$ ground state, out of which the C II transition arises. The excitation in regions of at least
moderate ionization (see § 2.5.3) is dominated by electrons, while the deexcitation should proceed principally via spontaneous radiative decay. Following Spitzer’s (1978) discussion of the excitation balance, the electron density is related to the column density ratio \( N(\text{C~II}^*)/N(\text{C~II}) \) by (Lehner et al. 2004):

\[
 n_e = 0.53 \frac{T^{1/2}}{\Omega_{12}(T)} e^{(E_{12}/kT)\left(\frac{N(\text{C~II}^*)}{N(\text{C~II})}\right)} \text{ cm}^{-3} \tag{2.5}
\]

where \( \Omega_{12}(T) \) is the temperature-dependent collision strength from Blum & Pradhan (1992) and Keenan et al. (1986). This yields an upper limit to the electron density because the column of C~II \( \lambda 1334 \) is a lower limit due to saturation and C~II* \( \lambda 1335 \) is an upper limit. Using the limit to C~II* for the combined HVCs toward ZNG 1 we find \( n_e \lesssim (0.36 \text{ cm}^{-3})T_4^{1/2} \) \((3\sigma)\) for \( T_4 \equiv T/(10^4 \text{K}) \sim 1 \) to 5 within a few percent. The density limit rises to \( n_e \lesssim 1.5 \text{ cm}^{-3} \) for \( T_4 = 10 \), but the collision strengths for \( T_4 \gtrsim 5 \) are extrapolated from the lower temperature calculations and thus are uncertain. At such temperatures, the ionization fraction of C~II should be small, as well.

Si II may be used as a proxy for C~II. If one assumes solar relative abundances, the implied column density of C~II is \( \log N(\text{C~II}) \approx 14.43 \). Depletion is unlikely to affect this estimate much, as Si II and C~II likely have similar depletion characteristics in clouds with “halo cloud” (Sembach & Savage 1996) abundances. Differing ionization levels for C and Si could affect this determination. Adopting \( \log N(\text{C~II}) = 14.43 \), we find \( n_e \lesssim (0.25 \text{ cm}^{-3})T_4^{1/2} \) \((3\sigma)\) for the high velocity gas.

These estimates assume C~II* is distributed like C~II, where \( \gtrsim 2/3 \) of the column is associated with component 1. If one individually assesses the densities for components 1 and 2, the limits \((3\sigma)\) are \( n_e \lesssim (0.55 \text{ cm}^{-3})T_4^{1/2} \) and \( \lesssim (0.95 \text{ cm}^{-3})T_4^{1/2} \) for components 1 and 2, respectively.
2.5.2 Gas-Phase Abundance

Since O I and H I have nearly identical ionization potentials and are strongly coupled through charge exchange reactions (Field & Steigman 1971), \( N(\text{O I})/N(\text{H I}) \) can be used as a reliable metallicity indicator. The ionization corrections relating \( \text{O I}/\text{H I} \) to \( \text{O}/\text{H} \) are extremely small.

We have measured a total O I column density of \( \log N(\text{O I}) = 13.38 \pm 0.08 \) and a total H I column density of \( \log N(\text{H I}) = 16.50 \pm 0.06 \). Thus the abundance of oxygen is \( \log \text{O}/\text{H} = -3.12 \pm 0.10 \). Assuming the solar abundance of oxygen is \( \log \text{O}/\text{H} = -3.34 \pm 0.05 \) (Asplund et al. 2005), the gas phase abundance of the high velocity gas is then \( [\text{O}/\text{H}] = +0.22 \pm 0.10 \), where \( [X/Y] = \log[N_X/N_Y] - \log\{X/Y\}_\odot \).\(^9\) Thus, the neutral gas in the HVCs toward ZNG 1 has a super-solar oxygen abundance, the highest measured for any HVC. We assume this abundance is representative of the highly-ionized HVC gas as well.

The measured HVC abundance is high compared with the current best solar abundance, the interstellar gas-phase abundance of oxygen in the solar neighborhood \( \langle \log \text{O}/\text{H} \rangle = -3.41 \pm 0.01 \), which is likely affected by modest depletion; Cartledge et al. 2004), the average abundance of young F and G dwarfs in the solar neighborhood \( \langle \log \text{O}/\text{H} \rangle = -3.35 \pm 0.15 \); Sofia & Meyer 2001), and the abundances of H II regions in the solar neighborhood \( \langle \log \text{O}/\text{H} \rangle = -3.58 \) to \(-3.33 \); Rudolph et al. 2006 and references therein). While determinations of the solar oxygen abundance have varied significantly recently, the gas-phase oxygen abundance in the HVCs toward ZNG 1 is larger than, or at least consistent, with all of the determinations. These HVCs have significantly higher metallicities than all other known HVCs, and the gas found locally in the Galactic disk. Depletion

\(^9\)The older solar system abundances of Grevesse & Noels (1992) give \([\text{O}/\text{H}] = +0.01 \pm 0.10\).
effects are unlikely to be significant in this determination; if depletion into the solid phase is important, the total gas+dust phase abundance of the HVCs would be even larger.

2.5.3 Ionization Fraction

We can estimate the fraction of the gas that is ionized by comparing the H I column with an estimate of the total column density of hydrogen \( N(\text{H}) \equiv N(\text{H} \ I) + N(\text{H} \ II) \), where we assume \( \text{H}_2 \) is negligible. We estimate the total H column from the total column of Si: \( N(\text{H}) \approx N(\text{Si}) (\text{Si}/\text{H})^{-1} \), where \( N(\text{Si}) \gtrsim N(\text{Si} \ II) + N(\text{Si} \ III) + N(\text{Si} \ IV) \). The inequality arises because Si III is saturated, and we do not have observations of higher stages of ionization (though these should make little contribution). We adopt \( \log(\text{Si}/\text{H}) = \log(\text{Si}/\text{H})_{\odot} + 0.22 = -4.27 \), which assumes solar relative Si/O and a base Si abundance from Asplund et al. (2005). In regions with significant dust, the gas-phase Si/O may be subsolar. We assume the conditions in this gas are such that depletion of Si/O is not significant. The total H column derived in this way using the column densities in Table 2.4 is \( \log N(\text{H}) \gtrsim 18.03 \), giving \( \log N(\text{H} \ I)/N(\text{H}) \lesssim -1.48 \). The total H column is \( \gtrsim 30 \) times that of the neutral column, and the ionization fraction is then \( x(\text{H}^+) \equiv N(\text{H}^+)/N(\text{H}) \gtrsim 0.97 \). This large ionization fraction implies \( N_\text{H} \approx N_{\text{H}^+} \approx N_e \), and justifies our assumption in §2.7 that \( n_\text{H} \approx n_e \).

This represents the value for the HVCs integrated over components 1 and 2. Very similar values are derived if the components are taken individually. Assuming the velocity structure of H I follows that of O I, since their ionization fractions are locked together by a strong charge exchange reaction, we use the O I columns integrated over the velocity ranges of components 1 and 2 to estimate H I in
each component assuming a constant log(O/H) = −3.12 (§ 2.5.2). This approach yields log \( N(\text{H})/N(\text{H}) \) \( \lesssim -1.44 \) and \( -1.56 \) for components 1 and 2, respectively, implying ionization fractions \( x(\text{H}^+) \gtrsim 0.96 \) and \( \gtrsim 0.97 \).

2.5.4 Path Length Through the HVCs

The results of the previous subsections can be used to estimate the path length through the HVCs. The path length through a cloud is \( \Delta l \approx N(\text{H})n^{-1}_H \) (this assumes constant \( n_H \), though we discuss clumpy media below). Because we do not measure the total hydrogen column, \( N(\text{H}) \), we use Si or C as a proxy for H (as in § 2.5.3): \( \Delta l_{\text{Si}} \approx N(\text{Si})(\text{Si}/\text{H})^{-1}n^{-1}_H \). Using the electron density limits from § 2.5.1 for \( n_H \), we derive \( \Delta l_{\text{Si}} > (1.1 \text{ pc}) T_4^{-1/2} (3\sigma) \) for the integrated HVCs. For temperatures consistent with the temperature limits on component 1 (see Table 2.5), this implies \( \Delta l_{\text{Si}} > 0.6 \text{ pc} \). Similar values can be derived using the columns of C II and C IV \( (\Delta l_C > (0.5 \text{ pc}) T_4^{-1/2}) \). These estimates apply to both components of the HVC, following the discussion of § 2.5.1 and do not depend on ionization assumptions.

Taking components 1 and 2 individually, and using the electron density limits derived for each in § 2.5.1, we find limits \( (3\sigma) \) of \( \Delta l_{\text{Si}} > (0.25 \text{ pc}) T_4^{-1/2} \) and \( > (0.15 \text{ pc}) T_4^{-1/2} \) for components 1 and 2.

Clumping of the gas into regions of different densities cannot lower this value, as the majority of the gas seen in these ions must be at densities consistent with the limits from C II*. If a large fraction of the column of gas were in high density clumps, C II* absorption would be present. These path lengths are inconsistent with typical sizes of circumstellar matter (e.g., discussion in Sahai et al. 2007). We discuss this further in Section 2.7.
2.6 Velocity Structure, Kinematics, and Ionization Structure

2.6.1 Profile Comparisons

Comparing the apparent column density profiles of the high and low ions provides a visual means by which we can examine the kinematic structure of these species. Figure 2.9 shows the apparent column density vs. $v_{\text{LSR}}$ for the high ions Si IV, C IV, and O VI. Two velocity components are clearly observed in Si IV and C IV with LSR centroid velocities of roughly $-140$ and $-110$ km s$^{-1}$. The centroid velocities of the components coincide well between the two ions (see Table 2.5) indicating that these ions reside in the same gas.

The C IV/Si IV ratio changes significantly from component 1 to component 2 (Figure 2.9). Si IV is more prominent in component 1 than component 2 ($\log N_a = 12.63 \pm 0.03$, $\log N_a = 12.47 \pm 0.05$, respectively), but the opposite is true for C IV ($\log N_a = 13.25 \pm 0.06$, $\log N_a = 13.53 \pm 0.07$, respectively). Since C IV has a greater ionization potential than Si IV, this suggests component 2 has a higher degree of ionization, perhaps implying higher temperatures which would be consistent with the results of component fitting (Table 2.5). This is also supported by the increasing O VI and decreasing low ion contributions. From Figures 2.10 and 2.11 we see that more Si III resides in component 2 than does Si IV; yet there is more C IV than Si IV in that component. The ionization potentials for Si III, Si IV, and C IV are 16.3, 33.5, and 47.9 eV, respectively, which suggests that there are at least two processes involved in ionizing that component. The bottom panel of Figure 2.9 shows the apparent column densities vs. $v_{\text{LSR}}$ for the strong lines of C IV, Si IV, and O VI. The velocity distribution of O VI deviates from the common component structure seen in C IV and Si IV, with an increasing column from $v_{\text{LSR}} \sim -120$ to $-90$ km s$^{-1}$. As the columns of C IV and Si IV start to
Figure 2.9. A comparison between the apparent column densities of the high ions in the ZNG1 sight line. The top two panels show both lines of the Si IV and C IV doublets. The good agreement between the profiles of each member of the doublet implies little saturation. The bottom panel shows O VI with scaled versions of Si IV and C IV.
decrease at \( \sim -110 \text{ km s}^{-1} \), \( N(\text{O VI}) \) continues to increase up to \( \sim -90 \text{ km s}^{-1} \), perhaps suggestive of an increase in temperature with velocity leading to higher ionization states.

Figure 2.10 shows a comparison of the apparent column density profiles of Si II \( \lambda 1526 \) with the ions Si II \( \lambda 1304 \), O I \( \lambda 1302 \), Si III \( \lambda 1206 \), Si IV \( \lambda 1393 \), C IV \( \lambda 1550 \), and O VI \( \lambda 1031 \). We note that the low ions are mostly confined to \( v_{\text{LSR}} \lesssim -125 \text{ km s}^{-1} \). The low ions reveal a third component with a centroid velocity of roughly \(-127 \text{ km s}^{-1}\) which is not obvious in the profiles of C IV and Si IV. This third component lies roughly between component 1 (\(-140 \text{ km s}^{-1}\)) and component 2 (\(-110 \text{ km s}^{-1}\)). Component 1 appears to be present in the low ions as well as the high ions. However, component 2 is extremely weak in the low ions. The low ions may show multiple very weak components over the velocity range \( \sim -135 \text{ to } -90 \text{ km s}^{-1} \).

2.6.2 Column Density Ratios and Possible Ionization Mechanisms

Two HVC components are seen in the highly ionized C IV and Si IV, while there are at least 3 components seen in the low ions. The component structure is less certain in the O VI due both to the lower resolution of \textit{FUSE} than STIS and intrinsically broader absorption in O VI. Determining the mechanism(s) by which these species are ionized may aid in constraining the environment in which these HVCs originate.

The principal diagnostics of the ionization mechanisms are the column density ratios of various ions; these can be compared with other sight lines and also with predictions from theoretical models. In Table 2.7 we report the high ion column

\[\text{Table } 2.7\text{ note: The values adopted for Si IV and C IV are from Table 2.5. The values for O VI and N V are taken from Table 2.3 with N V being 3}\sigma \text{ upper limits. The ratios for}\]

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Figure 2.10. Apparent column densities of various ions compared with Si II λ1526. The $N_a(v)$ profile for Si IV λ1393 is multiplied by a factor of four. Components 1 and 2 have velocity ranges of $-162$ to $-126$ km s$^{-1}$ and $-126$ to $-90$ km s$^{-1}$, respectively. The centroid velocities are $-142$ and $-111$ km s$^{-1}$. The ions Si II and O I appear to show a third component with a centroid velocity of $\sim -125$ km s$^{-1}$.
Figure 2.11. Logarithmic apparent column density ratios as a function of $v_{\text{LSR}}$. The ions plotted are Si II $\lambda 1304$, Si III $\lambda 1206$, Si IV $\lambda 1393$, C IV $\lambda 1548$, and O VI $\lambda 1031$. The upward (downward) arrows represent lower (upper) limits. The hatched regions in the C IV/Si IV ratio represent the values derived from component fitting (see Table 2.7). The hatched region in the C IV/O VI ratio represents the maximum and minimum values for this ratio, although clearly a trend is seen as the ratio decreases toward higher velocities. The light gray arrows in the C IV/O VI ratio represents the lower limit for component 1 (see Table 2.7). Components 1 and 2 have velocity ranges of $-162$ to $-126$ km s$^{-1}$ and $-126$ to $-90$ km s$^{-1}$, respectively.
density ratios $N$(C IV)/$N$(Si IV), $N$(C IV)/$N$(N V), and $N$(C IV)/$N$(O VI). The ratio $N$(C IV)/$N$(Si IV) is derived from the results of component fitting, the ratio $N$(C IV)/$N$(N V) is derived from the results of component fitting for C IV and the 3σ upper limit for N V derived from the AOD method, and the ratio $N$(C IV)/$N$(O VI) is derived from the ratio of their $N_a(v)$ profiles. Figure 2.11 shows the ratios of apparent column densities for various ions as a function of $v_{\text{LSR}}$. For the ratios involving O VI (FUSE) we smoothed and rebinned the STIS data (Si IV and C IV) to match the resolution and pixel size of FUSE.

$N$(C IV)/$N$(O VI) are derived from Figure 2.11 (see text for more details). The references for the collisional ionization mechanisms are: radiative cooling: Heckman et al. (2002), Gnat & Sternberg (2007), Edgar & Chavelier (1986), conductive interfaces: Borkowski et al. (1990), turbulent mixing layers: Slavin et al. (1993), shock ionization: Dopita & Sutherland (1996), SNRs: Slavin & Cox (1992), halo-SNRs: Shelton (1998). a. The quoted ratios assume gas cooling from 10$^6$ K with a cooling flow velocity of 100 km s$^{-1}$ for isobaric and isochoric (and intermediate) conditions. The data was taken from Edgar & Chevalier (1986) for the first set of values, and from Gnat & Sternberg (2007) for the second. b. The quoted ratios assume magnetic field orientations in the range 0 – 85°, and interface ages in the range 10$^5$ – 10$^7$ yrs. These ratios should be considered crude estimates as they were estimated from graphs in Borkowski et al. (1990). c. The quoted ratios assume gas with entrainment velocities in the range 25 – 100 km s$^{-1}$ and mixing-layer temperatures in the range 1 – 3 × 10$^5$ K. d. The quoted ratios assume shock velocities in the range 150 – 500 km s$^{-1}$, and magnetic parameters in the range 0 – 4 μG cm$^{-3/2}$. e. The quoted ratios are for SNR ages 10$^5.6$–$6.7$ yr. f. The quoted ratios are for SNR ages 10$^6.0$–$7.2$ yr.
### TABLE 2.7

COMPONENT-TO-COMPONENT COLUMN DENSITY RATIOS

<table>
<thead>
<tr>
<th>Component Number</th>
<th>$V_{LSR}$ [km s$^{-1}$]</th>
<th>$N$(C IV)/$N$(Si IV)</th>
<th>$N$(C IV)/$N$(N V)</th>
<th>$N$(C IV)/$N$(O VI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\sim -142$</td>
<td>4.2 ± 0.7</td>
<td>$&gt; 3.3$</td>
<td>$&gt; 2.1$</td>
</tr>
<tr>
<td>2</td>
<td>$\sim -111$</td>
<td>11.5 ± 2.3</td>
<td>$&gt; 6.0$</td>
<td>0.4 – 3.2</td>
</tr>
</tbody>
</table>

Predicted Ratios for Different Ionization Mechanisms

- **Radiative Cooling**
  - $8.7 – 33.0$
  - $0.9 – 2.7$
  - $0.0 – 0.2$
- **Radiative Cooling$^a$**
  - $3.0 – 40.0$
  - $0.5 – 13.0$
  - $0.1 – 5.0$
- **Conductive Interfaces$^b$**
  - $5.5 – 30.9$
  - $0.8 – 2.6$
  - $0.1 – 0.9$
- **Turbulent Mixing Layers$^c$**
  - $0.9 – 28.8$
  - $7.4 – 29.5$
  - $1.1 – 7.4$
- **Shock Ionization$^d$**
  - $1.3 – 33.0$
  - $0.7 – 38.6$
  - $0.0 – 1.1$
- **Supernova Remnant (SNR)$^e$**
  - $8.6 – 16.7$
  - $2.4 – 2.9$
  - $0.1 – 1.9$
- **Halo SNR$^f$**
  - $\cdots$
  - $1.8 – 9.0$
  - $0.1 – 3.0$
Component 1 ($-162$ to $-126$ km s$^{-1}$) is characterized by strong absorption in the low ions and weak absorption in O VI. From Figure 2.11, we place a limit $\log(N(C\ IV)/N(O\ VI)) \gtrsim +0.5$ (3$\sigma$). If one integrates the O VI over the full velocity range of $-162$ to $-126$ km s$^{-1}$, this ratio is $\log(N(C\ IV)/N(O\ VI))= +0.3 \pm 0.1$. However, the straight integration is dubious since the component structure in C IV appears to be different than that of O VI. The C IV to Si IV ratio seen in Figure 2.11 is $\log(N(C\ IV)/N(Si\ IV)) \sim +0.6 \pm 0.2$, consistent with the results of component fitting. Both Si II and Si III are more abundant than Si IV in this component. We find $\log(N(Si\ II)/N(Si\ IV)) \approx +0.7$ for component 1.

The low ions (e.g., O I, Si II) show a component centered between components 1 and 2 of the high ions at $v_{\text{LSR}} \sim -127$ km s$^{-1}$. There is less or little absorption in O VI, C IV, and Si IV at these velocities. The C IV and Si IV absorption in this region is consistent with the contributions from the wings of components 1 and 2. The O I/Si II ratio in this range is about twice as high as in component 1, suggesting a slightly smaller ionization fraction, $x(H^+) \sim 0.9$.

Component 2 ($-126$ to $-90$ km s$^{-1}$) is characterized by strong O VI absorption and weak absorption for the low ions. From Figure 2.11, we find $+0.4 \lesssim \log(N(C\ IV)/N(O\ VI)) \lesssim +3.2$. Integrating the O VI over the full velocity range of $-126$ to $-80$ km s$^{-1}$ gives $\log(N(C\ IV)/N(O\ VI)) = +0.1 \pm 0.1$. It is unclear which is more appropriate because the O VI and C IV profiles do not share the same component structure in this velocity range, however, they could be part of the same physical structure. The C IV to Si IV ratio seen in Figure 2.11 is $\log(N(C\ IV)/N(Si\ IV)) \sim +1.0 \pm 0.3$, consistent with the results of component fitting. Both Si II and Si III are also more abundant than Si IV in this component like in the other one, although the Si II to Si IV ratio decreases toward higher
velocities.

O VI dominates the region from $-100$ to $-80$ km s$^{-1}$ while the Si IV and C IV absorption continues to decline, and there is very little if any absorption in the low ions. This shows that several ionization mechanisms are likely at play.

To investigate the possible mechanisms responsible for the production of the highly-ionized high velocity gas, we focus on Si IV, C IV, N V, and O VI. We compare the ratios of the high ions with those predicted from selected theoretical models in Table 2.7. Although we compare our results with all these models, we only discuss the models for which all the ratios are consistent with our measured values.

The ratios predicted from the models assume solar relative abundances. Where the models used older estimates of the solar abundance, we have adjusted the results to current solar abundance estimates adopted from Asplund et al. (2005). The adjustments are done following Fox et al. (2004): 

$$\log \left[ \frac{N(X)}{N(Y)} \right]_\text{new} = \log \left[ \frac{N(X)}{N(Y)} \right]_\text{old} + \Delta \log A_X - \Delta \log A_Y$$

where $\Delta \log A_X = \log A_X(\text{adopted}) - \log A_X(\text{old})$. It would however, be preferable to recalculate the models with updated atomic parameters and solar abundances.

