THE GLOBAL CONTENT, DISTRIBUTION, AND KINEMATICS OF INTERSTELLAR O VI IN THE LARGE MAGELLANIC CLOUD

J. Christopher Howk, Kenneth R. Sembach, Blair D. Savage, Scott D. Friedman, and Alex W. Fullerton

ABSTRACT

We present Far Ultraviolet Spectroscopic Explorer (FUSE) observations of interstellar O vi absorption toward 12 early-type stars in the Large Magellanic Cloud (LMC). The observations have a velocity resolution of \( \lesssim 20 \) km s\(^{-1}\) (FWHM) and clearly show O vi 1031.926 Å absorption at LMC velocities toward all 12 stars. From these observations we derive column densities of interstellar O vi in this nearby galaxy; the observed columns are in the range log \( N(\text{O vi}) \) = 13.9–14.6, with a mean of 14.37 and a standard deviation of \( \pm 3.8\% \) (\( ^{\pm 0.14}_{\pm 0.21} \) dex). The observations probe several sight lines projected onto known superbubbles in the LMC, but these show relatively little (if any) enhancement in O vi column density compared to sight lines toward relatively quiescent regions of the LMC. The observed LMC O vi absorption is broad, with Gaussian dispersions \( \sigma \approx 30–50 \) km s\(^{-1}\). This implies temperatures \( T \lesssim (2–5) \times 10^6 \), indicating that much of the broadening is non-thermal because O vi has a very low abundance at such high temperatures. The O vi absorption is typically displaced \( \sim –30 \) km s\(^{-1}\) from the corresponding low-ionization absorption associated with the bulk of the LMC gas. The general properties of the LMC O vi absorption are very similar to those of the Milky Way halo. The average column density of O vi and the dispersion of the individual measurements about the mean are identical to those measured for the halo of the Milky Way, even though the metallicity of the LMC is a factor of \( \sim 2.5 \) lower than the Milky Way. The velocity dispersion measured for the LMC material is also consistent with recent measurements of the Galactic halo. The striking similarities in these quantities suggest that much of the LMC O vi may arise in a vertically extended distribution similar to the Galactic halo. We discuss the measurements in the context of a halo composed of radiatively cooling hot gas and/or turbulent mixing layers. If the observed O vi absorption is tracing a radiatively cooling galactic fountain flow, the mass flow rate from one side of the LMC disk is of the order \( M \sim 1 M_\odot \) yr\(^{-1}\), with a mass flux per unit area of the disk \( M/\Omega \sim 2 \times 10^{-2} M_\odot \) yr\(^{-1}\) kpc\(^{-2}\).

1 INTRODUCTION

Current theory suggests that the interstellar medium (ISM) in galaxies is strongly influenced by the input of energy and matter from stars. This is particularly true for spiral and irregular galaxies, which are typically experiencing ongoing star formation. The effects of the interactions of (multiple) stars and supernovae with the ISM in spiral and irregular galaxies is expected to produce pockets of superheated gas (e.g., Heiles 1990; Norman & Ikeuchi 1989; Mac Low & McCray 1988), and the holes visible in the neutral hydrogen distributions of galaxies are often interpreted as the signature of such effects (Kim et al. 1999; Puche et al. 1992; Deul & den Hartog 1990; Brinks & Baja 1986). In regions with high densities of early-type stars, the energy input from the stars and supernovae can shape interstellar matter on kiloparsec scales. For disk galaxies, with larger pressure gradients in the vertical, \( z \), direction than the radial direction, the superheated, high-pressure gas is thought to flow away from the disk, feeding matter and energy into the thick disk or halo of the system (e.g., de Avillez 2000; Norman & Ikeuchi 1989; Bregman 1980).

The Large Magellanic Cloud (LMC) is the nearest disk galaxy to the Milky Way. Its proximity (\( d \sim 50 \) kpc) and low inclination angle (\( i \approx 30^\circ–40^\circ \)) provide a relatively clear view of this system (see Westerlund 1997), with very little foreground or line-of-sight confusion. The LMC has long served as a laboratory for studies of the ISM. Excellent maps of the ISM within the LMC are available for the warm (\( \lesssim 10^4 \) K) gas, both neutral (Kim et al. 1998) and ionized (e.g., Smith 1999; Kennicutt et al. 1995; Davies, Elliott, & Meaburn 1976), as well as the hot gas (Snowden & Petre 1994; Wang et al. 1991). The ability to resolve individual stars from each other and the ISM in this system provides a unique opportunity to determine the energy budget of the largest interstellar structures within the galaxy (e.g., Oey 1996).

Studies of the hot gaseous content of the LMC are of particular importance for understanding the energy input into the ISM from stars. One manner