In general, the higher stages of ionization become more important as the LSR velocity increases from $-150$ to $-90$ km s$^{-1}$. If collisional ionization dominates the ionization of the high ions, the bottom two panels of Figure 2.11 suggest component 2 is at a higher temperature than component 1. If the gas of component 2 were in collisional ionization equilibrium (CIE), it would require temperatures of $(1 - 2) \times 10^5$ K to match the C IV/O VI ratios (Gnat & Sternberg 2007). However, the limits on $N$(N V) and the strength of Si III are inconsistent with pure CIE.

Of the possible mechanisms that may give rise to the high ions for component
1, only non-equilibrium radiative cooling (RC; Gnat & Sternberg 2007), turbulent mixing layers (TMLs; Slavin et al. 1993, Esquivel et al. 2006), and halo-supernova remnants (halo-SNRs; Shelton 1998) give column density ratios consistent with the observations (see Table 2.7 and references therein). In the case of radiative cooling, only near the temperature \(2 \times 10^4 \text{ K}\) do the predicted column densities agree with the observed column densities and ratios. This temperature is allowed by the \(b\)-values of this component (see Table 2.5). However, the RC model predicts a higher \(\text{Si II}\) to \(\text{Si IV}\) ratio \((\log N(\text{Si II})/N(\text{Si IV}) \approx 0.8 - 1.0)\) than observed in this temperature regime \((\log N(\text{Si II})/N(\text{Si IV}) \approx 0.2 - 0.8)\). Therefore, the RC model cannot single-handedly explain the observations. The TML model of Slavin et al. for \(\log T = 5.3\) and \(v = 100 \text{ km s}^{-1}\), where \(T\) is the temperature of the mixing layer and \(v\) is the transverse velocity, best matches the observed \(\text{C IV}/\text{Si IV}\) ratio, although our value of \(4.17 \pm 0.65\) is still significantly higher than the metallicity-corrected value this model predicts.\(^{11}\) This temperature is also above the maximum temperature allowed from component fitting for this component. A velocity higher than the highest they considered \((100 \text{ km s}^{-1})\) may improve the agreement given the trends in their predictions. Our \(\text{C IV}/\text{Si IV}\) ratio for component 1 is consistent with the TML models of Esquivel et al. (2006). Esquivel et al. assume ionization equilibrium and their models are evolving, having not reached a steady state.\(^{12}\) The \(\text{Si IV}\) column density was not calculated by Shelton (1998) for her halo-SNR model, so we are unable to test our most stringent ratio against the halo-SNR model for either component.

\(^{11}\)The metallicity corrected values are 0.87–2.51, corresponding to velocities of 25 and 100 km s\(^{-1}\), respectively. Our ratio of \(4.17 \pm 0.65\) is within the preadjusted range of 1.58–4.57 based on the abundances of Grevesse (1984).

\(^{12}\)The models of Slavin et al. do not assume ionization equilibrium. They differ from Esquivel et al. in that they predict the column densities assuming a steady state has been reached.
For component 2, TMLs, shock ionization (SI; Dopita & Sutherland 1996), and halo-SNRs give column density ratios consistent with our measurements. The RC models of Gnat & Sternberg (2007) can match the observed ratios of component 2. However, the total column densities predicted by the models do not match the observed column densities where the ratios are consistent. The observed C IV/Si IV ratio fits best with the TML model of Slavin et al. for \( \log T = 5.0 \) or 5.5 and \( v = 25 \text{ km s}^{-1} \). The highest of these temperatures is inconsistent with the C IV \( b \)-value. The TML model of Esquivel et al., on the other hand, seems to be incompatible with our C IV/Si IV ratio. A better agreement may be possible at a lower transverse velocity than the minimum velocity they consider (50 km s\(^{-1}\)).

The SI model, which matches the observed C IV/Si IV ratio of 11.5 ± 2.3, has a magnetic parameter of \( 2\mu G \text{ cm}^{3/2} \) and a shock velocity of 200 km s\(^{-1}\). This model could conceivably give similar ratios for the same magnetic parameter but with a velocity somewhere between 300 and 400 km s\(^{-1}\), given the trends in their results.

The multiphase nature of this gas combined with its complicated component structure makes determining the mechanism(s) responsible for the ionization difficult. The ZNG 1 sight line is most likely too complicated to be described by a single model, nor is it likely that the idealized situations in which the models are run encompass the true nature of this gas. We cannot rule out turbulent mixing layers or halo supernova remnants for the \(-140 \text{ km s}^{-1}\) cloud (component 1); similarly, we cannot rule out turbulent mixing layers, shock ionization, or halo supernova remnants for the \(-110 \text{ km s}^{-1}\) cloud (component 2) as possible ionization mechanisms. The kinematics of the HVCs toward ZNG 1 are not inconsistent with these mechanisms.

Given the small \( b \)-values for component 1, it may be likely that photoionization
also plays an important role in ionizing that component. Although we will show that ZNG 1 itself is unlikely to provide for its ionization, the gas along the ZNG 1 sight line must be subject to radiation escaping from the Milky Way and also the extragalactic background radiation (e.g., see § 6 of Fox et al. 2005). Furthermore, radiation emitted from cooling hot gas could also play a role if these HVCs are in close proximity to such material. Photoionization could explain the presence of C II, Si II, Si III, and the other low ions, and Knauth et al. (2003) showed that it is possible to match our observed C IV/Si IV ratio via photoionization by X-ray/EUV emitting gas. However, neither the Milky Way’s escaping radiation nor the extragalactic background radiation can account for the observed O VI (Fox et al. 2005). The ionization of the high ions, and O VI in particular, must involve collisions. Moreover, since the high and low ions seem to coexist in component 1, and possibly throughout parts of component 2, there must be changing physical conditions throughout this multiphase gas.

We finally note that \( N(\text{S III}) > 2 \times N(\text{S II}) \) in component 1, as well as integrated over the HVCs (see Table 2.4). This is unusual for gas in the Milky Way. It is in contrast with the ionization state of the photoionized warm ionized medium of the Galaxy for which S II makes up \( \sim 75\% \) of the sulfur (as demonstrated by Haffner et al. 1999 and the data given in Howk et al. 2006). This also suggests a relatively high state of ionization for this gas, even for the component that seems likely to be affected by photoionization. This may be reflecting the presence of hot collisionally-ionized material or of a strong, hard ionizing spectrum (but not so hard that is overionizes Si since in component 1 \( N(\text{Si IV}) < N(\text{Si III}) \)). Helium recombination radiation could play a role in ionizing S II to S III.
2.7 The Circumstellar Hypothesis

Here we examine the hypothesis that the HVCs seen toward ZNG 1 represents circumstellar material near ZNG 1 itself. As a PAGB star, ZNG 1 may be expected to have some circumstellar material. Although ZNG 1 is sufficiently hot to provide for the ionization of a planetary nebula (PN), no Hα emission is detected about this star (Napiwotzki & Heber 1997). PAGB stars in globular clusters seem less likely to give rise to a visible planetary nebula phase than their field star brethren (Moehler 2001).

The high-velocity gas along this sight line is significantly different than planetary nebula gas. The velocity of the HVCs relative to the stellar photosphere is \(\sim -150\) to \(-190\) km s\(^{-1}\), much higher than planetary nebulae studied in absorption (e.g., K648 in M 15 has an expansion velocity of 12–17 km s\(^{-1}\) according to Bianchi et al. 2001, while the young PN ESO 457–2 studied by Sterling et al. 2005 shows an expansion of only \(\sim 30\) km s\(^{-1}\)). Furthermore, the columns of material in PNe are typically significantly larger than those seen here (e.g., Williams et al. 2003, Sterling et al. 2005), with many showing very strong absorption from high ions (e.g., C IV) or from excited fine structure states (e.g., S III\(^*\), O I\(^*\), Si II\(^*\); see Sterling et al. 2005, Williams et al. 2003, 2008). The latter are a reflection of the relatively high densities of PN shells, with values \(n_e > 1000\) cm\(^{-3}\) being the norm (Williams et al. 2003, Sterling et al. 2005, 2007). These densities are in strong contrast to the upper limit of \(n_e \leq (0.36\) cm\(^{-3}\)\)T\(^{1/2}\) reported in Section 2.5.

While the high velocity gas seen toward ZNG 1 seems unlikely to represent a traditional planetary nebula about the star, it could still be circumstellar in nature. In this scenario, the density of the material would be too low and/or the material too close to the star to produce detectable Hα emission. However, the
lower limits to the path lengths derived in Section 2.5.4 are inconsistent with this. In addition, the lack of C II* is inconsistent with gas very near the star, where radiative pumping can play a role in populating the upper \(2P_{3/2}\) fine structure level of C II. For example, Trapero et al. (1996) observed circumstellar HVC gas (at LSR velocities of \(-158\) and \(-51\) \(\text{km s}^{-1}\)) associated with the close binary \(\eta\) Tau. They observed C II* \(\lambda 1335\) absorption which was much stronger than the C II \(\lambda 1334\) absorption in the spectra of both stars of the binary, with optical pumping from \(\eta\) Tau responsible for the strong C II*.

Nonetheless, in order to strongly rule out the circumstellar hypothesis we also investigate photoionization models of material about the star ZNG 1. Any circumstellar material is going to be strongly affected by the radiation from the central star. We should be able to produce models consistent with the observations of the HVCs if this is the case. The results of these models strongly suggest this hypothesis is not viable.

We use the Cloudy ionization code (version 07.02.00; last described by Ferland et al. 1998) to calculate the ionization structure of gas about ZNG 1. The ionizing spectrum is assumed to be a model stellar atmosphere calculated with TLUSTY (Hubeny & Lanz 1995). We assumed an effective temperature \(T_{\text{eff}} = 45,000\) K and a surface gravity \(\log g = 4.48\) with a luminosity \(\log L/L_\odot = 3.5\) (see Table 1). The elements H, He, C, and N were treated in non-LTE, while other elements were treated in LTE. We assume the atmosphere is made up of 99% He (by number), with C and N at 10 times the solar abundance (by total mass), and O at twice solar. All other elements were scaled to solar abundances except Fe, for which we adopt \([\text{Fe/H}] = -1.27\). Shocks within the wind of ZNG 1 might produce X-rays, and we have tested the effects of including wind-produced X-rays. For this,
we assume emission from a $T = 10^6$ K plasma with a luminosity relative to the stellar bolometric luminosity of $L_X/L_{bol} = 10^{-7}$ (e.g., Pallavicini et al. 1981). The inclusion of X-rays has very little impact on our models.

We assume the gas is distributed in a constant density shell with $n_H = 0.4$ cm$^{-3}$. This is equivalent to the $3\sigma$ limit to the electron density from the integrated C II$^*$ diagnostic (the photoionized gas from the models has a temperature $T \approx 10^4$ K) or a $2\sigma$ limit for component 1 alone (see §2.5.1). The gas is nearly fully ionized, so $n_H \approx n_e$. We adopt a gas-phase metallicity of $\log Z/Z_\odot = +0.20$ given our [O/H] measurement, and assume solar relative abundances. (The relative solar abundances of the gas should not be compared with those of the photosphere, which has negligible hydrogen. The HVCs, if circumstellar, would represent gas lost from a much different part of the star than as seen as the current photosphere.) We do not include dust for heating or attenuation purposes, but we do include the effects of a Galactic cosmic ray background. We calculate the ionization structure of the gas from an initial inner shell radius, proceeding until the H I column of the HVC is matched. We calculate the total column densities of ions in the gas for inner shell radii in the range $\log(r_0/\text{cm}) = 16.0$ to 20.0, i.e., 0.003 to 33 pc. The lower value is similar to the inner radii of some planetary nebulae (e.g., Sterling et al. 2007). The upper value is unphysically large for such a structure, but we extend the calculations that far to probe the sensitivities of the column densities to this parameter.

The results of the photoionization models are inconsistent with a circumstellar origin for the HVC toward ZNG 1 for a number of reasons. Similar to Section 2.5.4, the most fundamental difficulty is the predicted thickness of the resulting shell, which is shown in the top panel of Figure 2.12. Because the limits on the density
are so low, a large thickness is required to match the observed H I column density of the HVC. For all models with inner shell radii $r_0 < 1$ pc, the thickness of the shell exceeds $10$ pc, implying a shell diameter in excess of the core radius and the half-mass radius of the globular cluster M5 itself (Harris 1996). It is highly unlikely that a shell of such thickness and low density could survive in this environment. Furthermore, such sizes are well in excess of typical PN size scales, as well as typical sizes for circumstellar material observed about typical PAGB stars (see e.g., discussion in Sahai et al. 2007). To find shells with thicknesses $< 2$ pc requires $r_0 \gtrsim 20$ pc; once again, such a large inner surface to the shell is inconsistent with a circumstellar origin.

We stress that the derived thicknesses are robust predictions of the models dependent only on the adopted density, the H I column density, and the ionizing luminosity of the star. The low density and large luminosity of the star drive the density of neutral hydrogen to very low values, thereby requiring a large path length for even the very low H I column of this HVC. The predicted thickness is insensitive to the presence of X-rays from the wind of ZNG 1. This calculation should also be insensitive to the details of the model stellar atmosphere, so long as the ionizing hydrogen flux is approximately correct (we have tested this sensitivity by calculating models that make use of main sequence OB star atmospheres with similar effective temperatures and surface gravities, finding very similar results). The thickness is, of course, sensitive to the assumed density of the gas. Raising the density to as high as $n_H \approx 1.5$ cm$^{-3}$ seems difficult given the constraints from the C II* absorption and the $b$-values for component 1 (see Table 4), and that would only decrease the shell thicknesses in Figure 2.12 by a factor of about four.

We also note that the ionic ratios found in the HVC, either from the total
Figure 2.12. Cloudy models of a circumstellar shell about ZNG 1. **Top:** The shell thickness as a function of inner shell radius, $r_0$. This depends on the assumed hydrogen density and the ionizing flux of the star. We assume $n_H = 0.4 \text{ cm}^{-3}$, near the upper limit provided by the C II$^+$; lowering the density would increase the shell thickness. **Bottom:** The column density ratios as a function of inner shell radius. We plot the model predictions for the Si II/Si IV, C II/C IV, and C IV/Si IV ratios as the smooth curved lines. The observational constraints for component 1 are shown using the same symbols. The lower limit is for C II/C IV given the likely saturation in the C II profile. The $\pm 1\sigma$ range is shown for the other two ratios. The C IV/Si IV ratio (triangles) cannot be matched by our models. The Si II/Si IV ratio is matched for an inner shell radius of $\approx 9 \text{ pc}$, which is consistent with the constraint provided by C II/C IV. As discussed in the text, the C IV/Si IV ratio for the integrated HVC is even further from the models.
integrated absorption or from the narrow component 1, are difficult to match with our photoionization models. This is shown in the bottom panel of Figure 2.12. The observed C IV/Si IV ratio cannot be matched by our photoionization models. The maximum C IV/Si IV ratio produced in our models is 1.4, which occurs for \( r_0 \lesssim 0.1 \) pc. This should be compared with the observed ratio of 4.2±0.7 (Table 6) for component 1, which has a lower \( b \)-value and displays more prominent low ion absorption than component 2, suggesting it is more likely to be photoionized.

The observed C IV/Si IV ratio for the integrated HVCs (components 1 and 2) is 7.1 ± 1.0. The C II/C IV and Si II/Si IV ratios, which are independent of the assumed relative abundance, can both be matched at large values of the inner radius, \( r_0 \). The limit to the C II/C IV ratio for component 1 is matched for \( r_0 \gtrsim 3 \) pc (\( \gtrsim 1.5 \) pc for the integrated ratio), while the Si II/Si IV ratio is matched for \( r_0 \approx 9 \) pc for both the component 1 and the integrated ratios. The total column densities of C IV and Si IV predicted by the models are not consistent with the data at the same values of \( r_0 \) required to match their ratio. Negligible O VI is produced via photoionization.

The difficulty in matching the C IV/Si IV ratio and the large inner shell radii required by the other ionic ratios suggest that the HVC is not ionized directly by ZNG 1. This is, of course, dependent on the shape of the stellar spectrum over the energy range 33 eV to \( \gtrsim 65 \) eV. We have tested the effects of adopting alternative model atmospheres. CoStar model atmospheres (Schaerer & de Koter 1997) of main sequence stars with similar temperatures can match the C IV/Si IV ratio observed in these HVCs. However, they cannot simultaneously match this ratio and the C II/C IV and Si II/Si IV ratios, and they too require large path lengths inconsistent with a circumstellar origin. We also note that Smith et al.
(2002) have argued the CoStar models produce spectra that are too hard over the 41 to 54 eV range, which could significantly affect the C IV/Si IV diagnostic. While models invoking shock ionization in addition to photoionization by ZNG 1 could be considered, these will tend to drive down the ionization fraction of H I, requiring even thicker shells. In short, we feel a robust conclusion can be drawn from our models and the physical conditions derived above: the properties of the HVCs toward ZNG 1 are inconsistent with the hypothesis that these clouds have a circumstellar origin.

2.8 Discussion

Along the ZNG 1 sight line, high-velocity absorption is seen in O VI, C IV, and Si IV along with lower ionization and neutral states. As we discussed previously, neither a circumstellar origin (see §2.7) nor a local origin (e.g., in Loop I; see §2.3) is likely for this absorption. The high-velocity absorption toward ZNG 1 therefore represents an example of interstellar highly-ionized HVCs, sharing ionization and other characteristics (e.g., multiphase structure, column density ratios, $b$-values) with highly-ionized HVCs observed toward extragalactic objects (e.g., Fox et al. 2006). The presence of the high ions, especially O VI, suggests the presence of hot gas ($10^6$ K) interacting with cooler gas ($10^4$ K) in the regions giving rise to this absorption. The theoretical models capable of matching the high-ion column densities and column density ratios in these HVCs include turbulent mixing layers, shocks, and supernova remnants. Furthermore, the multiphase nature of this gas implies that more than one ionization mechanism is responsible for the creation of the ions in the HVCs. While collisional ionization is required to explain the O VI and portions of the other high ions, photoionization is likely to play an important
role in the lower ionization species.

The O VI absorption toward ZNG 1 is reminiscent of high-velocity “wings” seen in O VI, C III, and H I toward AGNs (e.g., Sembach et al. 2001; 2003, Savage et al. 2005, Fox et al. 2006). These authors do not identify any negative-velocity wings. One interpretation advanced to explain the highly-ionized wings and other HVCs is that they probe a hot Galactic fountain or Galactic wind. In this scenario, supernovae and stellar winds create large overpressurized bubbles that may eject material and energy from the disk into the halo of the Milky Way. Depending on the speeds of the outflow (often at the sound speed of the hot gas), some material can fall back on the disk (this is a fountain scenario, see Shapiro & Field 1976. Houck & Bregman 1990). If the speeds of the outflow are greater than the escape velocity, a Galactic wind will push the material beyond the potential well of the Galaxy. Galactic outflows (and the returning material) often have a complex multiphase mixture of cool and hot gas, as revealed by observations of starburst and dwarf galaxies and by galaxy wind models (e.g., see Veilleux et al. 2005, Heckman et al. 2002, Lehner & Howk 2007). The HVCs along the ZNG 1 sight line are complex multiphase structures, consistent with these observations and models, and the presence of high ions suggests they are closely connected to energetic phenomena in the Galaxy. The blueshifted velocities of the HVCs toward ZNG 1 indicate flows (radial or vertical) with a component directed toward the sun. This may be indicative of a large-scale Galactic circulation, where we are seeing the return of material rather than the ejection.

The origins of highly-ionized HVCs in a galactic fountain-type flow is certainly plausible, but it requires that the HVCs originate in the Galaxy. Thus, their metallicities should be near solar and their distances not too great in such a model.
The distances of highly-ionized HVCs toward QSOs and AGNs are unknown, and the metallicity estimates for these HVCs often depend sensitively on the specific ionization model adopted (see below). However, the distance and metallicity of the highly-ionized HVCs toward ZNG 1 are known. The distance of M5 is well determined and places a strict upper limit for the distance to the HVCs of $d < 7.5$ kpc. The metallicity of the HVC gas is $[\text{O/H}] = +0.22\pm0.10$. Since our metallicity estimate was derived from a comparison of O I and H I, no ionization correction is needed (see § 2.5.2). Together, the metallicity and distance constraints rule out an extragalactic origin for these HVCs; instead, it seems probable that these clouds are related to energetic phenomena that drive gas flows in the Milky Way. These are the only highly-ionized HVCs confirmed to be within the Galaxy.

The super-solar metallicity suggests these HVCs originated near the central regions of the Galaxy. Smartt & Rolleston (1997) and Rolleston et al. (2000) showed that the oxygen abundance of early B-type main-sequence stars decreases by $-0.07 \pm 0.01$ dex kpc$^{-1}$ as one moves away from the Galactic center. The expected metallicity of disk gas at a radial distance similar to ZNG 1 is thus $[\text{O/H}] \sim +0.35$ if we calculate this from the solar neighborhood toward the Galactic center. The metallicity of these HVCs may be less because they originated closer to the sun than M5. On the other hand, if O is depleted by about 0.1 dex, $[\text{O/H}]$ of the HVCs toward ZNG 1 would match the O abundance near the Galactic center.

The close proximity of ZNG 1 to the Galactic center, the complex multiphase structure of the high-velocity gas in this direction, its super-solar metallicity, and its large velocities raise the possibility that these HVCs may not only be linked to a Galactic fountain, but in some way to a wind driven from the vicinity of the Galactic center (e.g., Sofue 2000, Yao & Wang 2007). Bland-Hawthorn &
Cohen (2003) and Keeney et al. (2006) each produced a phenomenological model of a Galactic nuclear wind. The former produced their model based on *Midcourse Space Experiment* observations of infrared dust emission from the Galactic center and *ROSAT* X-ray observations, while the model of Keeney et al. was developed to explain highly-ionized HVCs along the Mrk 1383 and PKS 2005–489 sight lines. The model presented by Bland-Hawthorn & Cohen has a bipolar wind with initial velocities of $1700 - 3000 \text{ km s}^{-1}$, rising from the Galactic center in a $\sim 45^\circ$ conical shape, which becomes cylindrical at a height above the plane of $\sim 5 \text{ kpc}$ and with a radius of $\sim 6 \text{ kpc}$. The model described by Keeney et al. is similar to that of Bland-Hawthorn & Cohen, except that the conical shape turns cylindrical at a $z$-height of $\sim 2 \text{ kpc}$ and the cylinder has a radius of $\sim 1.5 \text{ kpc}$. ZNG 1 lies within the outer bounds of the outflow cone in the wind model of Bland-Hawthorn & Cohen and just outside that of Keeney et al. While the initial velocities at the base of such a wind are high, Sofue (1984) showed that this wind could slow down considerably. The shock velocities of an evolving wind considered by Bland-Hawthorn & Cohen (2003) and Sofue (2000, 1984) are of the order of one to a few hundred km s$^{-1}$. If the model of Bland-Hawthorn & Cohen is representative of the Milky Way’s nuclear wind, then the highly-ionized HVCs observed toward ZNG 1 may be gas near the leading edge of the conical section of the wind that is falling back onto the Galaxy. Such infall can occur if thermal instabilities form denser gas with too little buoyancy to be supported against gravity.

If a significant amount of material is participating in outflows or fountain-like processes in the inner Galaxy, other sight lines passing through this region should show signs of these flows. A few extragalactic sight lines that are within about $\pm 25^\circ$ longitude from the Galactic center were observed with *FUSE* or STIS, and
all of them (with enough signal) show highly-ionized high-velocity absorption. These include ZNG 1 \( (v_{\text{LSR}} < 0) \), PG 1553+113 \( (v_{\text{LSR}} < 0) \) (see below), Mrk 1383 \( (v_{\text{LSR}} > 0) \) (Keeney et al. 2006, Fox et al. 2006), PKS 2005–489 \( (2 \text{ with } v_{\text{LSR}} < 0) \) (Keeney et al. 2006, Fox et al. 2006), ESO 141–G55 \( (v_{\text{LSR}} > 0) \) (Fox et al. 2006), and PKS 2155–304 \( (v_{\text{LSR}} > 0) \) (Collins et al. 2004, Fox et al. 2006). Similar to the HVCs toward ZNG 1, all these HVCs are multiphase. Therefore, sight lines that pass through or near the central region show the signature of outflow and infalling material, consistent with large circulation motion with the inner regions of the Milky Way. We note that the sight line toward PG 1553+113 \( (l = 21.9^\circ, b = +44.0^\circ) \) lies only 13.1° from ZNG 1 and shows a high negative velocity O VI absorption detected at 3.5σ (see §2.3). The velocity \((-170 \leq v_{\text{LSR}} \leq -100 \text{ km s}^{-1})\), column density \( \log N(\text{O VI}) = 13.57^{+0.11}_{-0.13} \)\), and the shape of the O VI profile (see Figure 6 in Fox et al. 2006) are quite similar to those of the HVCs toward ZNG 1, suggesting that this HVC could be part of a similar flow.

Unfortunately, the metallicity for the HVC toward PG 1553+113 cannot be estimated: the column density of H I cannot be measured due to low signal-to-noise ratios in the FUSE SiC channel data. For the other sight lines mentioned above, which probe the inner Galaxy, \( N(\text{H I}) \) is only estimated for two HVCs in the spectrum of PKS 2155–304 (Collins et al. 2004) and estimated with very large uncertainties for one HVC in the spectrum of PKS 2005–489 (Keeney et al. 2006). For PKS 2155–304, we calculate \([\text{O/H}] < +0.37 \) and \(< +1.62 \) for the −140 and −270 km s\(^{-1}\) clouds, respectively, based on the column densities of O I and H I estimated by Collins et al. (2004). These values could be consistent with a super-solar metallicity. On the other hand, photoionization models by Collins et al. give subsolar values of \(-0.47^{+0.15}_{-0.24} \) and \(-1.20^{+0.28}_{-0.45} \), inconsistent with
the origins of these clouds in a Galactic fountain or outflow. We note that these uncertainties only include errors in the column density measurements, with no contribution from uncertainties in the modeling. These model-derived metallicities are highly dependent on the adopted ionizing spectrum and model assumptions. For example, J.C. Howk et al. (2007, in preparation) show that using a QSO-type and QSO+galaxy type radiation fields can produce metallicities that are different by a factor three in IGM absorbers. Collins et al. adopted a QSO-only radiation field, which provided a better fit to the data than a purely stellar radiation field. However, it is not clear how their metallicity estimates would change if their radiation field included ionizing radiation from the Galaxy as well as QSOs. Furthermore, Si IV and C IV were used to constrain their models, even though it is likely that collisional processes may produce part of the absorption of these high ions (see discussion in Collins et al. 2004). For PKS 2005–489, the metallicity is largely unknown given the order of magnitude uncertainty in $N$(H I). We therefore believe that without a full understanding of the ionization in highly-ionized HVCs, metallicity estimates derived purely from photoionization models should be considered tentative at best.

Highly-ionized HVCs along the sight lines HE 0226–4110, PG 0953+414 (Fox et al. 2005) and PG 1116+215 (Ganguly et al. 2005) also have metallicities derived from a comparison of O I to H I. The metallicities of the HVCs toward HE 0226–4110 (+175 km s$^{-1}$ cloud), and PG 1116+215 (+100 and +184 km s$^{-1}$ clouds) are $[O/H] < -0.07$, $< +0.05$, and $-0.66^{+0.39}_{-0.16}$, respectively. Those values are all $\gtrsim 2\sigma$ lower than the $[O/H]$ measurement for the HVCs toward ZNG 1. The low metallicities may imply an extragalactic origin for these HVCs. This does not affect the hypothesis that the HVCs toward ZNG 1 trace outflows or
circulation/feedback in the inner Galaxy since these sight lines do not pass through the central regions of the Galaxy. It is also not clear that these metallicities are significantly subsolar. Like for the H I HVCs, it is very unlikely that highly-ionized HVCs have a single origin. For instance, based on their kinematics and projection on the sky, several highly-ionized HVCs appear to be associated with known H I HVCs such as Complexes A and C, the Magellanic Stream, and the Outer Arm (e.g., see Fox et al. 2006). The HVCs toward ZNG 1 show, for the first time, that some of the highly-ionized HVCs likely have their origins in the Galaxy. We note that the ionization characteristics and physical conditions of the ZNG 1 HVCs are similar to other highly-ionized HVCs (e.g., $N(\text{C IV})/N(\text{Si IV})$, $N(\text{C IV})/N(\text{O VI})$, $b$-values, multiphase structure). This may imply that similar ionization mechanisms may be at work in creating the high ions, but it also means that highly-ionized Galactic and extragalactic HVCs cannot be easily separated based on their ionization characteristics alone. We finally note that the properties (i.e., no H I 21 cm emission, $|v_{\text{LSR}}| > 100$ km s$^{-1}$) of the highly-ionized HVCs toward ZNG 1 fit the category of highly-ionized HVCs considered by Nicastro et al. (2003). These authors proposed a Local Group origin for highly-ionized HVCs because it would better explain their kinematic distribution. The highly-ionized HVCs toward the ZNG 1 sight line show that this argument alone is rather weak. Distances and metallicity estimates are key to distinguish Galactic from extragalactic HVCs, but these are most often estimated indirectly for highly-ionized HVCs, relying on photoionization models. More observations of distant stars may allow direct distance limits for other clouds, as we have done for ZNG 1.

If a Galactic nuclear wind exists and produces significant columns of high ions such as Si IV and C IV (that will be observable with the future Cosmic Origins
Spectrograph, COS), it should be visible along other sight lines in the general direction of ZNG 1. Stellar sight lines in this region of the sky may be useful for placing distance constraints on the gas, while AGNs could be used to probe its structure, including its velocity structure. The QSO SDSS J150556.55+034226.3, observed with STIS, lies within 5° of ZNG 1. This QSO has been observed with a low resolution mode of STIS, but is bright enough for future high-resolution UV spectroscopy.

Finally, we note that these HVCs could be related to HVC complex L given their relative proximity on the sky and velocities (see § 2.3). Since the angular separation is several times the angular extent of the H I component of complex L, this association is, however, by no means firm. Hα emission may be useful in not only studying this connection, but also in tracing feedback flows in the inner Galaxy. Haffner (2005) has mapped intermediate and high negative velocity gas toward complex L (at \( l > 0^\circ \)). He finds pervasive emission in this region at \(-95 \leq v_{\text{LSR}} \leq -50 \ \text{km s}^{-1}\). Hα emission in this range is seen within 2° of ZNG 1 with the WHAM survey, though not in the pointing nearest ZNG 1. Haffner also finds extended Hα emission from ionized gas associated with complex L \((-150 \leq v_{\text{LSR}} \leq -80 \ \text{km s}^{-1})\). Future mapping of this emission and UV absorption with COS of the central region of the Galaxy may reveal a connection between the HVCs studied here and the material associated with complex L. More importantly, such observations bear on the connection of all this matter to feedback-driven flows in the inner Galaxy.
2.9 Summary

We have presented \textit{Far Ultraviolet Spectroscopic Explorer} and Space Telescope Imaging Spectrograph observations of the PAGB star ZNG 1 which resides in the globular cluster Messier 5, using these data to study the high-velocity gas along this sight line. The major results of this work are as follows.

1. We have analyzed the high velocity absorption toward ZNG 1 and find the presence of Si IV, C IV, and O VI along with lower ionization species such as C II, Si II, N II, O I, Al II, Fe II, and Si III. These high and low ions are observed in the same velocity range, although they do not share the same component structure. We have catalogued the column densities and $b$-values using primarily the AOD and component fitting methods.

2. We investigated the possibility that the gas along the ZNG 1 sight line is circumstellar. Limits to the electron density of the gas strongly constrain the path length to be $\gtrsim 0.6$ pc, inconsistent with a circumstellar origin. Furthermore, detailed photoionization calculations also argue against a circumstellar origin based on path length and metal ion ratios.

3. We measured the metallicity of the HVCs to be $[\text{O}/\text{H}] = +0.22 \pm 0.10$ using the O I and H I absorption. This, combined with the well determined distance to the globular cluster M5 where ZNG 1 resides (7.5 kpc), implies that these clouds have a Galactic origin. This is the first evidence that highly-ionized HVCs may be found near the Galactic disk. The ZNG 1 HVCs have the highest metallicity of any known HVCs.

4. We argue that the ZNG 1 HVCs are not associated with Loop I and reside closer to the Galactic center than this structure. We argue that these HVCs
may be associated with a Galactic nuclear wind, or Galactic fountain-like circulation in the inner Galaxy, where the HVCs represent gas falling back to the disk.

5. The exact details of the physical processes responsible for the ionization of these HVCs are yet to be resolved, and it is likely that a complex interplay between several processes is at work. These HVCs are characterized by changing physical conditions, as component 1 (−140 km s\(^{-1}\)) is likely to be significantly affected by photoionization consistent with the small \(b\)-values and the stronger presence of lower ionization species, while component 2 (−110 km s\(^{-1}\)) must be mostly collisionally ionized as required by the strong presence of O \(\text{VI}\) and less lower ionization species. The theoretical models consistent with the data for component 1 are turbulent mixing layers and halo-supernova remnants; the models consistent component 2 are turbulent mixing layers, shock interfaces, and halo-supernova remnants. At least qualitatively, the complex phase structure is consistent with energetic circulation associated with a Galactic wind or outflow.

6. It will be difficult to firmly identify a population of extragalactic highly-ionized HVCs (including intergalactic Local Group gas or material condensed from an extended Galactic Corona) without direct estimates or limits of distance and metallicity, since the kinematics and ionization properties of other highly-ionized HVCs observed toward extragalactic sight lines appear similar to those of the HVCs toward ZNG 1.
3.1 Introduction

The space-based instruments such as the Far Ultraviolet Spectroscopic Explorer (FUSE), and the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (and preceding those, the International Ultraviolet Explorer (IUE)) have been essential to probe the ions that absorb in the ultraviolet region of the spectrum. The ions such as Si IV, C IV, N V, and O VI probe transition-temperature gas at temperatures of a few times $10^4$ to $10^6$ K. At these temperatures these ions cool rapidly – much faster than the electrons are able to recombine with the ions. Gas at these temperatures are byproducts from the energetic processes that create and redistribute metals throughout the Galaxy and govern the evolution of the Milky Way.

In the last decade there have been several surveys important for the understanding of the ionized gas in and around the Milky Way. Zsargó et al. (2003) studied 22 halo stars in order to probe the O VI in the Galactic halo. Savage et al. (2003) studied the FUSE O VI toward 100 extragalactic objects and 2 distant halo stars to understand the distribution and kinematics of O VI in the Galactic halo. Bowen et al. (2008) analyzed the sight lines toward 148 OB stars to study the
distribution of O VI in the Galactic disk and how it extends away from the mid-plane. Savage & Wakker (2009) combined the O VI results of Bowen et al. (2008) with previous studies of Al III, Si IV, and C IV (Savage, Meade, & Sembach 2001) supplemented with new STIS Si IV and C IV measurements culminating in the study of 109 stars and 30 extragalactic objects to probe the extent of H I, Al III, Si IV, C IV, and O VI away from the Galactic midplane and into the Galactic halo.

The above mentioned high-ion surveys, however, were at a resolution such that the fine velocity structure of each absorption profile largely remained hidden. Using the highest resolution grating available, the E140H grating on STIS, we can probe velocity structures with a resolution of 1.5 to 2.7 km s\(^{-1}\) (FWHM). At this resolution, we can deconstruct absorption profiles into their individual absorbing components (i.e., individual clouds) that would appear blended in lower resolution instruments (e.g., HD 116852, Fox et al. 2003; HD 119608, Sembach et al. 1997; HD167756, Savage et al. 1994; HD 177989, Savage et al. 2001; and HD 215733, Fitzpatrick & Spitzer 1997).

The ability to deconstruct absorption profiles into the individual components allows us to analyze two potentially different types of components - broad and narrow. The width of an absorption profile is an indication of the temperature of the absorbing gas. The broad components represent a combination of a hot gas and nonthermal contributions to the profile width. The narrow components are associated with a cooler gas that is either a product of photoionization, or the remains of a once hot gas that has cooled. Since we are able to probe broad and narrow absorption profiles, we are able to analyze components that potentially probe two fundamentally different ionization regimes - photoionization and...
collisional ionization.

The structure of this chapter is as follows: In §3.2 we briefly discuss our selection criteria for the sight lines. We discuss the data and reductions in §3.3 and the analysis of the absorbers in §3.4. We discuss the physical conditions and general statistics of the total integrated, and component-wise absorption in §3.5. We discuss our results in the context of temperature and ionization mechanisms in §3.6. Finally, we provide a brief summary in §3.7.

3.2 Overview of the Sight Lines

The sight lines for this work were chosen based on three criteria; 1) that they were observed with the high-resolution E140H grating of STIS, 2) that the background star was an early-type, O or B Galactic star, and 3) that the wavelength coverage included at least two of the three ions Si IV, C IV, and N V. These ions are tracers of the hot, energetic environments that we want to probe, the radiation from the O and B target stars peak in the far-ultraviolet where the wavelengths of these ions reside, and the high resolution of the E140H observations allows us to deconstruct the fine velocity structure of the absorption profiles. Several of the remaining stars were then rejected because the stellar continua were too difficult to model and the absorption profiles were unclear. The stars that fit the criteria are listed in Table A.1. The stars are ordered by their Galactic longitude and a unique ID number is provided to help the reader to find a particular star in figures and tables. The spectral types and luminosity classes were taken from other work, the references to which are given in Table A.1. The distances were derived via spectroscopic parallax in the same manner as was done in Bowen et al. (2008).
Figure 3.1. An artist’s rendition of the Milky Way based on new Spitzer results showing the locations of the stars in our survey. The numbers correspond to the star IDs in Table A.1 (Illustration credit: R. Hurt (SSC), JPL-Caltech, NASA.)
3.3 Observations and Reductions

The observations for this work were made by STIS on HST, and FUSE. In the following sections we discuss the data reduction and handling procedures for the data sets.

3.3.1 STIS E140H

For this study we chose observations that were made with the E140H high-resolution STIS setup, that employs an echelle grating and a cross disperser to disperse the spectrum. The E140H grating can be used with three apertures; 0.1” × 0.03”, 0.2” × 0.09”, and 0.2” × 0.2”. These three apertures have a resolving power (λ/Δλ) of 200,000, 114,000, and 114,000, respectively. This corresponds to a velocity resolution of 1.5 km s^{-1}, 2.7 km s^{-1}, and 2.7 km s^{-1} (FWHM). The STIS detector pixel size is 0.68 km s^{-1}, 1.32 km s^{-1}, and 1.32 km s^{-1}, respectively. For a description of the design and construction of STIS see Woodgate et al. (1998), and a summary of the STIS on-orbit performance is given by Kimble et al. (1998).

Table A.3 summarizes the STIS data for each star, including the aperture used, and the wavelength coverage. The data were retrieved from the Multi-mission Archive at Space Telescope (MAST) and reduced with the CALSTIS (ver. 2.22) pipeline in order to provide orbital Doppler shift adjustments, detector nonlinearity corrections, dark image subtraction, flat-field division, background subtraction, wavelength zero-point calibration, and to convert the wavelengths into the helio-

1These three apertures each have their own line spread function (LSF), which we adopt from the STIS Instrument Handbook (Kim Quijano et al. 2007).

2We refer to $b$-values often in this study. The resolution in terms of $b$-values is 0.9 km s^{-1} and 1.6 km s^{-1} for the FWHM of 1.5 km s^{-1} and 2.7 km s^{-1}, respectively.
centric reference frame. The individual exposures were weighted by their inverse variance and combined into a single spectrum. We then applied a shift to each star in order to transform the star’s heliocentric reference frame into the local standard of rest (LSR) frame. This assumes a solar motion of +20 km s\(^{-1}\) in the direction \((\alpha, \delta)_{1900} = (18^h, +30^\circ) \approx (56^\circ, +23^\circ)\).

3.3.2 \textit{FUSE}

\textit{FUSE} data exist for 45 of the 50 stars in the sample. The stars for which \textit{FUSE} data does not exist are HD196867 (star ID 2), HD36408B (14), HD40005 (15), HD110434 (39), and HD118246 (44). Table A.4 summarizes the \textit{FUSE} data. The resolution is \(\sim 20 - 25\) km s\(^{-1}\) with a binned output pixel size of 3.74 km s\(^{-1}\). The data were reduced using the \texttt{CalFUSE} (ver. 3.2) pipeline. The \texttt{CalFUSE} processing is described in Dixon et al. (2007), and the spectroscopic capabilities and early on-orbit performance of \textit{FUSE} are described in Moos et al. (2000) and Sahnow et al. (2000), respectively.

Data were obtained from the SiC1, SiC2, LiF1, and LiF2 channels. For each \textit{FUSE} segment, the intermediate data files produced by \texttt{CalFUSE} were shifted to a common wavelength scale and combined into a single file. The detector and scattered-light background were scaled and subtracted by \texttt{CalFUSE}. The absolute zero point of the wavelength scale for the individual absorption lines is uncertain and was determined using the STIS data. The ions Mg \(\text{II} \lambda\lambda 1239, 1240\), Si \(\text{II} \lambda\lambda 1190, 1193, 1260, 1304, 1526\), Fe \(\text{II} \lambda\lambda 1608, 1611\), and Cl \(\text{I} \lambda\lambda 1347, 1379\) were compared with similar ions in \textit{FUSE} to shift the \textit{FUSE} data. Where applicable, the data from the various channels were coadded to obtain the O \(\text{VI}\) profile with the best signal-to-noise (S/N) ratio.
3.4 Measurements of the Interstellar Absorption

We have measured column densities, equivalent widths, $b$-values, and signal-to-noise ratios for the ions C IV, Si IV, N V, and O VI. Where absorption is absent and not contaminated, we provide $3\sigma$ upper limits for the column densities and equivalent widths. We make use of two methods; the apparent optical depth (AOD) method as described by Savage & Sembach (1991), and a component fitting method as described by Fitzpatrick & Spitzer (1997) These methods are discussed in $\S$ 3.4.1 and $\S$ 3.4.2 respectively.

3.4.1 AOD Measurements

We focus our attention on the ions Si IV $\lambda\lambda1393, 1402$, C IV $\lambda\lambda1548, 1550$, N V $\lambda\lambda1238, 1242$ and O VI $\lambda1031$. We cannot use the O VI $\lambda1037$ line because it is always contaminated by C II, C II*, and H$_2$. Figures B.1 through B.38 show the normalized absorption profiles for the primary ions of interest for the Galactic sight lines that show absorption. The sight lines not shown only provide upper limits for the primary high ions available in STIS. We obtained each normalized profile by fitting a Legendre polynomial to the adjacent continuum. In many cases, the continuum was modeled with a low order ($\leq 5$), but on occasion it was necessary to go to higher orders (6 – 9). We were able to model the continua for all but the Si IV $\lambda1393$ lines of HD218915 (ID 7) and HD163758 (ID 50). The continua about these profiles were complicated and were too difficult to adequately fit.

Table A.5 gives the total integrated measurements of the equivalent widths, column densities, $b$-values, and S/N. We measured equivalent widths of interstellar features following Sembach & Savage (1992) including their treatment of the
uncertainties. We assumed statistical uncertainties for the FUSE data were dominated by the effects of fixed pattern noise, while the uncertainties for the STIS data were treated as statistical Poisson uncertainty. In addition, we include an uncertainty in the placement of the continuum added in quadrature to the statistical uncertainty following Sembach & Savage (1992).

We derived the column densities from the apparent optical depth $\tau_a(v)$. The apparent optical depth is an instrumentally-blurred version of the true optical depth of an absorption feature in the absence of saturation. The observed intensity of the line as a function of velocity ($I(v)$) normalized by the estimated continuum intensity ($I_c(v)$) is $I(v)/I_c(v) = e^{-\tau_a(v)}$ and is related to the apparent column density per unit velocity, $N_a(v)$ [atoms cm$^{-2}$ (km s$^{-1}$)$^{-1}$] by

$$N_a(v) = \frac{m_e c \tau_a(v)}{\pi e^2 f \lambda} = 3.768 \times 10^{14} \frac{\tau_a(v)}{f \lambda}, \quad (3.1)$$

where $\lambda$ is the wavelength in Å, and $f$ is the atomic oscillator strength. For lines which showed no significant absorption, we adopt $3\sigma$ upper limits following Wakker et al. (1996). For a more detailed description of this method, we refer the reader to Chapter 2, §2.4.1.

3.4.2 Component Fitting

To separate an absorption profile into individual clouds, we use the method of component fitting which models the absorption profile as individual Maxwellian “clouds” (components). We used a modified version of the software described in Fitzpatrick & Spitzer (1997). The best-fit values describing the gas are determined by comparing the model profiles convolved with an instrumental line-spread function (LSF) with the data. The LSFs are not purely Gaussian, and we adopt the
LSFs from the STIS Instrument Handbook (Kim Quijano et al. 2007). The three parameters \( N_i, b_i, \) and \( v_i \) for each component, \( i \), are input as an initial guesses and subsequently varied to minimize \( \chi^2 \). The fitting process enables us to find the best fit of the component structure using the data from one or more transitions of the same ionic species simultaneously.

Of the 50 sight lines, 38 show enough absorption to do a component fitting analysis on. We applied this component-fitting procedure to the C IV, Si IV, and N V doublets. The column density and \( f \)-values of N V are low compared to Si IV, C IV, and O VI, making the absorption of N V almost always very weak. The N V profile fits were all broad and had fewer detectable components than Si IV and C IV (we did not fit the low resolution O VI). In addition to fitting the profiles, in certain cases we used the code to simultaneously fine-tune the best fit continuum about each line (see Fitzpatrick & Spitzer 1997). In this way, the continuum for each of these special cases was adjusted with a second-order Legendre polynomial correction to the continuum determined from the AOD method.

We fit the Si IV and C IV ions separately, i.e., we did not assume a common component structure for both ions a priori. We started each fit with the smallest number of components that reasonably modeled the profile, and added more components as necessary. In this manner, if the addition of a particular component increased the \( \chi^2 \) goodness of fit parameter, we removed that component. We allowed the software to determine the components freely (i.e., we did not fix any of the input parameters). This procedure was repeated for each profile until the best fit was achieved. In a few cases, (e.g., HD195965, HD93840), more than one component model appeared reasonable. In those cases, we adopted the fit that we believed most accurately described the profile, however, it may be that our
adopted model for those profiles is not unique. Some sight lines that had simple absorption profiles turned out to be difficult to fit (e.g., HD102065, ID 36). In these cases, the profiles looked simple, but there was little in common between the Si IV and C IV profiles. It is not necessary that these two species have similar components, but when they do, it lends confidence to the fits. Furthermore, the component fitting results are highly dependent on continuum placement. We determined the continua in the AOD analysis, using the \( N_a(v) \) profiles as a guide. However, it may be that our adopted continua for the sight lines that were difficult to fit are not unique. Other absorption profiles were easily modeled, and the resulting model uniquely describes the profile. In such cases the column densities, \( b \)-values, velocity centroids, and the associated errors can be considered very reliable. The only other obstacle worth mention is the areas of strong saturation. It is impossible to accurately model these regions because there is no way to determine the correct number of components. The resulting fit usually has one (or very few) component(s) that fit the saturated region, and the column densities and \( b \)-values are unreliable.

The results from component fitting for Si IV and C IV are given in Table A.6 and the component models can be seen in Figures B.1 through B.38. The maximum temperature, \( T_{Max} \), in Table A.6 is determined by assuming only thermal broadening. This gives \( T \lesssim A(60.6)b^2 \) where \( A \) is the atomic weight of the ion, and \( b \), the Doppler parameter in km s\(^{-1}\), is obtained from the fit. The temperatures of the gas are likely to be less than these values due to the contributions to the \( b \)-values from non-thermal motions, and these values should be considered upper limits to the temperature.
3.5 Physical Characteristics

We next consider the physical characteristics implied by our Si IV and C IV (and to a lesser extent, N V and O VI) measurements. We highlight the general statistical properties in §3.5.1 provide the number of components per kpc in the disk and halo (and Carina) in §3.5.2 calculate the midplane densities and consider the vertical distribution away from the Galactic midplane in §§3.5.3 and 3.5.3.1 and discuss ionization, broad and narrow components, and temperatures in §§3.5.4, 3.5.6 and 3.5.5.

3.5.1 General Statistical Properties

In this section, we discuss the general statistical properties of our sight lines. Of the 50 sight lines, we were able to decompose 38 of the sight lines into their individual component structure. From these 38 sight lines, a total of 134 nonsaturated components are found in Si IV, and 139 nonsaturated components in C IV. Figure 3.2 shows the distributions of $b$-values and the logarithmic column densities in C IV and Si IV for the individual components of the sight lines that we were able to fit. Saturated components were excluded from the histograms and statistics. The histograms of $b$-values have a binsize of 1 km s$^{-1}$, and the logarithmic column densities have a binsize of 0.1 dex (cm$^{-2}$). We denote the disk stars in the histogram with blue, halo stars (which we define as stars that are $\geq 500$ pc above the midplane) with red, and the combined disk+halo distribution with black. The vertical dashed lines in the $b$-value histograms denote the boundary between broad and narrow components. We choose a $b$-value of 6.5 km s$^{-1}$ for Si IV and a $b$-value of 10 km s$^{-1}$ for C IV as the division between broad and narrow components. This corresponds to a gas temperature of $7 \times 10^4$
K in the absence of nonthermal broadening, and \(5 \times 10^4\) K if we assume roughly equal thermal and nonthermal contributions to the line width (see §3.5.6). Carina sight lines were excluded from the histograms because the Carina region is a very active star-forming region and skews the statistics that best represent the disk as a whole.

The means (\(\mu\)), standard deviations (\(\sigma\)), and medians (\(\mu_{1/2}\)) are given in Figure 3.2 for each histogram. The logarithmic column density statistics were calculated in logarithmic space. For convenience, these values are reproduced in Table 3.1 (along with the linear column density statistics). The \(b\)-value medians are less than the means, and from Figure 3.2 we see that the histograms of \(b\)-values are right-skewed in all three plotted regimes (disk, halo, and disk+halo). This is characteristic of a log-normal distribution, and is observed for both Si IV and C IV accounting for the rather large standard deviations. The histograms of the logarithmic column densities for both Si IV and C IV, in all three plotted regimes, are also roughly log-normal.
Figure 3.2. Histograms showing the distributions of $b$-values and logarithmic column densities for the individual, nonsaturated components of Si IV (bottom) and C IV (top). Histograms specific to the disk, halo, and disk+halo are denoted by blue, red, and black lines, respectively. The vertical dashed lines denote the boundary between broad and narrow components (6.5 and 10 km s$^{-1}$ for Si IV and C IV, respectively).
TABLE 3.1

INDIVIDUAL NONSATURATED COMPONENT COLUMN
DENSITY AND $B$-VALUE STATISTICS

<table>
<thead>
<tr>
<th></th>
<th>Disk+Halo</th>
<th>Disk</th>
<th>Halo</th>
<th>Carina</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N(\text{Si IV})/10^{12} \rangle$</td>
<td>4.99 ± 5.73</td>
<td>4.01 ± 3.78</td>
<td>6.60 ± 7.76</td>
<td>7.86 ± 8.24</td>
</tr>
<tr>
<td>Median $N(\text{Si IV})/10^{12}$</td>
<td>2.92</td>
<td>2.80</td>
<td>3.58</td>
<td>4.86</td>
</tr>
<tr>
<td>$\langle N(\text{C IV})/10^{13} \rangle$</td>
<td>1.89 ± 2.02</td>
<td>1.78 ± 1.78</td>
<td>2.10 ± 2.43</td>
<td>2.60 ± 2.27</td>
</tr>
<tr>
<td>Median $N(\text{C IV})/10^{13}$</td>
<td>1.11</td>
<td>1.03</td>
<td>1.27</td>
<td>1.59</td>
</tr>
<tr>
<td>$\langle \log[N(\text{Si IV})] \rangle$</td>
<td>12.47 ± 0.47</td>
<td>12.41 ± 0.44</td>
<td>12.56 ± 0.50</td>
<td>12.65 ± 0.51</td>
</tr>
<tr>
<td>Median $\log[N(\text{Si IV})]$</td>
<td>12.47</td>
<td>12.45</td>
<td>12.55</td>
<td>12.67</td>
</tr>
<tr>
<td>$\langle \log[N(\text{C IV})] \rangle$</td>
<td>13.01 ± 0.53</td>
<td>12.99 ± 0.54</td>
<td>13.06 ± 0.52</td>
<td>13.22 ± 0.45</td>
</tr>
<tr>
<td>Median $\log[N(\text{C IV})]$</td>
<td>13.05</td>
<td>13.01</td>
<td>13.10</td>
<td>13.20</td>
</tr>
<tr>
<td>$\langle b(\text{Si IV}) \rangle$</td>
<td>9.66 ± 6.54</td>
<td>9.45 ± 6.93</td>
<td>10.00 ± 5.91</td>
<td>10.11 ± 8.28</td>
</tr>
<tr>
<td>Median $b(\text{Si IV})$</td>
<td>8.50</td>
<td>7.43</td>
<td>8.99</td>
<td>8.09</td>
</tr>
<tr>
<td>$\langle b(\text{C IV}) \rangle$</td>
<td>14.19 ± 10.14</td>
<td>15.14 ± 10.92</td>
<td>12.37 ± 8.31</td>
<td>14.02 ± 10.79</td>
</tr>
<tr>
<td>Disk+Halo</td>
<td>Disk Halo Carina</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median $b$(C IV)</td>
<td>10.75</td>
<td>11.24</td>
<td>9.52</td>
<td></td>
</tr>
<tr>
<td>Carina</td>
<td>7.90</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The units of column density are cm$^{-2}$ and $b$-values are km s$^{-1}$. 
Tables 3.2, 3.3, and 3.4 summarize the \( \text{Si IV} \) and \( \text{C IV} \) column density statistics separated into broad and narrow components for the disk, halo, and Carina regions, respectively. Saturated components were excluded from the calculations. We provide the average linear and logarithmic column densities, the median column density, and the number of components in each sample. Table 3.5 gives the percentage of the number of components that are narrow, and the percentage of the total column density that resides in narrow components. Saturated components were excluded from the calculations. We see that in both cases the narrow components make up a substantial amount of the total number of components and total column density. We note, however, that there is a bias toward detecting narrow components over broad components. We discuss this selection effect in § 3.5.6.

3.5.2 \( \text{Si IV} \) and \( \text{C IV} \) Component Densities

The component density (number of components per kpc) serves as a measure of the number of gaseous interfaces in the ISM. The results of various theoretical models are dependent on the interfaces between gases (e.g., turbulent mixing layers (Slavin et al. 1993), conductive interfaces (Borkowski et al. 1990), shock ionization (Dopita & Sutherland 1996)). Knowledge of the number of interfaces per unit distance can help theorists to refine the models and observers to apply the models properly.

The component densities for the disk, halo, Carina, and all three combined (total) are tabulated in Table 3.6.\(^3\) The values given are the mean and standard deviation. These were calculated by summing the number of broad/narrow components.

\(^3\)Table 3.6 note: Average number of components per kpc. Errors are the standard deviation (1\( \sigma \)). The quantity in parenthesis is the number of components for that sample.
### TABLE 3.2

**COLUMN DENSITY STATISTICS FOR THE BROAD AND NARROW NONSATURATED DISK COMPONENTS**

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle N(\text{Si IV}) \rangle/10^{12} )</td>
<td>3.47 ± 4.03</td>
<td>4.43 ± 3.59</td>
</tr>
<tr>
<td>( \langle \log[N(\text{Si IV})] \rangle )</td>
<td>12.27 ± 0.52</td>
<td>12.52 ± 0.34</td>
</tr>
<tr>
<td>Median</td>
<td>12.17</td>
<td>12.47</td>
</tr>
<tr>
<td># Comps</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>( \langle N(\text{C IV}) \rangle/10^{13} )</td>
<td>1.06 ± 1.35</td>
<td>2.32 ± 1.89</td>
</tr>
<tr>
<td>( \langle \log[N(\text{C IV})] \rangle )</td>
<td>12.69 ± 0.58</td>
<td>13.22 ± 0.37</td>
</tr>
<tr>
<td>Median</td>
<td>12.67</td>
<td>13.30</td>
</tr>
<tr>
<td># Comps</td>
<td>27</td>
<td>36</td>
</tr>
</tbody>
</table>

Note: Column densities are in units cm\(^{-2}\).

Components in each sight line, and dividing the result by the distance to the target star. The average and standard deviation were then calculated from these values. The number in parenthesis is the sample size for that particular quantity. We have included the saturated components in these calculations. Therefore, it is likely that the number of components per kpc could be slightly higher due to there being possibly more components in the saturated regions than we were able to accurately fit.
TABLE 3.3

COLUMN DENSITY STATISTICS FOR THE BROAD AND NARROW NONSATURATED HALO COMPONENTS

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N(\text{Si IV}) \rangle/10^{12}$</td>
<td>$2.02 \pm 1.67$</td>
<td>$8.62 \pm 8.54$</td>
</tr>
<tr>
<td>$\langle \log [N(\text{Si IV})] \rangle$</td>
<td>$12.15 \pm 0.41$</td>
<td>$12.74 \pm 0.43$</td>
</tr>
<tr>
<td>Median</td>
<td>12.26</td>
<td>12.70</td>
</tr>
<tr>
<td># Comps</td>
<td>11</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N(\text{C IV}) \rangle/10^{13}$</td>
<td>$0.97 \pm 0.89$</td>
<td>$3.30 \pm 2.96$</td>
</tr>
<tr>
<td>$\langle \log [N(\text{C IV})] \rangle$</td>
<td>$12.78 \pm 0.47$</td>
<td>$13.35 \pm 0.41$</td>
</tr>
<tr>
<td>Median</td>
<td>12.72</td>
<td>13.44</td>
</tr>
<tr>
<td># Comps</td>
<td>17</td>
<td>16</td>
</tr>
</tbody>
</table>

Note: Column densities are in units cm$^{-2}$.
**TABLE 3.4**

COLUMN DENSITY STATISTICS FOR THE BROAD AND NARROW NONSATURATED CARINA COMPONENTS

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N(\text{Si IV}) \rangle / 10^{12}$</td>
<td>$5.42 \pm 5.28$</td>
<td>$9.74 \pm 9.65$</td>
</tr>
<tr>
<td>$\langle \log[N(\text{Si IV})] \rangle$</td>
<td>$12.51 \pm 0.50$</td>
<td>$12.77 \pm 0.49$</td>
</tr>
<tr>
<td>Median</td>
<td>12.50</td>
<td>12.88</td>
</tr>
<tr>
<td># Comps</td>
<td>17</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N(\text{C IV}) \rangle / 10^{13}$</td>
<td>$2.16 \pm 1.84$</td>
<td>$3.10 \pm 2.63$</td>
</tr>
<tr>
<td>$\langle \log[N(\text{C IV})] \rangle$</td>
<td>$13.15 \pm 0.45$</td>
<td>$13.13 \pm 0.44$</td>
</tr>
<tr>
<td>Median</td>
<td>13.17</td>
<td>13.30</td>
</tr>
<tr>
<td># Comps</td>
<td>23</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: Column densities are in units cm$^{-2}$. 

96
<table>
<thead>
<tr>
<th></th>
<th>Si IV</th>
<th>C IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Disk</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% by Number</td>
<td>44%</td>
<td>43%</td>
</tr>
<tr>
<td>% of $N$</td>
<td>44%</td>
<td>31%</td>
</tr>
<tr>
<td><strong>Halo</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% by Number</td>
<td>31%</td>
<td>52%</td>
</tr>
<tr>
<td>% of $N$</td>
<td>19%</td>
<td>23%</td>
</tr>
<tr>
<td><strong>Carina</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% by Number</td>
<td>44%</td>
<td>53%</td>
</tr>
<tr>
<td>% of $N$</td>
<td>36%</td>
<td>41%</td>
</tr>
</tbody>
</table>
### TABLE 3.6

COMPONENTS/KPC

<table>
<thead>
<tr>
<th></th>
<th>Narrow Si IV</th>
<th>Broad Si IV</th>
<th>Narrow C IV</th>
<th>Broad C IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1.10 ± 1.23(77)</td>
<td>1.12 ± 0.89(89)</td>
<td>1.11 ± 1.04(83)</td>
<td>1.20 ± 1.63(77)</td>
</tr>
<tr>
<td>Disk</td>
<td>1.32 ± 1.50(40)</td>
<td>1.17 ± 1.04(37)</td>
<td>1.25 ± 1.21(38)</td>
<td>1.44 ± 2.04(37)</td>
</tr>
<tr>
<td>Halo</td>
<td>0.58 ± 0.49(15)</td>
<td>0.90 ± 0.74(26)</td>
<td>0.60 ± 0.44(18)</td>
<td>0.73 ± 0.77(19)</td>
</tr>
<tr>
<td>Carina</td>
<td>&gt; 1.12 ± 0.63(22)</td>
<td>&gt; 1.29 ± 0.32(26)</td>
<td>&gt; 1.40 ± 0.84(27)</td>
<td>&gt; 1.04 ± 0.16(21)</td>
</tr>
</tbody>
</table>
3.5.3 Si IV and C IV Midplane Densities

The volume density of a given ion is the number of those particular ions that occupy a unit volume. The average volume density for each sight line is calculated by $\bar{n} = N/d$ (in units cm$^{-3}$), where $N$ is the total integrated column density, and $d$ is the distance to the star. The Milky Way is inhomogeneous, and there is evidence that the gas in the Milky Way is patchy (e.g., see §3.5.3.1), therefore, the gas along each sight line will likely vary around the average in volume density.

Figure 3.3 shows the average volume density for each sight line as a function of Galactic longitude for Si IV (upper panel) and C IV (lower panel). The distances for each sight line are represented by the relative area of the plotted circle (see upper right corner of the plot). The six Carina nebula stars are represented by red and are all located near Galactic longitude $l = 290^\circ$. The halo stars are represented in blue, and the disk stars are represented in black. Upper and lower limits are represented by down and up arrows, respectively. Errors are 1σ.

The Carina sight lines generally show a higher average volume density, otherwise the volume density is fairly uniform as a function of Galactic longitude. This suggests that whatever the processes are that give rise to Si IV and C IV, they are ubiquitous throughout the Galaxy. There is no obvious trend in volume density with the exception of a higher density near Carina longitudes (i.e., near $l = 290^\circ$). Since we probe a variety of physical environments, and since there is no identifiable characteristic volume density associated with any of these environments (other than Carina), the volume density alone cannot be used as a signature of any specific physical environment. The higher volume densities near Carina, however, are likely due to the extremely active star formation in that region. That the sight lines toward this region show a higher volume density than
Figure 3.3. Average volume density ($\bar{n} = N/d$) along the sight lines as a function of Galactic longitude. The relative area of the circle is representative of the star’s distance (see upper right corner). The Carina stars are plotted in red and the halo stars in blue. Upper and lower limits to the density are denoted by down and up arrows, respectively. Errors are $1\sigma$. 
the other sight lines in our sample may imply that the Carina region is the most active region in our survey.

Figure 3.4 shows the total integrated logarithmic column densities plotted against distance. Upper and lower limits are represented by down and up arrows, respectively. Open circles represent disk stars, filled circles represent halo stars, and the circles with a cross represent Carina stars. The dashed curve represents the mean midplane density for each ion. Carina and halo stars were not included in the calculation of the midplane density, and limits were treated as nominal values. The midplane density calculation takes the form \( \langle n_0 \rangle = \langle N/d \rangle \) where \( N(d) \) is the column density (distance) of each sight line. Calculating the midplane density in this manner gives \( n_0(\text{Si IV}) = 3.6 \times 10^{-9} \text{ cm}^{-3} \) with a standard deviation of \( \sigma(\text{Si IV}) = 7.3 \times 10^{-9} \text{ cm}^{-3} \) and a median of \( \mu_{1/2}(\text{Si IV}) = 9.1 \times 10^{-10} \text{ cm}^{-3} \), and \( n_0(\text{C IV}) = 8.0 \times 10^{-9} \text{ cm}^{-3} \), \( \sigma(\text{C IV}) = 9.7 \times 10^{-9} \text{ cm}^{-3} \), \( \mu_{1/2}(\text{C IV}) = 6.0 \times 10^{-9} \text{ cm}^{-3} \). Since our disk stars are within 500 pc from the midplane, a distance much less than the scale heights of 3.2 kpc (Si IV) and 3.6 kpc (C IV) from Savage & Wakker (2009), we expect our estimates of the midplane density for Si IV and C IV to accurately represent the midplane densities.

Other studies have provided midplane densities for the Milky Way in Si IV, C IV, and O VI. Savage & Wakker (2009) find \( n_0(\text{Si IV}) = 2.32 \times 10^{-9} \text{ cm}^{-3} \), \( n_0(\text{C IV}) = 8.02 \times 10^{-9} \text{ cm}^{-3} \), and \( n_0(\text{O VI}) = 1.64 \times 10^{-8} \text{ cm}^{-3} \) (no errors were given). These values were derived from their restricted sample which excluded sight lines through prominent H II regions, sight lines through known supernova remnants, sight lines toward stars with strong X-ray emission, and extragalactic sight lines with \( b > 45^\circ \). The sample sizes for each of these midplane densities is 65, 76, and 85, respectively. Bowen et al. (2008) used \textit{FUSE} to conduct a survey...
of O VI throughout the Milky Way. They find \( n_0(\text{O VI}) = (1.33 \pm 0.15) \times 10^{-8} \) cm\(^{-3}\) for the northern Milky Way, and \( n_0(\text{O VI}) = (1.34 \pm 0.17) \times 10^{-8} \) cm\(^{-3}\) for the southern. The sample sizes for each of these measurements is 220 and 210, respectively. We calculate a midplane density for O VI of \( n_0 \lesssim 3.3 \times 10^{-8} \) cm\(^{-3}\), \( \sigma = 3.9 \times 10^{-8} \) cm\(^{-3}\), \( \mu_{1/2} = 1.8 \times 10^{-8} \) cm\(^{-3}\). The midplane densities of Si IV and C IV from Savage & Wakker and O VI from Bowen et al. are consistent with our results. These midplane densities reveal that, on average, O VI is most abundant, followed by C IV and then Si IV. These results are in descending order with respect to the ionization potentials. This suggests that, on average, the dominant ionization mechanism of the midplane is collisional ionization, since O VI is highly unlikely to be produced by photoionization in the quantities observed. We note, however, that C IV and Si IV are more easily photoionized than O VI, and it may be that in certain regions (e.g., near a hot star or near radiatively cooling hot gas) photoionization is the dominant ionization mechanism for those ions.

We also calculated the mean volume densities separately for the broad and narrow disk components (Table 3.7). For each sight line, we summed the column densities in the narrow components and divided by the distance. This was done for the broad components as well. We did not use the saturated values in the calculations because of the uncertainty in column densities of saturated profiles derived from the component fitting procedure. Otherwise, these values encompass the entire data set for the disk. The distribution of \( n_0 \) is characteristic of a log-normal distribution, and accounts for the large standard deviations. There is likely a bias which tends to underestimate the volume density of the narrow components more so than the broad. This is because the saturated components

\[^{4}\text{Table 3.7 note: Volume densities based on component fits. Saturated components were not included in the calculations. All values are in units (} \times 10^{-9} \text{) cm}^{-3}. The quantity in parenthesis is the number of sight lines.\]
TABLE 3.7

MIDPLANE DENSITY FOR THE BROAD AND NARROW DISK COMPONENTS

<table>
<thead>
<tr>
<th></th>
<th>C IV</th>
<th></th>
<th>Si IV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>⟨n₀⟩</td>
<td>α</td>
<td>n₀₁/₂</td>
<td>⟨n₀⟩</td>
</tr>
<tr>
<td>Broad</td>
<td>7.67</td>
<td>8.08</td>
<td>6.06(22)</td>
<td>1.95</td>
</tr>
<tr>
<td>Narrow</td>
<td>&gt; 2.95</td>
<td>2.51</td>
<td>2.19(13)</td>
<td>&gt; 1.56</td>
</tr>
</tbody>
</table>

that we excluded from our calculations likely contain more narrow components than broad. We did not do similar calculations for the halo and Carina stars. To do meaningful volume density calculations for the halo stars, it is necessary to separate the northern halo stars from the southern ones, as the volume density above the Galactic plane may not be the same as below (such as Bowen et al. 2008 have found in their O VI scale heights). Our sample size for the halo is too small to generate reliable values. Likewise, we did not calculate the volume densities for the Carina region because it is clear that the volume density along the sight line up to the Carina region is much less than what it is in the Carina region. Using the entire pathlength in the calculation would greatly underestimate the volume densities in the Carina region, and overestimate the volume densities in the space up to Carina.

A general trend of increasing column density with distance is seen in Figure 3.4. The Carina sight lines show the highest column density with the exception of HD93843. This likely reflects the active star formation taking place in the Carina.
Figure 3.4. Total integrated logarithmic column densities plotted against distance. Upper and lower limits are represented by down and up arrows, respectively. Open circles denote disk stars, filled circles represent halo stars, and the circles with a cross denote Carina sight lines. Errors are 1σ.
region. There is more dispersion in the values of Si IV than its C IV counterpart in the shorter-distance sight lines. This reflects the fact that Si IV is more easily created than C IV since it has the smaller ionization potential.

The fact that the column densities of Si IV and C IV increase with distance suggests that much of this gas is interstellar and not primarily circumstellar in origin. Furthermore, since the sight lines probe regions of the Galaxy over a broad range of Galactic longitudes (Fig. 3.1), then the mechanisms that give rise to Si IV and C IV are likely found everywhere in the Galaxy.

3.5.3.1 Si IV and C IV Vertical Distribution

The Galactic scale height \((h)\) of a gas is a measure of how the gas extends away from the Galaxy. If we assume a plane-parallel atmosphere for the Milky Way, the scale height is related to the volume density \((n)\), midplane density \((n_0)\), and vertical distance from the midplane \((z)\) via \(n = n_0 \exp [-|z|/h]\). Thus, the scale height is the distance from the midplane where the density of the gas is reduced by a factor of \(e \approx 2.72\). The scale height is a rough estimate depending on whether irregularities in the gas (i.e., the patchyness) is taken into account, and also that the plane-parallel approximation is less valid farther away from the Galactic center and disk.

Figure 3.5 shows the \(\log N \sin |b|\) versus \(\log |z|\) for Si IV (upper panel) and C IV (lower panel). Upper and lower limits are represented by down and up arrows, respectively. Open circles denote disk stars, filled circles represent halo stars, with positive latitude halo stars denoted by the lighter shade of gray and negative latitude halo stars in black. The circles with a cross denote Carina sight lines. Carina sight lines were excluded from the calculations.
Figure 3.5. $\log N \sin |b|$ versus $\log |z|$ for Si IV and C IV. The dashed curves represent a smooth exponential gas stratification away from the Galactic midplane with scale heights of 3.6 kpc for C IV and 3.2 kpc for Si IV as denoted at the far right of the figure. These values of the scale heights were derived from Savage & Wakker (2009). The midplane densities used are those from Figure 3.4. Upper and lower limits are represented by down and up arrows, respectively. Open circles denote disk stars, filled circles represent halo stars with positive latitude halo stars in gray and negative latitude halo stars in black. The circles with a cross denote Carina sight lines.
The dashed curves represent a smooth exponential gas stratification away from the Galactic midplane with the scale heights 3.2 kpc for Si IV and 3.6 kpc for C IV taken from Savage & Wakker (2009). These curves were generated by plotting \( \log n_0 h + \log \left[ 1 - \exp \left( -|z|/h \right) \right] \) versus \( \log |z| \) for the specified scale heights (h). This follows from the relationship of the column density to the volume density. Column density (N) at a height above the midplane of |z| is related to volume density (n) via

\[
N = \int_0^{l_{\text{star}}} n(l) \, dl = \int_0^{z_{\text{star}}} n_0 e^{-|z|/h} \csc |b| \, dz,
\]

where the integration is performed over the path length (l), and b is the Galactic latitude. We used the midplane densities derived from Figure 3.4. We do not have stars distant enough from the midplane to derive the scale heights, however, our results are consistent with the scale heights of Savage & Wakker.

The errors in the measurements are much smaller than the dispersion of the scaled column densities around the dashed lines representing the scale heights. The large dispersion is due to an irregular (patchy) interstellar gas rather than measurement error. There is no obvious trend in the halo stars except that the four positive latitude stars have a larger dispersion than their six negative latitude counterparts. The column density increases with the distance above the midplane as expected.

### 3.5.4 Ionic Column Density Ratios

Theoretical models of the ionization mechanisms that can give rise to Si IV, C IV, and O VI make different predictions for the ratios of these ions. Thus, the ratios of Si IV, C IV, and O VI can be used as a diagnostic of the ionization
mechanism(s) of the ionized gas in the Milky Way. Figure 3.6 shows the total integrated logarithmic column density ratios of C IV compared to O VI and Si IV for our 50 sight lines. The numbers near the data points correspond to the star ID. Limits are denoted by arrows and the filled circles are the halo stars.

The shaded regions represent ranges for theoretical models (TML = turbulent mixing layers (Slavin et al. 1993); RC = radiative cooling (Gnat & Sternberg 2007); SNR = supernova remnants (Slavin & Cox 1992); SI = shock ionization (Dopita & Sutherland 1996); CI = conductive interfaces (Borkowski et al. 1990)). The ratios predicted from the models assume solar relative abundances. Where the models used older estimates of the solar abundance, we have adjusted the results to current solar abundance estimates adopted from Asplund et al. (2005). The adjustments are done following Fox et al. (2004): \[ \log\left[ \frac{N(X)}{N(Y)} \right]_{\text{new}} = \log\left[ \frac{N(X)}{N(Y)} \right]_{\text{old}} + \Delta \log A^\oplus_X - \Delta \log A^\oplus_Y \] where \( \Delta \log A^\oplus_X \equiv \log A^\oplus_X (\text{adopted}) - \log A^\oplus_X (\text{old}) \). It would however, be preferable to recalculate the models with updated atomic parameters and solar abundances.

Stars located in similar regions would be expected to have similar column density ratios. Since the stars are ordered by their Galactic longitude, their IDs can be used as a rough guide as to their general Galactic location. Calculations of the mean of the ratios for the disk stars (lower right of Figure 3.6) give \( \frac{N(\text{C IV})}{N(\text{O VI})} = 0.48 \pm 0.31 \) (std. dev.) and \( \frac{N(\text{C IV})}{N(\text{Si IV})} = 5.68 \pm 5.62 \). Calculations of the mean of the ratios for the halo stars give \( \frac{N(\text{C IV})}{N(\text{O VI})} = 0.75 \pm 0.54 \) (std. dev.) and \( \frac{N(\text{C IV})}{N(\text{Si IV})} = 3.52 \pm 0.99 \). The means are plotted by the dashed lines for the disk, and the dash-dot lines for the halo. Limits were not included in the calculations. Sembach & Savage (1992) find a similar result for the 12 halo stars in their sample \( \frac{N(\text{C IV})}{N(\text{Si IV})} = 3.6 \pm 1.3 \).
is much more dispersion in the C IV to Si IV ratio in the disk stars compared to the halo stars. This is indicative of the disk being a more active region of the Galaxy with a wider range of phenomena, and that the gas is irregularly distributed (patchy) more so toward the disk.

3.5.5 Temperature Constraints

The width of an individual absorption component is determined by thermal and nonthermal (turbulent) contributions. If we have two different ions with significantly different masses, then we have a window into the temperatures and nonthermal contributions of the gas. This assumes that these two ions arise in the same gas and that the thermal and nonthermal motions can be characterized by a Gaussian distribution. The temperature $T$ of a gas for an element of mass $m$ is related to the $b$-value by

$$b^2 = \frac{2kT}{m} + b_{nt}^2 = (0.129)^2 \frac{T}{A} + b_{nt}^2,$$  \hspace{1cm} (3.3)

where $A$ is the atomic weight, $b_{nt}$ is the nonthermal contribution, and $k$ is Boltzmann’s constant. The numerical constant is such that the $b$-value and $b_{nt}$ are in km s$^{-1}$. In order to apply this technique, we identified “matching” components in Si IV and C IV via the criterion that their centroid velocities were reasonably close (consistent within the errors). With $b$-value measurements from the matching components in Si IV and C IV, we can solve a system of equations for the temperature and nonthermal contribution.

The temperature has a linear relationship with the square of the $b$-value. Therefore, curves of constant temperature show up as straight lines when plotting the squared $b$-values. Figure 3.7 shows the squared $b$-values of Si IV versus
Figure 3.6. Logarithmic column density ratios of C IV compared to O VI and Si IV. The shaded regions represent ranges for theoretical models (TML = turbulent mixing layers; RC = radiative cooling; SNR = supernova remnants; SI = shock ionization; CI = conductive interfaces). Limits are denoted by arrows and the filled circles are the halo stars. All values represent the total integrated column density ratios. Open circles denote disk stars filled circles represent halo stars, and the circles with a cross denote Carina sight lines.
C IV for the matching, non-saturated components. The inset figure is the zoomed region in the lower left corner \( (b^2 = [0,100]) \) and corresponds to the narrow components. The solid line represents the line of equivalent \( b \)-values (pure nonthermal motions). The dashed line represents the line of pure thermal broadening. These two lines define the boundary of what is physically possible assuming the Si IV and C IV are mixed together and arise in the same gas phase. Indeed, this is a major advantage of this type of presentation; data points that lie outside the physically possible region are easily identified. These points may be attributed to measurement errors, or it may be that the gas represented by these data points is multiphase, or that the components are in fact not associated with each other but happen to share a similar velocity. We used this criteria to further prune our matching component sample to data points that fall within the physically possible region, or were within \( 2\sigma \) of either boundary. The other lines in Figure 3.7 extending from the lower left toward the upper right are lines of constant temperature with values \( 10^4 \), \( 10^5 \), \( 10^{5.5} \), and \( 10^6 \) K. The tick marks on these lines represent the nonthermal contributions to the \( b \)-value and are given in \( \text{km s}^{-1} \).

An advantage of Figure 3.7 is that combinations of \( T \) and \( b_{nt} \) for each data point can be easily seen. Furthermore, it is easily seen if the breadths of the individual matching components are dominated by thermal or nonthermal broadening. A noteworthy observation from Figure 3.7 is that most of the data points reside in an area that implies cool temperatures around \( 10^4 \) to \( 10^5 \) K with modest nonthermal contributions \( (\lesssim 10 \text{ km s}^{-1}) \). In this regime, the gas may be photoionized, or trace gas that has cooled in a nonequilibrium manner.
Figure 3.7. Squared $b$-values of Si IV vs. C IV for the matching components. Open circles denote disk stars, filled circles represent halo stars, and Carina sight lines are denoted with a cross. The solid line represents the line of equivalent $b$-values. The dashed line represents the line of pure thermal broadening. These two lines define the boundary of physically possible measurements assuming Si IV and C IV are mixed and arise in the same gas phase. The other lines extending toward the upper right are lines of constant temperature. The tick marks on these lines represent the nonthermal contributions to the $b$-value and are in km s$^{-1}$. 

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3.5.6 Broad and Narrow Components

The width of an absorption profile is an indication of the temperature of the gas that is responsible for that profile (§ 3.5.5). A narrow absorption profile is generally an indication of a cooler gas, while a broad absorption profile is generally an indication of a hotter gas with nonthermal contributions to the line width. The hotter the gas, the more violently and frequently the atoms in that gas collide. These collisions can ionize the gas, and at high temperatures this process of collisional ionization can produce C IV and Si IV. The other mechanism for ionizing an atom is for photons with the correct energies to strip the atom of its electrons. Part of the goal of this work is to constrain the relative importance of each of these mechanisms. We chose, as the division between broad and narrow components, a \( b \)-value of 6.5 km s\(^{-1}\) for Si IV, and a value of 10 km s\(^{-1}\) for C IV. These correspond to a temperature of roughly \( 7 \times 10^4 \) K if no nonthermal broadening is present \( (T \approx A(60.6)b^2; A \approx 12 \) for C IV, 28 for Si IV). However, it is almost always the case that nonthermal broadening is present. If we assume that there is roughly an equal contribution from the nonthermal and thermal motions, then the temperature of the gas is closer to \( 5 \times 10^4 \) K. This temperature is near the low end of the transition temperatures between warm and hot gas \( (5 \times 10^4 \) K to \( 10^6 \) K). In this temperature range rapid cooling takes place because of nonequilibrium conditions. Gas at temperatures above \( 10^6 \) K and below \( (0.3 - 3) \times 10^4 \) K cools slowly under equilibrium conditions.

Observations taken with most spectrographs are limited to the study of only broad absorption structures (e.g., \textit{FUSE} has a resolution of \( \sim 20 \) km s\(^{-1}\), \textit{IUE} has a resolution of \( \sim 25 \) km s\(^{-1}\)). The high resolution of the STIS E140H grating (FWHM \( \sim 1.5 \) and 2.7 km s\(^{-1}\)) allows us to probe individual adjacent velo-
ity structures with widths comparable to the resolution of this grating. These structures appear as one blended profile when observed with a lower resolution instrument.

Figure 3.8 shows the logarithmic Si IV and C IV column densities versus their corresponding $b$-values for all of the components (including saturated components and components with no matching partners). The vertical dotted lines mark the division between broad and narrow components. The light gray curve signifies the detection limit and was generated from the optical depth $\tau = 1.497 \times 10^{-15} N f \lambda/b$, where $N$ is the column density in cm$^{-2}$, $f$ is the oscillator strength, $\lambda$ is the wavelength in Å, and $b$ is the $b$-value in km s$^{-1}$. We have taken $\tau = 0.1$ as a lower limit for detection, and we have used the $f \lambda$ of the strong transitions of the C IV and Si IV doublets. Below this curve is the regime we are largely unable to detect components.

Inspection of Figure 3.8 reveals that the dispersion in Si IV and C IV column densities is greater in the region of narrow components. However, we are unable to detect components (if they exist) with large $b$-values and modest column densities such that they fall below the detection limit. Thus, there is clearly a detection bias. Furthermore, the components with the largest column densities ($\log N > 15.0$ cm$^{-2}$) and low $b$-values are saturated where little information is available and are likely invalid. Therefore, it cannot be claimed with certainty that the narrow components inherently have a higher dispersion. However, the greater dispersion in the narrow components, if real, could be indicative of different ionization mechanisms in the narrow components relative to the broad components.

Figure 3.9 shows $\log [N(\text{Si IV})/N(\text{C IV})]$ versus $b$-values for the nonsaturated
Figure 3.8. \( \log N \) vs. \( b \)-values for Si IV vs. C IV. Open circles denote disk stars, filled circles represent halo stars, and Carina sight lines are denoted with a cross. The solid gray curve represents the detection limit. The vertical lines represent the division between narrow and broad \( b \)-values (6.5 km s\(^{-1}\) for Si IV, and 10 km s\(^{-1}\) for C IV). Errors are 1\( \sigma \).
matching components of Si IV and C IV. The vertical lines represent the division between narrow and broad $b$-values. For Si IV, there are 14 narrow and 25 broad nonsaturated matching disk components, 8 narrow and 16 broad nonsaturated matching halo components. For C IV, there are 21 narrow and 18 broad nonsaturated matching disk components, 11 narrow and 13 broad nonsaturated matching halo components. The mean \( \log \left( \frac{N(\text{Si IV})}{N(\text{C IV})} \right) \) for the narrow Si IV disk components is \( \langle \log \left( \frac{N(\text{Si IV})}{N(\text{C IV})} \right) \rangle = -0.57 \pm 0.40 \) (std. dev.) and for the broad disk components is \( -0.49 \pm 0.35 \) (red lines in the figure). For the halo counterparts, the means are \( -0.42 \pm 0.33 \) and \( -0.46 \pm 0.32 \) for the narrow and broad components, respectively (blue lines). The mean \( \log \left( \frac{N(\text{Si IV})}{N(\text{C IV})} \right) \) for the narrow C IV disk components is \( -0.47 \pm 0.47 \) and for the broad disk components is \( -0.52 \pm 0.24 \). For the halo counterparts, the means are \( -0.44 \pm 0.33 \) and \( -0.41 \pm 0.35 \) for the narrow and broad components, respectively. A greater dispersion is seen toward the narrow components compared to the broad components in both Si IV and C IV, however, as can be seen in Figure 3.8, there is a detection bias such that components with larger $b$-values are not as readily detected.

The mean values of \( \log \left( \frac{N(\text{Si IV})}{N(\text{C IV})} \right) \) for the broad and narrow components are comparable for both the disk and halo (the red and blue horizontal lines). The similarity in the means between the broad and narrow components suggests that the \( N(\text{Si IV}) \) to \( N(\text{C IV}) \) ratio alone cannot be used as a diagnostic to differentiate between the two ionization regimes of broad and narrow components.

Figure 3.10 shows \( \log \left( \frac{N(\text{Si IV})}{N(\text{C IV})} \right) \) versus \( N(\text{C IV}) \). The upper panel shows the total integrated values for each sight line and the bottom panel shows the individual component values for the nonsaturated matching components. The red
Figure 3.9. $\log[N(\text{Si IV})/N(\text{C IV})]$ vs. $b$-values for the nonsaturated matching components of Si IV and C IV. Open circles denote disk stars, filled circles represent halo stars, and Carina sight lines are denoted with a cross. The vertical lines represent the division between narrow and broad $b$-values (6.5 km s$^{-1}$ for Si IV, and 10 km s$^{-1}$ for C IV). The red and blue lines represent the mean and dispersion for disk and halo components, respectively. Separate values are given for the narrow and broad components. Errors are 1$\sigma$. 

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lines in the lower panel represent the mean (horizontal) and dispersion (vertical) of log \( \frac{N(\text{Si IV})}{N(\text{C IV})} \) for the disk sample over the column density range covered by the horizontal line. These values (calculated in the log space) are 

\[
-0.44 \pm 0.32 \text{ for } N(\text{C IV}) \leq 0.2 \times 10^{14} \text{ cm}^{-2},
-0.45 \pm 0.39 \text{ between } N(\text{C IV}) = (0.2 \text{ and } 0.5) \times 10^{14} \text{ cm}^{-2}, \text{ and}
-0.97 \pm 0.17 \text{ between } N(\text{C IV}) = (0.5 \text{ and } 1.0) \times 10^{14} \text{ cm}^{-2}
\]
(although we note there are only 3 data points here). The mean ratio does not change appreciably between the first two intervals, and we note that the third interval has too few data points to draw a firm conclusion. The means, medians, and standard deviations appear in the upper right of each panel of Figure 3.10. These values are calculated in log space, and for convenience are reproduced in Table 3.8 (along with the values calculated in linear space and converted to log space). Carina sight lines were not included in any of the calculations.

Savage & Wakker (2009) conducted a survey that included the ions Si IV and C IV toward 109 stars and 30 extragalactic objects. They calculated \( \langle \log \frac{N(\text{Si IV})}{N(\text{C IV})} \rangle \) for their refined sample of Galactic disk stars and extragalactic low halo\(^5\) sight lines for \(|b| < 45^\circ\) and find \( \langle \log \frac{N(\text{Si IV})}{N(\text{C IV})} \rangle = -0.55 \pm 0.21 \text{ and } -0.60 \pm 0.11 \), respectively. Their values are in agreement with ours within the dispersions and given the different instruments used (their data are from \textit{IUE}, \textit{Copernicus}, GHRS, along with \textit{FUSE} and STIS).

For both the total integrated values, and the individual matching nonsaturated component values, there is a higher dispersion (as measured by the standard deviation) in the Si IV to C IV ratio for the disk stars than the halo stars. For the total integrated values, there is a decrease in dispersion of 0.09 dex (for the

\(^5\text{We note that we define “halo” stars in a different manner than Savage & Wakker (2009) do. We define halo stars as } \geq 500 \text{ pc from the midplane, while they define “low” halo sight lines as extragalactic sight lines with Galactic latitudes } |b| < 45^\circ, \text{ and “high” halo sight lines as extragalactic sight lines with } |b| > 45^\circ.\)
Figure 3.10. log\[N(Si IV)/N(C IV)\] vs. \(N(C IV)\). The upper panel is the total integrated values for each sight line and the bottom panel is the individual matching component values. Open circles denote disk stars, filled circles represent halo stars, and Carina sight lines are denoted with a cross. The red lines represent the mean and dispersion of the ratio over the column density range covered by the horizontal line. Errors are 1\(\sigma\).
# Table 3.8

## Total Integrated and Component Column Density Ratio Statistics

<table>
<thead>
<tr>
<th></th>
<th>Disk+Halo</th>
<th>Disk</th>
<th>Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Integrated Values</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\langle \log[N(\text{Si IV})/N(\text{C IV})]\rangle$</td>
<td>$-0.56 \pm 0.21$</td>
<td>$-0.59 \pm 0.24$</td>
<td>$-0.51 \pm 0.15$</td>
</tr>
<tr>
<td>$\log[\langle N(\text{Si IV})/N(\text{C IV})\rangle]$</td>
<td>$-0.51^{+0.18}_{-0.30}$</td>
<td>$-0.53^{+0.20}_{-0.36}$</td>
<td>$-0.48^{+0.14}_{-0.20}$</td>
</tr>
<tr>
<td>Median</td>
<td>$-0.53$</td>
<td>$-0.58$</td>
<td>$-0.52$</td>
</tr>
<tr>
<td><strong>Component Values</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\langle \log[N(\text{Si IV})/N(\text{C IV})]\rangle$</td>
<td>$-0.50 \pm 0.32$</td>
<td>$-0.49 \pm 0.36$</td>
<td>$-0.50 \pm 0.25$</td>
</tr>
<tr>
<td>$\log[\langle N(\text{Si IV})/N(\text{C IV})\rangle]$</td>
<td>$-0.38^{+0.27}_{-0.84}$</td>
<td>$-0.34^{+0.29}_{-1.21}$</td>
<td>$-0.44^{+0.20}_{-0.37}$</td>
</tr>
<tr>
<td>Median</td>
<td>$-0.54$</td>
<td>$-0.54$</td>
<td>$-0.53$</td>
</tr>
</tbody>
</table>
logarithmic average) in going from the disk to the halo, and for the individual nonsaturated component values, there is a decrease of 0.11 dex (for the logarithmic average) in going from the disk to the halo (see Table 3.8). This is comparable to the 0.10 dex difference discovered by Savage & Wakker (2009). This decrease in dispersion in going from the disk to the halo likely reflects the difference in energy input between the two regions. Energy is injected into the disk through supernovae, stellar winds, and from energetic photons from the hot young stars, while the halo is more quiescent.

3.6 Discussion

The uniqueness of this study is the very high resolution of the observations. We are able to resolve each absorption profile into its component structure. In so doing, we are able to partition the components into two general categories; broad and narrow components. We define narrow components as having a $b$-value of $< 6.5 \text{ km s}^{-1}$ in Si IV and $< 10 \text{ km s}^{-1}$ in C IV. These $b$-values correspond to a temperature of $\sim 7 \times 10^4 \text{ K}$ if no nonthermal broadening is present, and $\sim 5 \times 10^4 \text{ K}$ if we assume that there is roughly an equal contribution from the nonthermal and thermal motions (see §3.5.6). The narrow components represent cool gas where we do not expect to find much C IV in collisional ionization equilibrium, and lower resolution studies are not able to do identify these narrow components. But how common are these narrow components?

Of the 50 sight lines, we were able to decompose 38 into their individual component structure (Figures B.1 through B.38). From these 38 sight lines, 54/134 (40%) of the nonsaturated components in Si IV are narrow, and 67/139 (48%) of the nonsaturated components in C IV are narrow (see Tables 3.2, 3.3, and 3.4). For
the disk, we find 26/59 (44%) narrow components in Si IV and 27/63 (43%) narrow components in C IV. The halo narrow component quantities are 11/36 (31%) in Si IV, and 17/33 (52%) in C IV. For the Carina region, the narrow component quantities are 17/39 (44%) in Si IV, and 23/43 (53%) in C IV. Thus, we see that narrow components are ubiquitous throughout the Galaxy and constitute a large portion of the gas we observed.

What mechanisms can give rise to the ionization of the narrow components? We identified components in Si IV that have similar velocity centroids as components in C IV (centroids that are consistent within errors). Figure 3.7 allows us to estimate the temperatures of the matching components by eye. Most of the matching components have a temperature less than $10^5$ K, and many of those have a temperature close to $10^4$ K (the inset plot in Figure 3.7 corresponds to the narrow components). If we assume that Si IV and C IV exist under ionization equilibrium at these temperatures, then photoionization is the most likely source of the ionization. Without an ionizing radiation field there would be little Si IV and C IV at these temperatures under CIE. A source of the photoionizing radiation field could be the radiation from the OB stars, although we show that this applies to very few components. Another possible source of the photoionizing radiation could be X-rays radiated from nearby hot gas. Indeed, Knauth et al. (2003) found that the intermediate velocity cloud (IVC) toward HD 14434 may have been ionized in this manner. However, if the gas is not in equilibrium, then it is possible that this gas was collisionally ionized at very hot temperatures ($\sim 10^6$ K) and has since cooled. Near $10^5$ K, the gas cools rapidly (faster than the recombination rate), “freezing in” the existing Si IV and C IV ions (Kafatos 1973; Shapiro & Moore 1976). Thus, the ionized gas in the narrow components is

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either photoionized, or is the remains of a once hot collisionally ionized gas that has rapidly cooled in a nonequilibrium manner.

To answer the question of whether the gas in the narrow components is photoionized or the remains of a once hot gas that has rapidly cooled, we turn to the ionic ratios. We compare the observed ionic ratios with the predictions from theoretical models. The models for which we have ratios to compare are turbulent mixing layers (TML; Slavin et al. 1993), radiative cooling (RC; Gnat & Sternberg 2007), supernova remnants (SNR; Slavin & Cox 1992), shock ionization (SI; Dopita & Sutherland 1996), and conductive interfaces (CI; Borkowski et al. 1990). Table 3.9 summarizes the ratios predicted from these models. We quote a range of possible values each model can produce, however, this is a crude estimate because, with the exception of the radiative cooling model of Gnat & Sternberg (2007), we cannot reproduce the exact temperature-ratio dependence for the models. It would be a great service to observational astronomy if the theoretical models were updated with the current solar abundances and if the data were made available for observers to incorporate into their figures as Gnat & Sternberg have done.

Figure 3.11 is identical to the bottom panel of Figure 3.9, but also includes the predictions from the theoretical models. We plot the ratio log\[ \frac{N(\text{Si IV})}{N(\text{C IV})} \]

\begin{itemize}
  \item \textbf{Table 3.9 note:} a. The quoted values are from Knauth et al. (2003). The full range of possible ratios for this mechanism is not known.
  \item \textbf{7}The quoted ratios for RC assume gas cooling from $10^6$ K with a cooling flow velocity of 100 km s$^{-1}$ for isobaric and isochoric (and intermediate) conditions. The quoted ratios for CI assume magnetic field orientations in the range $0 - 85^\circ$, and interface ages in the range $10^3 - 10^7$ yrs. These ratios should be considered crude estimates as they were estimated from graphs in Borkowski et al. (1990). The quoted ratios for TML assume gas with entrainment velocities in the range 25 – 100 km s$^{-1}$ and mixing-layer temperatures in the range $1 - 3 \times 10^5$ K. The quoted ratios for SI assume shock velocities in the range 150 – 500 km s$^{-1}$, and magnetic parameters in the range $0 - 4 \mu$G cm$^{-3/2}$. The quoted ratios for SNR are for SNR ages $10^{5.6 - 6.7}$ yr.
\end{itemize}
<table>
<thead>
<tr>
<th>Model</th>
<th>log$[N$(Si IV)/$N$(C IV)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative Cooling (RC)</td>
<td>$-1.51$ to $0.30$</td>
</tr>
<tr>
<td>Conductive Interfaces (CI)</td>
<td>$-1.49$ to $-0.04$</td>
</tr>
<tr>
<td>Turbulent Mixing Layers (TML)</td>
<td>$-1.46$ to $0.05$</td>
</tr>
<tr>
<td>Shock Ionization (SI)</td>
<td>$-1.52$ to $-0.11$</td>
</tr>
<tr>
<td>Supernova Remnant (SNR)</td>
<td>$-1.22$ to $-0.93$</td>
</tr>
<tr>
<td>Photoionization from OB Stars (PI:OB)</td>
<td>$&gt; 0.10$</td>
</tr>
<tr>
<td>Photoionization from X-rays (PI:X-ray)$^a$</td>
<td>$\sim -0.50$ to $\sim -0.60$</td>
</tr>
</tbody>
</table>
against the C IV b-values for the nonsaturated matching components, and we label the maximum possible temperature at the top. Since C IV has a higher ionization potential than Si IV, and we are plotting the matching components between C IV and Si IV, it is not necessary to make a similar plot for the Si IV b-values as it would provide no further information. The possible ratios for the CI, SI, TML, and SNR models are the ratios that lie between the two lines representing the maximum and minimum for each model as labeled. These models apply for high temperatures ($\gtrsim 10^5$ K), and again, we cannot reproduce the accurate temperature dependence of the ratios for these models, so the estimates are crude. When possible, we indicated an approximate temperature range where the models were calculated by the extent of the lines representing the models. While these models do not apply to the low temperature gas of the narrow components, they could be responsible for the ionization if the gas was once hot enough for these models to apply, and has since cooled via radiative cooling. The region of possible ratios for the isobaric and isochoric RC models are to the right of the red and green curves due to possible nonthermal contributions. Photoionization from OB stars tend to produce more of the more easily ionized Si IV than the less easily ionized C IV. Therefore we would expect the ratio of Si IV to C IV to be greater than unity. This region is marked on the plot as PI:OB near the upper left based on calculations in Knauth et al. (2003). The region below and to the left of the RC models we have labeled as PI:X-ray. This represents the photoionization from X-rays emitted from a hot gas as was likely responsible for the ionization of the IVC gas of Knauth et al. (2003).

From Figure 3.11 and Table 3.9 we can see how the data compare to the theoretical models. The temperatures implied by the narrow components are in-
Figure 3.11. Same as the bottom panel of Figure 3.9 but with ionization model predictions. Maximum temperature is labeled at the top. The ionization models are conductive interfaces (CI), shock ionization (SI), turbulent mixing layers (TML), supernova remnants (SNR), radiative cooling (RC), photoionization by OB stars (PI:OB), and photoionization by X-rays radiated from cooling hot gas (PI:X-ray).
consistent with the temperatures needed for the collisional ionization models of turbulent mixing, conductive interfaces, shocks, and supernova remnants. However, it is possible that one or more of these mechanisms was responsible for the ionization of some of the narrow components if the gas of those components was once much hotter and has since cooled. Indeed, about half of the narrow components are consistent with radiative cooling. The average $\log[N(\text{Si} \ IV)/N(\text{C} \ IV)]$ ratio in the narrow components is $\sim -0.5$ with a range of 0.25 to –1.15. There are a few components above 0.1 that are consistent with photoionization from OB stars and are inconsistent with all the other models (except possibly RC) making photoionization from OB stars the likely ionization mechanism for these components. The remaining narrow components that OB photoionization and radiative cooling do not account for may be the result of photoionization from the energetic emission from cooling hot gas.

3.7 Summary

We have presented Space Telescope Imaging Spectrograph and Far Ultraviolet Spectroscopic Explorer observations of 50 early-type (O and B) Milky Way stars. From this sample, 34 reside in the Galactic disk, 10 reside $\geq 500$ pc from the midplane (halo stars), and 6 reside in the Carina nebula. We have analyzed the interstellar Si IV and C IV (and to a lesser extent, N V) at the highest resolution of STIS along these sight lines. We complemented our observations with FUSE O VI where available (45 sight lines). We did a component fitting analysis on 38 of the sight lines, decomposing the absorption profiles into their component structure. We have separated the components into broad and narrow components defined by the temperatures implied by the $b$-values. Narrow components have
b-values ≤ 6.5 km s\(^{-1}\) for Si IV, and ≤ 10 km s\(^{-1}\) for C IV. The major results of this work are as follows.

1. We find that narrow components make up a large part of the component total, both in number, and in terms of the percentage of the total column density along each sight line (Table 3.5). In the disk, we find 44% (Si IV) 43% (C IV) of the total number of components are narrow, and 44% (Si IV) 31% (C IV) of the total column density resides in narrow components. We find similar results in the halo and Carina. Thus, narrow components are ubiquitous throughout the Galaxy.

2. We defined narrow components such that the temperatures of these components fell below \(\sim (5 - 7) \times 10^4\) K depending on the amount of nonthermal contributions. The narrow components represent cool gas where we do not expect to find much C IV in collisional ionization equilibrium, yet we find considerable amounts of C IV at these temperatures.

3. The presence of C IV in the narrow components can be due to photoionization from radiatively cooling hot gas, or the remains of a hot gas that has cooled radiatively. Very few of the narrow components are consistent with photoionization from OB stars.

4. We calculated the mean midplane densities (§ 3.5.3) and find \(n_0(\text{Si IV}) = 3.6 \times 10^{-9} \text{ cm}^{-3}\) and \(n_0(\text{C IV}) = 8.0 \times 10^{-9} \text{ cm}^{-3}\). We also calculated the midplane densities separately for the broad and narrow components (Table 3.7). We find for the broad components \(n_0(\text{C IV}) = 7.7 \times 10^{-9} \text{ cm}^{-3}\) and \(n_0(\text{Si IV}) = 2.0 \times 10^{-9} \text{ cm}^{-3}\). For the narrow components, we find \(n_0(\text{C IV}) = 3.0 \times 10^{-9} \text{ cm}^{-3}\) and \(n_0(\text{Si IV}) = 1.6 \times 10^{-9} \text{ cm}^{-3}\).
5. We tabulated the average number of broad and narrow components per kpc (Table 3.6). In the disk, we find $1.32 \pm 1.50$ (narrow Si IV), $1.17 \pm 1.04$ (broad Si IV), $1.25 \pm 1.21$ (narrow C IV), and $1.44 \pm 2.04$ (broad C IV). We find comparable numbers for the Carina region and the mean halo component density about half that of the disk and Carina.

6. Since we probe a variety of physical environments, and since there is no identifiable characteristic volume density associated with any of these environments, the volume density alone cannot be used as a signature of any specific physical environment. The higher volume densities near Carina, however, are likely due to the active star formation in that region.

7. The mean values of $\log \left[ N(\text{Si IV}) / N(\text{C IV}) \right]$ for the broad components are comparable to the mean values for the narrow components. This suggests that the $N(\text{Si IV})$ to $N(\text{C IV})$ ratio alone cannot be used as a diagnostic to differentiate between the two ionization regimes associated with broad and narrow components.

8. A greater dispersion is seen in the Si IV to C IV ratio in the disk sight lines relative to the halo sight lines. This difference in dispersion is seen in both the total integrated values and the individual matching component values. This decrease in dispersion in going from the disk to the halo likely reflects the difference in energy input between the two regions, with the halo being the more quiescent.
CHAPTER 4

CONCLUDING REMARKS AND FUTURE PROSPECTS

In studying highly-ionized interstellar gas, we have answered two important questions. The first; can highly-ionized HVCs originate from within the Milky Way? We have given strong evidence that at least one has. The highly-ionized HVCs along the sight line toward the globular cluster Messier 5 near the inner Galaxy are located within the Milky Way, and have the highest metallicity of any known HVC. These two properties (distance and metallicity) were instrumental in determining the Galactic origin of these HVCs. These are the first highly-ionized HVCs shown to originate from within our Galaxy.

The second question; how common are the narrow components that represent the cool ISM gas? With the aid of high resolution observations, we have found that almost 50% of the Si IV and C IV absorption in our sight lines, whether disk, halo, or Carina, resides in narrow components. The narrow components are ubiquitous throughout the Galaxy. It is a little surprising to find considerable amounts of C IV in these components whose temperatures are well below what is necessary for collisional ionization. It is pleasantly surprising, however, because it provides motivation to rethink the possible ionization mechanisms that could give rise to this ion in cool gas.

On the topic of ionization mechanisms; a common handicap in both of the studies in this dissertation was the theoretical models that we compared with the
observations. With the exception of radiative cooling by Gnat & Sternberg (2007),
the models are not user friendly in that the data is not readily available in machine
readable language, and they are modeled from outdated solar abundances. We
attempted to rescale the column density ratios to account for the most recent
solar abundances, however, this is only a desperate substitute until the models are
updated. It would also of great value to make the raw theoretical data available
as Gnat & Sternberg have done.

To carry the work in this dissertation further, there are several paths to take.
Several sight lines in the survey show absorption at high velocities. It might be
interesting to separate these and see how they compare to the HVCs in Chapter 2.
It would also be of interest to compare some of the lower ionized species in our
sample to Si IV and C IV, as they are more likely to probe photoionized regions.
Furthermore, in this work we made little use of the N V absorption. The N V
absorption is relatively weak compared to Si IV and C IV, and almost always
shows up in broad components. However, we can compare the column density
ratios of N V (and the lower resolution O VI) to the column densities of Si IV and
C IV as a function of velocity, and in so doing, we may be able to get a better
fix on the ionization mechanisms. Finally, and perhaps most importantly, we
should separate the observations into their various probed structures and search
for trends that could provide signatures of these structures. These signatures
would be useful as diagnostics for other observations where information about the
physical structures are not readily known.
Here we provide the tables referenced in Chapter 3 that are too cumbersome to embed inside the chapter. Table A.1 summarizes the 50 sight lines, giving the star ID, star name, a description of the star, the spectral type/luminosity class, the Galactic coordinates, the spectroscopic parallax distance, and the distance above the midplane. Table A.2 summarizes the physical regions probed by the sight lines. The star ID and name is provided, followed by a brief description of the physical region. Table A.3 summarizes the STIS data. The star ID and name is given in the first and second column, respectively. The remaining columns are the dataset ID, the primary investigator/proposal ID, the exposure time in kiloseconds, wavelength coverage range, and the STIS aperture used in the observations. Table A.4 summarizes the FUSE data. The star ID and name is given in the first two columns, followed by the dataset ID, the primary investigator, the exposure time in kiloseconds, and the aperture. The stars HD196867 (star ID 2), HD36408B (14), HD40005 (15), HD110434 (39), and HD118246 (44) do not appear in this table because FUSE data does not exist for these stars. Table A.5 summarizes the AOD measurements of C IV, N V, Si IV, and O VI for each star. $\lambda$ is the wavelength of the ion, $W_\lambda$ is the equivalent width of the absorption profile, log $N$ is the total integrated column density, $\Delta v$ is the integration range, $\langle v \rangle$ is the average velocity of the absorption, and S/N is the signal to noise ratio. The
dimension of each quantity, where applicable, is given at the top of the table. Errors are 1σ. Limits are 3σ and are denoted with < or > for an upper or lower limit, respectively. Table A.6 summarizes the component fitting results of C IV and Si IV for each star that showed enough absorption to do a component fitting analysis. Information provided is the centroid velocity of the component, the $b$-value, the logarithmic column density, and the maximum temperature derived from the $b$-value. Errors are 1σ. Saturated components are denoted with a (>), and a colon (:). The colon is to emphasize that the numerical values derived from saturated components by the component fitting analysis are very uncertain, as there are likely more than just one component in that region. Table A.7 is identical to Table A.6 except for only the matching components.
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Note: Spectral type, V, and distance taken from Bowen et al. (2007) except where noted.

The properties for the noted stars were obtained in the manner following Bowen et al. (2007).

The absolute magnitudes were taken from Bowen et al. for O3 to B3 stars. The absolute magnitudes for B4 and later stars were taken from Wegner (2006).

If Hipparcos component solutions for multiple star systems exist, we use the brightest of the components for the magnitude in calculating d<sub>sp</sub>. If a star has multiple Sp/L designations, we quote the average of the distances calculated for each Sp/L.

Spectral type/luminosity class references:

(1) Burgh et al. (2007);

(2) Hiltner et al. (1969);
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Note: The resolving powers (λ/Δλ) of the STIS E140H gratings are roughly 200,000, 114,000, and 114,000 for the 0.1" × 0.03", 0.2" × 0.09", and 0.2" × 0.2" apertures, respectively.
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Note: The LWRS and the MDRS apertures are $30'' \times 30''$, and $4'' \times 20''$, respectively.

There is no *FUSE* data for the stars HD196867 [2], HD36408B [14], HD40005 [15], HD110434 [39], and HD118246 [44].
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[1] HD177989

[2] HD196867

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[6] HD209339

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N V 1242.804 < 3 < 12.46 $-28,+22$ $-3$ 19.1 ± 3.4 43
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**TABLE A.5**

*Continued*

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[40] HD116852

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[42] HD122879

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| C IV    | 1550.770   | 66 ± 2      | 13.57 ± 0.01 | -69, +36  | -33             | 21.2 ± 1.7 | 36  |
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[43] HD124314

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[44] HD118246

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Note: No data was available for this quantity. The value quoted is the assumed value when calculating the upper limit. Where no value is listed but an upper limit is given, a $b$-value of 20 km s$^{-1}$ was assumed.
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[10] HD15137

C IV

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Si IV

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C IV

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<td>$4.86 \pm 0.16$</td>
<td>$13.05 \pm 0.02$</td>
<td>$0.17 \pm 0.01$</td>
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</table>

Si IV

<table>
<thead>
<tr>
<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [$10^5$K]</th>
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<tbody>
<tr>
<td>$5.53 \pm 0.03$</td>
<td>$10.05 \pm 0.04$</td>
<td>$13.01 \pm 0.00$</td>
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<tr>
<td>$8.14 \pm 0.05$</td>
<td>$2.88 \pm 0.09$</td>
<td>$12.17 \pm 0.02$</td>
<td>$0.14 \pm 0.01$</td>
</tr>
<tr>
<td></td>
<td>( v , [\text{km} , \text{s}^{-1}] )</td>
<td>( b)-value ( [\text{km} , \text{s}^{-1}] )</td>
<td>( \log N , [\text{cm}^{-2}] )</td>
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<td>( 12.73 \pm 1.44 )</td>
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<td>[18] HD18100</td>
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<td>[19] HD58510</td>
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<tr>
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<td>( 17.47 \pm 0.59 )</td>
<td>( 3.97 \pm 1.09 )</td>
<td>( 12.35 \pm 0.11 )</td>
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<td>( 30.13 \pm 0.45 )</td>
<td>( 5.94 \pm 0.96 )</td>
<td>( 12.67 \pm 0.09 )</td>
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<td>( 25.26 \pm 0.48 )</td>
<td>( 29.89 \pm 0.69 )</td>
<td>( 13.71 \pm 0.02 )</td>
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<tr>
<td></td>
<td>( 83.65 \pm 1.39 )</td>
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200
TABLE A.6

Continued

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<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [$10^5$K]</th>
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<td>16.60 ± 0.28</td>
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<td>39.80 ± 1.00</td>
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<td>3.64 ± 1.30</td>
<td>11.32 ± 0.09</td>
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[20] HD93840

C IV

$-12.38 ± 1.05$ 17.12 ± 1.44 13.54 ± 0.03 2.13 ± 0.36

Si IV

$-13.66 ± 0.14$ 15.42 ± 0.20 13.11 ± 0.01 4.05 ± 0.10

[21] HD90087

C IV

$-13.01 ± 1.08$ 33.15 ± 1.38 13.43 ± 0.02 8.00 ± 0.67

$-3.56 ± 0.59$ 10.26 ± 1.11 12.93 ± 0.07 0.77 ± 0.17

Si IV

$-3.52 ± 0.08$ 9.01 ± 0.11 12.71 ± 0.00 1.38 ± 0.03

[22] HD93205

C IV

$-139.80 ± 2.43$ 30.60 ± 2.83 12.99 ± 0.04 6.81 ± 1.26

$-106.34 ± 0.30$ 12.78 ± 0.57 13.10 ± 0.03 1.19 ± 0.11
\[
\begin{array}{cccc}
\text{\(v\) [km s\(^{-1}\)]} & \text{\(b\)-value [km s\(^{-1}\)]} & \text{log \(N\) [cm\(^{-2}\)]} & \text{\(T_{\text{Max}}\) [10\(^5\)K]} \\
-72.76 \pm 0.08 & 5.83 \pm 0.20 & 13.12 \pm 0.02 & 0.25 \pm 0.02 \\
-46.05 \pm 0.04 & 7.43 \pm 0.09 & (>14.33 : \pm 0.01) & 0.40 \pm 0.01 \\
-23.20 \pm 0.77 & 46.13 \pm 0.87 & 13.96 \pm 0.01 & 15.49 \pm 0.58 \\
-5.52 \pm 0.47 & 9.20 \pm 0.84 & 12.68 \pm 0.05 & 0.62 \pm 0.11 \\
84.13 \pm 0.73 & 37.53 \pm 1.04 & 13.30 \pm 0.01 & 10.25 \pm 0.57 \\
\text{Si IV} & & & \\
-142.23 \pm 1.24 & 9.02 \pm 1.86 & 11.72 \pm 0.07 & 1.38 \pm 0.57 \\
-105.79 \pm 0.23 & 10.57 \pm 0.33 & 12.60 \pm 0.01 & 1.90 \pm 0.12 \\
-73.86 \pm 0.13 & 4.84 \pm 0.22 & 12.50 \pm 0.02 & 0.40 \pm 0.04 \\
-50.13 \pm 0.59 & 3.62 \pm 0.22 & (>16.20 : \pm 0.04) & 0.22 \pm 0.03 \\
-38.13 \pm 0.91 & 6.81 \pm 0.48 & (>13.63 : \pm 0.08) & 0.79 \pm 0.11 \\
-7.89 \pm 0.38 & 17.31 \pm 0.57 & 12.84 \pm 0.02 & 5.10 \pm 0.34 \\
\end{array}
\]

\[23\, \text{CPD592603}\]

\text{C IV} \\
-160.62 \pm 3.40 & 21.76 \pm 3.07 & 13.13 \pm 0.08 & 3.45 \pm 0.97 \\
-135.85 \pm 1.39 & 12.70 \pm 2.49 & 12.97 \pm 0.20 & 1.17 \pm 0.46 \\
-109.03 \pm 0.49 & 4.26 \pm 1.04 & 12.44 \pm 0.12 & 0.13 \pm 0.06 \\
-99.17 \pm 2.33 & 34.61 \pm 3.12 & 13.71 \pm 0.04 & 8.72 \pm 1.57 \\
-55.57 \pm 0.26 & 5.00 \pm 0.20 & (>14.05 : \pm 0.04) & 0.18 \pm 0.01 \\
-42.49 \pm 0.33 & 7.13 \pm 0.29 & (>14.02 : \pm 0.02) & 0.37 \pm 0.03
\]
TABLE A.6

Continued

<table>
<thead>
<tr>
<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [$10^5$K]</th>
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<tr>
<td>$-172.33 \pm 0.40$</td>
<td>6.54 $\pm$ 0.59</td>
<td>12.04 $\pm$ 0.03</td>
<td>0.73 $\pm$ 0.13</td>
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<td>$-140.86 \pm 0.59$</td>
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<td>12.69 $\pm$ 0.02</td>
<td>4.23 $\pm$ 0.49</td>
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<td>$-110.64 \pm 0.78$</td>
<td>2.82 $\pm$ 1.59</td>
<td>11.68 $\pm$ 0.20</td>
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<td>$-102.77 \pm 0.54$</td>
<td>15.35 $\pm$ 0.71</td>
<td>13.01 $\pm$ 0.03</td>
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<tr>
<td>$-59.96 \pm 1.41$</td>
<td>3.05 $\pm$ 0.43</td>
<td>($&gt;$)14.12 : $\pm$0.50</td>
<td>0.16 $\pm$ 0.04</td>
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<td>$-49.53 \pm 2.21$</td>
<td>43.27 $\pm$ 2.45</td>
<td>13.19 $\pm$ 0.03</td>
<td>31.87 $\pm$ 3.61</td>
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<tr>
<td>$-47.38 \pm 1.73$</td>
<td>6.56 $\pm$ 0.45</td>
<td>($&gt;$)14.80 : $\pm$0.31</td>
<td>0.73 $\pm$ 0.10</td>
</tr>
<tr>
<td>$-4.85 \pm 0.49$</td>
<td>12.38 $\pm$ 0.82</td>
<td>12.56 $\pm$ 0.04</td>
<td>2.61 $\pm$ 0.35</td>
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</tbody>
</table>

[24] HDE303308

C IV

| $-104.61 \pm 1.79$ | 16.55 $\pm$ 1.68       | 13.15 $\pm$ 0.06    | 1.99 $\pm$ 0.40      |
| $-86.82 \pm 0.76$  | 7.90 $\pm$ 1.07        | 13.17 $\pm$ 0.09    | 0.45 $\pm$ 0.12      |
| $-74.48 \pm 0.60$  | 6.38 $\pm$ 1.00        | 13.10 $\pm$ 0.12    | 0.30 $\pm$ 0.09      |
| $-49.11 \pm 0.28$  | 14.52 $\pm$ 1.01       | ($>$)14.29 : $\pm$0.02 | 1.53 $\pm$ 0.21      |
| $-46.80 \pm 0.13$  | 4.29 $\pm$ 0.60        | ($>$)16.17 : $\pm$0.66 | 0.13 $\pm$ 0.04      |
| $-18.80 \pm 4.35$  | 26.23 $\pm$ 3.28       | 13.53 $\pm$ 0.08    | 5.01 $\pm$ 1.25      |
| $-4.88 \pm 0.47$   | 4.03 $\pm$ 0.97        | 12.27 $\pm$ 0.12    | 0.12 $\pm$ 0.06      |
| 54.71 $\pm$ 1.20   | 15.89 $\pm$ 1.81       | 12.57 $\pm$ 0.04    | 1.84 $\pm$ 0.42      |
\[ \text{TABLE A.6} \]

Continued

<table>
<thead>
<tr>
<th>( v ) [km s(^{-1})]</th>
<th>( b)-value [km s(^{-1})]</th>
<th>( \log N ) [cm(^{-2})]</th>
<th>( T_{\text{Max}} ) [10(^5)K]</th>
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<td>(19.51 \pm 1.42)</td>
<td>(13.27 \pm 0.09)</td>
<td>(6.48 \pm 0.94)</td>
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<td>(-73.49 \pm 0.43)</td>
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<td>(-10.11 \pm 0.40)</td>
<td>(15.88 \pm 0.56)</td>
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<td>(69.06 \pm 1.07)</td>
<td>(11.92 \pm 1.56)</td>
<td>(11.88 \pm 0.05)</td>
<td>(2.42 \pm 0.63)</td>
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</table>

[25] HD93206

C IV

<p>| (-96.74 \pm 0.34)    | (7.42 \pm 0.46)     | (13.72 \pm 0.05)    | (0.40 \pm 0.05)     |
| (-87.05 \pm 0.40)    | (3.29 \pm 0.60)     | (13.00 \pm 0.10)    | (0.08 \pm 0.03)     |
| (-84.44 \pm 3.84)    | (21.91 \pm 2.98)    | (13.85 \pm 0.04)    | (3.49 \pm 0.95)     |
| (-69.55 \pm 3.36)    | (6.11 \pm 3.34)     | (12.89 \pm 0.38)    | (0.27 \pm 0.30)     |
| (-61.46 \pm 1.48)    | (4.33 \pm 1.58)     | (12.86 \pm 0.34)    | (0.14 \pm 0.10)     |
| (-47.04 \pm 0.50)    | (10.90 \pm 1.15)    | (13.72 \pm 0.06)    | (0.86 \pm 0.18)     |
| (-31.65 \pm 0.24)    | (5.22 \pm 0.44)     | (13.47 \pm 0.06)    | (0.20 \pm 0.03)     |
| (-19.17 \pm 0.28)    | (6.58 \pm 0.74)     | (13.69 \pm 0.12)    | (0.32 \pm 0.07)     |
| (-4.17 \pm 0.18)     | (5.18 \pm 0.49)     | (13.54 \pm 0.11)    | (0.20 \pm 0.04)     |
| (4.19 \pm 10.07)     | (24.08 \pm 5.01)    | (13.69 \pm 0.26)    | (4.22 \pm 1.76)     |
| (8.20 \pm 0.34)      | (5.55 \pm 0.52)     | (13.28 \pm 0.09)    | (0.22 \pm 0.04)     |</p>
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<th>$T_{Max}$ [$10^5$K]</th>
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<td>$12.43 \pm 0.07$</td>
<td>$2.24 \pm 0.72$</td>
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TABLE A.6

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<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [10$^5$K]</th>
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<td>$4.47 \pm 0.77$</td>
<td>$12.51 \pm 0.13$</td>
<td>$0.34 \pm 0.12$</td>
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<td>$-77.62 \pm 0.21$</td>
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<td>$1.40 \pm 0.56$</td>
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[27] HD93843

C IV

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<th>$T_{Max}$ [10$^5$K]</th>
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<td>$13.20 \pm 0.13$</td>
<td>$0.75 \pm 0.17$</td>
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<td>$6.74 \pm 0.58$</td>
<td>$13.41 \pm 0.06$</td>
<td>$0.33 \pm 0.06$</td>
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<td>$12.60 \pm 0.28$</td>
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<td>$12.92 \pm 0.34$</td>
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206
\textbf{TABLE A.6}

\textit{Continued}

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$v$ [km s\textsuperscript{-1}] & $b$-value [km s\textsuperscript{-1}] & log $N$ [cm\textsuperscript{-2}] & $T_{Max}$ [10\textsuperscript{5}K] \\
\hline
$-13.67 \pm 6.28$ & $22.79 \pm 3.65$ & $13.50 \pm 0.16$ & $3.78 \pm 1.21$ \\
Si IV & & & \\
$-68.18 \pm 0.52$ & $6.78 \pm 0.55$ & $12.50 \pm 0.04$ & $0.78 \pm 0.13$ \\
$-59.30 \pm 0.37$ & $3.38 \pm 0.61$ & $12.29 \pm 0.11$ & $0.19 \pm 0.07$ \\
$-50.45 \pm 0.30$ & $4.62 \pm 0.49$ & $12.97 \pm 0.05$ & $0.36 \pm 0.08$ \\
$-41.63 \pm 0.69$ & $5.24 \pm 1.36$ & $12.67 \pm 0.18$ & $0.47 \pm 0.24$ \\
$-29.76 \pm 0.10$ & $2.66 \pm 0.25$ & $12.59 \pm 0.06$ & $0.12 \pm 0.02$ \\
$-23.04 \pm 2.17$ & $13.88 \pm 5.17$ & $12.89 \pm 0.18$ & $3.28 \pm 2.44$ \\
$-12.33 \pm 0.89$ & $3.14 \pm 2.78$ & $11.50 \pm 0.42$ & $0.17 \pm 0.30$ \\
$-0.63 \pm 3.38$ & $12.25 \pm 2.25$ & $12.49 \pm 0.20$ & $2.55 \pm 0.94$ \\
\hline
[28] HD99857 & & & \\
C IV & & & \\
$-30.34 \pm 0.75$ & $8.88 \pm 1.47$ & $12.76 \pm 0.11$ & $0.57 \pm 0.19$ \\
$-22.84 \pm 0.57$ & $26.28 \pm 0.72$ & $13.59 \pm 0.02$ & $5.03 \pm 0.28$ \\
Si IV & & & \\
$-43.16 \pm 0.31$ & $1.47 \pm 0.89$ & $11.45 \pm 0.14$ & $0.04 \pm 0.04$ \\
$-30.38 \pm 0.46$ & $10.82 \pm 0.89$ & $12.64 \pm 0.03$ & $1.99 \pm 0.33$ \\
$-19.22 \pm 0.32$ & $2.52 \pm 0.70$ & $11.74 \pm 0.12$ & $0.11 \pm 0.06$ \\
$-6.08 \pm 0.85$ & $11.59 \pm 1.08$ & $12.33 \pm 0.04$ & $2.29 \pm 0.43$ \\
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<th>$T_{Max}$ [$10^5$K]</th>
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</table>

[29] HD101131

C IV

- $-60.94 \pm 7.98$ $13.97 \pm 4.68$ $13.13 \pm 0.31$ $1.42 \pm 0.95$
- $-54.72 \pm 0.96$ $6.63 \pm 1.42$ $12.97 \pm 0.33$ $0.32 \pm 0.14$
- $-36.99 \pm 0.86$ $6.86 \pm 1.52$ $13.07 \pm 0.16$ $0.34 \pm 0.15$
- $-23.79 \pm 0.62$ $7.94 \pm 0.75$ $13.36 \pm 0.07$ $0.46 \pm 0.09$
- $-6.25 \pm 2.99$ $26.45 \pm 2.55$ $13.38 \pm 0.06$ $5.09 \pm 0.98$

Si IV

- $-57.77 \pm 0.50$ $6.84 \pm 0.40$ $12.73 \pm 0.04$ $0.80 \pm 0.09$
- $-52.58 \pm 0.24$ $1.93 \pm 0.71$ $12.03 \pm 0.15$ $0.06 \pm 0.05$
- $-37.90 \pm 0.34$ $5.22 \pm 0.40$ $12.77 \pm 0.04$ $0.46 \pm 0.07$
- $-23.89 \pm 0.13$ $6.97 \pm 0.21$ $(>) 13.62 : \pm 0.01$ $0.83 \pm 0.05$
- $-5.41 \pm 3.57$ $16.60 \pm 3.57$ $12.43 \pm 0.11$ $4.69 \pm 2.02$

[30] HD101190

C IV

- $-36.64 \pm 0.08$ $8.43 \pm 0.09$ $13.44 \pm 0.01$ $0.52 \pm 0.01$
- $-16.45 \pm 0.93$ $14.75 \pm 0.97$ $12.77 \pm 0.03$ $1.58 \pm 0.21$

Si IV

- $-35.55 \pm 0.04$ $6.63 \pm 0.06$ $(>) 13.62 : \pm 0.01$ $0.75 \pm 0.01$
- $-25.01 \pm 0.57$ $21.86 \pm 0.48$ $12.77 \pm 0.02$ $8.13 \pm 0.36$
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[31] HD101436

C IV

$-35.86 \pm 8.20$  $19.53 \pm 3.99$  $13.52 \pm 0.26$  $2.78 \pm 1.13$

$-28.07 \pm 0.37$  $10.16 \pm 0.76$  $13.49 \pm 0.13$  $0.75 \pm 0.11$

$-7.73 \pm 10.45$  $17.60 \pm 5.24$  $13.09 \pm 0.40$  $2.25 \pm 1.34$

Si IV

$-35.74 \pm 3.81$  $14.15 \pm 1.70$  $13.12 \pm 0.17$  $3.41 \pm 0.82$

$-29.59 \pm 0.07$  $5.48 \pm 0.31$  $(>)$  $14.36 : \pm 0.10$  $0.51 \pm 0.06$

$-10.13 \pm 7.73$  $14.43 \pm 4.66$  $12.47 \pm 0.30$  $3.54 \pm 2.29$

[34] HD103779

C IV

$-15.25 \pm 0.23$  $19.70 \pm 0.23$  $13.66 \pm 0.01$  $2.82 \pm 0.07$

$-6.46 \pm 0.07$  $5.15 \pm 0.12$  $13.46 \pm 0.01$  $0.19 \pm 0.01$

Si IV

$-35.89 \pm 0.70$  $6.92 \pm 1.01$  $11.94 \pm 0.09$  $0.82 \pm 0.24$

$-13.25 \pm 0.62$  $15.60 \pm 0.70$  $12.85 \pm 0.01$  $4.14 \pm 0.37$

$-6.98 \pm 0.06$  $4.43 \pm 0.14$  $12.74 \pm 0.02$  $0.33 \pm 0.02$

[35] HD104705

C IV

$-78.62 \pm 0.04$  $7.29 \pm 0.10$  $13.73 \pm 0.01$  $0.39 \pm 0.01$
TABLE A.6

Continued

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<th>$v$ [km s$^{-1}$]</th>
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<td>$-2.25 \pm 0.27$</td>
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<td>$0.16 \pm 0.01$</td>
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Si IV

| $-81.36 \pm 0.20$ | $4.67 \pm 0.18$        | $12.58 \pm 0.02$    | $0.37 \pm 0.03$     |
| $-74.89 \pm 0.28$ | $3.18 \pm 0.26$        | $12.06 \pm 0.07$    | $0.17 \pm 0.03$     |
| $-26.19 \pm 0.06$ | $4.16 \pm 0.12$        | $12.82 \pm 0.02$    | $0.29 \pm 0.02$     |
| $-17.93 \pm 0.19$ | $17.91 \pm 0.33$       | $13.18 \pm 0.02$    | $5.46 \pm 0.20$     |
| $-13.18 \pm 0.18$ | $4.63 \pm 0.21$        | $12.93 \pm 0.03$    | $0.36 \pm 0.03$     |
| $-4.19 \pm 0.14$  | $4.65 \pm 0.12$        | $13.06 \pm 0.02$    | $0.37 \pm 0.02$     |

[36] HD102065

C IV

| $-18.64 \pm 1.35$ | $44.82 \pm 1.68$        | $13.32 \pm 0.02$    | $14.62 \pm 1.10$    |
| $-5.35 \pm 1.28$  | $13.58 \pm 2.43$        | $12.50 \pm 0.11$    | $1.34 \pm 0.48$     |

Si IV

| $-16.82 \pm 0.48$ | $28.55 \pm 0.92$        | $12.96 \pm 0.02$    | $13.88 \pm 0.89$    |

[37] HD108002

C IV

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### TABLE A.6

*Continued*

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<td>$T_{\text{Max}}$ [10(^5)K]</td>
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[44] HD118246

C IV

| $-31.15 \pm 1.98$   | $26.88 \pm 1.31$    | $13.49 \pm 0.05$     | $5.26 \pm 0.51$      |
| $-27.78 \pm 0.93$   | $7.41 \pm 1.50$     | $12.69 \pm 0.13$     | $0.40 \pm 0.16$      |
| $-9.41 \pm 1.53$    | $10.92 \pm 2.93$    | $12.73 \pm 0.20$     | $0.87 \pm 0.47$      |

Si IV

| $-35.98 \pm 0.61$   | $29.10 \pm 0.53$    | $13.08 \pm 0.01$     | $14.41 \pm 0.53$     |
| $-25.62 \pm 0.37$   | $10.71 \pm 0.68$    | $12.70 \pm 0.03$     | $1.95 \pm 0.25$      |
| $-9.34 \pm 0.24$    | $5.62 \pm 0.33$     | $12.43 \pm 0.03$     | $0.54 \pm 0.06$      |

[45] HD121968

C IV

| $-69.61 \pm 1.00$   | $4.09 \pm 1.03$     | $12.35 \pm 0.25$     | $0.12 \pm 0.06$      |
| $-61.28 \pm 0.96$   | $6.91 \pm 1.08$     | $12.93 \pm 0.09$     | $0.35 \pm 0.11$      |
| $-45.56 \pm 0.39$   | $2.45 \pm 0.73$     | $12.11 \pm 0.11$     | $0.04 \pm 0.03$      |
| $-26.73 \pm 0.66$   | $29.70 \pm 0.46$    | $13.95 \pm 0.01$     | $6.42 \pm 0.20$      |
| $-20.43 \pm 0.87$   | $3.47 \pm 1.09$     | $12.54 \pm 0.25$     | $0.09 \pm 0.06$      |
| $-12.14 \pm 0.49$   | $6.67 \pm 0.52$     | $13.40 \pm 0.04$     | $0.32 \pm 0.05$      |
TABLE A.6

Continued

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<tr>
<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
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<th>$T_{Max}$ [10$^5$K]</th>
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<td>5.49 ± 1.22</td>
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<td>12.26 ± 0.07</td>
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<td>4.36 ± 2.95</td>
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<td>11.41 ± 1.94</td>
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</table>

[46] HD148937

C IV

$-160.90 ± 0.76$ | $7.10 ± 1.33$ | $12.28 ± 0.08$ | $0.37 ± 0.14$ |
$-137.33 ± 2.44$ | $40.38 ± 2.16$ | $13.12 ± 0.03$ | $11.87 ± 1.27$ |
$-121.51 ± 0.46$ | $5.34 ± 0.79$ | $12.36 ± 0.06$ | $0.21 ± 0.06$ |
$-105.34 ± 0.15$ | $5.61 ± 0.25$ | $12.91 ± 0.02$ | $0.23 ± 0.02$ |
$-32.76 ± 2.31$  | $11.96 ± 3.18$ | $12.67 ± 0.38$ | $1.04 ± 0.55$ |
$-14.28 ± 7.11$  | $19.52 ± 5.13$ | $13.00 ± 0.20$ | $2.77 ± 1.46$ |

Si IV

$-163.87 ± 0.10$ | $5.00 ± 0.17$ | $12.45 ± 0.02$ | $0.43 ± 0.03$ |
$-154.11 ± 0.21$ | $16.68 ± 0.19$ | $12.97 ± 0.01$ | $4.74 ± 0.11$ |
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<tr>
<th>$v$ [km s$^{-1}$]</th>
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[47] HD137595

C IV

| | |
|-----------------|-----------------|-----------------|-----------------|
| $-0.78 \pm 0.27$ | $6.53 \pm 0.40$ | $12.61 \pm 0.02$ | $0.31 \pm 0.04$ |

Si IV

| | |
|-----------------|-----------------|-----------------|-----------------|
| $-5.67 \pm 0.24$ | $6.27 \pm 0.39$ | $12.26 \pm 0.02$ | $0.67 \pm 0.08$ |
| $7.44 \pm 0.31$ | $3.52 \pm 0.48$ | $11.83 \pm 0.04$ | $0.21 \pm 0.06$ |

[48] HD152723

C IV

| | |
|-----------------|-----------------|-----------------|-----------------|
| $-25.47 \pm 0.52$ | $10.53 \pm 0.58$ | $13.37 \pm 0.04$ | $0.81 \pm 0.09$ |
| $-20.43 \pm 0.44$ | $24.56 \pm 0.69$ | $13.30 \pm 0.03$ | $4.39 \pm 0.25$ |
| $-15.68 \pm 0.08$ | $3.96 \pm 0.17$ | $13.26 \pm 0.03$ | $0.11 \pm 0.01$ |

Si IV

<p>| | |
| | |
|-----------------|-----------------|-----------------|-----------------|
| $-28.20 \pm 0.14$ | $5.48 \pm 0.10$ | ($&gt;$)13.56 : ±0.01 | $0.51 \pm 0.02$ |
| $-17.15 \pm 0.10$ | $2.21 \pm 0.04$ | ($&gt;$)15.63 : ±0.01 | $0.08 \pm 0.00$ |</p>
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### TABLE A.7

MATCHING COMPONENTS

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<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
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217
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<th>log (N) [cm(^{-2})]</th>
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<td>16.96 ± 0.93</td>
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<td>12.68 ± 0.11</td>
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218
TABLE A.7

Continued

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[8] HD224151

C IV

$-42.96 \pm 0.71$ | 7.43 ± 1.12 | 12.62 ± 0.05 | 0.40 ± 0.12 |
$-22.12 \pm 0.34$ | 7.54 ± 0.53 | 12.98 ± 0.02 | 0.41 ± 0.06 |
$8.15 \pm 1.69$ | 7.31 ± 2.64 | 12.18 ± 0.11 | 0.39 ± 0.28 |

Si IV

$-44.77 \pm 0.64$ | 8.04 ± 0.99 | 12.00 ± 0.04 | 1.10 ± 0.27 |
$-20.79 \pm 0.34$ | 8.59 ± 0.53 | 12.32 ± 0.02 | 1.26 ± 0.15 |
$6.64 \pm 0.88$ | 5.15 ± 1.40 | 11.58 ± 0.08 | 0.45 ± 0.25 |

[9] HD3827

C IV

$-11.33 \pm 0.04$ | 7.67 ± 0.06 | 13.34 ± 0.00 | 0.43 ± 0.01 |

Si IV

$-11.27 \pm 0.10$ | 8.50 ± 0.13 | 12.60 ± 0.01 | 1.23 ± 0.04 |

[10] HD15137

C IV

$-77.34 \pm 0.34$ | 4.71 ± 0.67 | 12.55 ± 0.06 | 0.16 ± 0.05 |
$-52.48 \pm 1.30$ | 24.80 ± 2.03 | 13.13 ± 0.03 | 4.48 ± 0.73 |

Si IV
<table>
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<tr>
<th>$v$ [km s(^{-1})]</th>
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<th>log $N$ [cm(^{-2})]</th>
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[13] HD24534

C IV

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Si IV

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[15] HD40005

C IV

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Si IV

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<th>2.76 ± 0.62</th>
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[18] HD18100

C IV

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Si IV

<p>| $-27.10 \pm 0.91$ | 9.56 ± 1.14 | 12.45 ± 0.05 | 1.56 ± 0.37 |</p>
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TABLE A.7

*Continued*

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<tr>
<th>(v) [km s(^{-1})]</th>
<th>(b)-value [km s(^{-1})]</th>
<th>(\log N) [cm(^{-2})]</th>
<th>(T_{\text{Max}}) [10(^5)K]</th>
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TABLE A.7

Continued

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<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T$ Max [10$^5$K]</th>
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<tbody>
<tr>
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<td>2.82 ± 1.59</td>
<td>11.68 ± 0.20</td>
<td>0.14 ± 0.15</td>
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<tr>
<td>−102.77 ± 0.54</td>
<td>15.35 ± 0.71</td>
<td>13.01 ± 0.03</td>
<td>4.01 ± 0.37</td>
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<tr>
<td>−59.96 ± 1.41</td>
<td>3.05 ± 0.43</td>
<td>(&gt;14.12 : ±0.50)</td>
<td>0.16 ± 0.04</td>
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<tr>
<td>−47.38 ± 1.73</td>
<td>6.56 ± 0.45</td>
<td>(&gt;14.80 : ±0.31)</td>
<td>0.73 ± 0.10</td>
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</table>

[24] HDE303308

C IV

| −86.82 ± 0.76    | 7.90 ± 1.07            | 13.17 ± 0.09        | 0.45 ± 0.12      |
| −74.48 ± 0.60    | 6.38 ± 1.00            | 13.10 ± 0.12        | 0.30 ± 0.09      |
| −49.11 ± 0.28    | 14.52 ± 1.01           | (>14.29 : ±0.02)    | 1.53 ± 0.21      |
| −46.80 ± 0.13    | 4.29 ± 0.60            | (>16.17 : ±0.66)    | 0.13 ± 0.04      |
| 54.71 ± 1.20     | 15.89 ± 1.81           | 12.57 ± 0.04        | 1.84 ± 0.42      |

Si IV

| −89.99 ± 0.18    | 4.61 ± 0.29            | 13.07 ± 0.04        | 0.36 ± 0.05      |
| −73.49 ± 0.43    | 5.46 ± 0.76            | 13.13 ± 0.10        | 0.51 ± 0.14      |
| −50.64 ± 0.28    | 12.36 ± 0.25           | (>14.33 : ±0.03)    | 2.60 ± 0.11      |
| 69.06 ± 1.07     | 11.92 ± 1.56           | 11.88 ± 0.05        | 2.42 ± 0.63      |

[25] HD93206

C IV

<p>| −96.74 ± 0.34    | 7.42 ± 0.46            | 13.72 ± 0.05        | 0.40 ± 0.05      |
| −87.05 ± 0.40    | 3.29 ± 0.60            | 13.00 ± 0.10        | 0.08 ± 0.03      |</p>
<table>
<thead>
<tr>
<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [10$^5$K]</th>
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<td>$12.89 \pm 0.38$</td>
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<td>$4.33 \pm 1.58$</td>
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<td>$0.86 \pm 0.18$</td>
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<td>$6.58 \pm 0.74$</td>
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<td>$0.32 \pm 0.07$</td>
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Si IV

<table>
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<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
<th>log $N$ [cm$^{-2}$]</th>
<th>$T_{Max}$ [10$^5$K]</th>
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<td>$0.07 \pm 0.01$</td>
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[26] HD93222

C IV

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<td>$13.58 \pm 0.02$</td>
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\textit{v} [km s\(^{-1}\)] & \textit{b}-value [km s\(^{-1}\)] & \textit{log} \textit{N} [cm\(^{-2}\)] & \textit{T}_{\text{Max}} [10^5K] \\
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46.65 ± 2.12 & 17.55 ± 2.82 & 12.43 ± 0.07 & 2.24 ± 0.72 \\
Si IV \\
–97.37 ± 0.16 & 3.97 ± 0.28 & 12.50 ± 0.05 & 0.27 ± 0.04 \\
–77.62 ± 0.21 & 4.80 ± 0.34 & 13.17 ± 0.05 & 0.39 ± 0.06 \\
–56.45 ± 1.08 & 9.06 ± 1.80 & 13.21 ± 0.20 & 1.40 ± 0.56 \\
–46.24 ± 0.36 & 4.56 ± 0.52 & 13.19 ± 0.09 & 0.35 ± 0.08 \\
–31.42 ± 0.14 & 4.25 ± 0.52 & (>)14.47 ± ±0.273 & 0.31 ± 0.08 \\
43.20 ± 0.71 & 13.15 ± 1.02 & 12.23 ± 0.03 & 2.94 ± 0.46 \\
[27] HD93843 \\
C IV \\
–50.05 ± 0.28 & 6.74 ± 0.58 & 13.41 ± 0.06 & 0.33 ± 0.06 \\
–38.82 ± 1.11 & 4.61 ± 1.68 & 12.60 ± 0.28 & 0.15 ± 0.11 \\
–28.77 ± 1.20 & 7.25 ± 2.23 & 12.92 ± 0.34 & 0.38 ± 0.24 \\
–14.11 ± 0.77 & 4.68 ± 1.83 & 12.41 ± 0.31 & 0.16 ± 0.12 \\
Si IV \\
–50.45 ± 0.30 & 4.62 ± 0.49 & 12.97 ± 0.05 & 0.36 ± 0.08 \\
–41.63 ± 0.69 & 5.24 ± 1.36 & 12.67 ± 0.18 & 0.47 ± 0.24 \\
–29.76 ± 0.10 & 2.66 ± 0.25 & 12.59 ± 0.06 & 0.12 ± 0.02 \\
–12.33 ± 0.89 & 3.14 ± 2.78 & 11.50 ± 0.42 & 0.17 ± 0.30 \\
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\end{tabular}
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TABLE A.7

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<th>$v$ [km s$^{-1}$]</th>
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TABLE A.7

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<tr>
<td>(v) [km s(^{-1})]</td>
<td>(b)-value [km s(^{-1})]</td>
<td>(\log N) [cm(^{-2})]</td>
<td>(T_{\text{Max}}) [10(^5)K]</td>
</tr>
<tr>
<td>−36.64 ± 0.08</td>
<td>8.43 ± 0.09</td>
<td>13.44 ± 0.01</td>
<td>0.52 ± 0.01</td>
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<td>−16.45 ± 0.93</td>
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<td>12.77 ± 0.03</td>
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<tr>
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<td>6.63 ± 0.06</td>
<td>(&gt; 13.62) ± 0.01</td>
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[31] HD101436

C IV

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[34] HD103779

C IV

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<tr>
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TABLE A.7

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<th>b-value [km s(^{-1})]</th>
<th>log (N) [cm(^{-2})]</th>
<th>(T_{\text{Max}}) [10(^5)K]</th>
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[37] HD108002

C IV

−83.31 ± 2.18  39.49 ± 2.91  13.90 ± 0.03  11.35 ± 1.67
−3.67 ± 2.73  37.92 ± 3.42  13.77 ± 0.04  10.47 ± 1.89

Si IV

−89.66 ± 0.60  14.28 ± 0.84  12.36 ± 0.02  3.47 ± 0.41
3.07 ± 0.90  32.29 ± 1.25  12.71 ± 0.02  17.75 ± 1.37

[40] HD116852

C IV

−38.04 ± 0.29  6.00 ± 0.53  13.00 ± 0.04  0.26 ± 0.05
−26.71 ± 1.22  33.56 ± 1.11  14.01 ± 0.02  8.20 ± 0.54
−12.40 ± 0.37  4.78 ± 0.78  12.73 ± 0.08  0.17 ± 0.05
13.46 ± 1.01  14.57 ± 1.54  13.10 ± 0.11  1.55 ± 0.33

Si IV

−39.21 ± 0.17  7.14 ± 0.30  12.87 ± 0.02  1.76 ± 0.25
−25.77 ± 0.66  26.38 ± 0.60  13.40 ± 0.01  8.01 ± 1.06
−13.38 ± 0.16  4.78 ± 0.30  12.64 ± 0.03  1.19 ± 0.21
15.92 ± 0.70  12.13 ± 0.90  12.55 ± 0.04  0.28 ± 0.16
TABLE A.7

Continued

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<th>$v$ [km s$^{-1}$]</th>
<th>$b$-value [km s$^{-1}$]</th>
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<th>$T_{Max}$ [$10^5$K]</th>
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230
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<th>( T_{\text{Max}} ) [10(^5)K]</th>
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<td>9.41 ± 1.53</td>
<td>10.92 ± 2.93</td>
<td>12.73 ± 0.20</td>
<td>0.87 ± 0.47</td>
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</tbody>
</table>

| C IV             |                |                |                 |

| 35.98 ± 0.61     | 29.10 ± 0.53   | 13.08 ± 0.01   | 14.41 ± 0.53    |
| 25.62 ± 0.37     | 10.71 ± 0.68   | 12.70 ± 0.03   | 1.95 ± 0.25     |
| 9.34 ± 0.24      | 5.62 ± 0.33    | 12.43 ± 0.03   | 0.54 ± 0.06     |

| Si IV            |                |                |                 |

| 69.61 ± 1.00     | 4.09 ± 1.03    | 12.35 ± 0.25   | 0.12 ± 0.06     |
| 61.28 ± 0.96     | 6.91 ± 1.08    | 12.93 ± 0.09   | 0.35 ± 0.11     |
| 45.56 ± 0.39     | 2.45 ± 0.73    | 12.11 ± 0.11   | 0.04 ± 0.03     |
| 26.73 ± 0.66     | 29.70 ± 0.46   | 13.95 ± 0.01   | 6.42 ± 0.20     |
| 20.43 ± 0.87     | 3.47 ± 1.09    | 12.54 ± 0.25   | 0.09 ± 0.06     |
| 12.14 ± 0.49     | 6.67 ± 0.52    | 13.40 ± 0.04   | 0.32 ± 0.05     |

| Si IV            |                |                |                 |

| 65.49 ± 0.82     | 6.38 ± 0.99    | 12.26 ± 0.07   | 0.69 ± 0.22     |
| 57.98 ± 0.32     | 2.58 ± 0.58    | 11.90 ± 0.13   | 0.11 ± 0.05     |

[44] HD118246

[45] HD121968
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[46] HD148937

C IV

| $-160.90 \pm 0.76$ | $7.10 \pm 1.33$ | $12.28 \pm 0.08$ | $0.37 \pm 0.14$ |
| $-121.51 \pm 0.46$ | $5.34 \pm 0.79$ | $12.36 \pm 0.06$ | $0.21 \pm 0.06$ |
| $-105.34 \pm 0.15$ | $5.61 \pm 0.25$ | $12.91 \pm 0.02$ | $0.23 \pm 0.02$ |
| $-32.76 \pm 2.31$ | $11.96 \pm 3.18$ | $12.67 \pm 0.38$ | $1.04 \pm 0.55$ |

Si IV

| $-163.87 \pm 0.10$ | $5.00 \pm 0.17$ | $12.45 \pm 0.02$ | $0.43 \pm 0.03$ |
| $-123.48 \pm 0.21$ | $5.55 \pm 0.15$ | $13.24 \pm 0.02$ | $0.52 \pm 0.03$ |
| $-106.35 \pm 0.05$ | $4.50 \pm 0.07$ | (>) $14.11 \pm 0.03$ | $0.34 \pm 0.01$ |
| $-33.23 \pm 0.15$ | $8.62 \pm 0.21$ | $12.48 \pm 0.01$ | $1.26 \pm 0.06$ |

[47] HD137595

C IV

| $-0.78 \pm 0.27$ | $6.53 \pm 0.40$ | $12.61 \pm 0.02$ | $0.31 \pm 0.04$ |

Si IV

<p>| $-5.67 \pm 0.24$ | $6.27 \pm 0.39$ | $12.26 \pm 0.02$ | $0.67 \pm 0.08$ |</p>
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</table>
APPENDIX B

HIGH ION ABSORPTION PROFILES - OVERVIEW FIGURES

Figures B.1 through B.38 show the profiles for the stars that show absorption. At the lower right corner is the star ID, star name, spectral type/luminosity class, Galactic coordinates, and distance derived from spectroscopic parallax. The plot to left shows the absorption profiles with the fitted continua (blue curves) for the available ions. The next plot shows the normalized profiles with vertical (green) lines representing the velocity centroids from the Si IV component fit. Next, the upper plot shows the $N_a(v)$ apparent optical depth profiles for each doublet and O VI. O VI $\lambda$1037 is always contaminated and cannot be used. The $N_a(v)$ profiles aid in continua fitting and identifying unresolved saturated structures. The lower plot shows the column density ratios as a function of velocity for the high ions. The ionic ratios are useful in identifying ionization mechanisms responsible for the ionization. The last plot to the far right shows the results from component fitting. The red curve is the resultant component model, and the blue lines show the individual components. The vertical (green) lines represent the velocity centroids for Si IV.
Figure B.4. HD209339 B0 IV

(6) HD209339 B0 IV

$\lambda = 104.6^{\circ}$, $b = 5.9^{\circ}$

d = 1.10 kpc

Normallized Flux

$N(\lambda)$ (10$^{-4}$ cm$^{-2}$ arcsec$^{-1}$)

$\log N(\lambda)$

Normallized Flux

Flux (10$^{-9}$ erg s$^{-1}$ cm$^{-2}$)

239
Figure B.6. HD224151 (8)

Figure B.6. HD224151 (8)
Figure B.9. HD24534 (13)

(13) HD24534 B0Ve
l=163.1°, b=-17.1°
d=0.60 kpc
Figure B.10. HD40005 (15)

Normalized Flux

$\log (N/\text{cm}^2 \text{s} \text{km s}^{-1})$ vs. $V'_{\text{cm}}$

Normalized Flux

$F_{\lambda}$ (erg s$^{-1}$ cm$^{-2}$ A$^{-1}$) vs. $V'_{\text{cm}}$
Figure B.11. HD18100 (18)

(18) HD18100 B1V
l=217.9°, b=-62.7°
d=2.00 kpc
Figure B.13. HD93840 (20)

(20) HD93840 BN1lb
l=282.1°, b=11.1°
d=4.70 kpc
Figure B.18. HD93206 (25)

(25) HD93206 09.71B:n
l=287.7°, b=-0.9°
d=2.60 kpc
Figure B.19. HD93222 OIII

HD93222 OIII

l=287.7°, b=-1.0°
d=3.60 kpc
Figure B.20. HD93843 0514F

$\gamma = \pm 2.3^\circ$, $b = -0.9^\circ$,

$d = 3.50$ kpc

$Z_{\odot}$ = 0.2

$V = 8.0$ km s$^{-1}$

$N'_{\gamma} (\text{cm}^{-2})$

$\log f(Y')$

Normallized Flux

(Flux [erg s$^{-1}$ cm$^{-2}$])
Figure B.22. HD101131 O6Vf

$\ell$=294.8$^\circ$, $b$=-1.6$^\circ$

$d$=2.00 kpc

(29) HD101131 (29)
Figure B.24. HD101436 (31)

(31) HD101436 06.5V
l=295.0°, b=-1.7°
d=2.20 kpc
Figure B.25. HD103779 (34)

Normalized Flux

\[ \frac{\text{Flux}}{10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{Å}^{-1}} \]

260
Figure B.27. HD102065 (36)
Figure B.29. HD114886 (41)

(1) HD114886 09II–III
l=305.5°, b=−0.8°
d=2.00 kpc

Normalized Flux
Figure B.30. HD122879 (42)
Figure B.31. HD124314 (43)
(46) HD148937 06.5f?p
l=336.4°, b=-0.2°
d=0.80 kpc
Figure B.35. HD137595 (47)

(47) HD137595 B2II–III
l=336.7°, b=18.9°
d=1.70 kpc
Figure B.36. HD152723 (48)


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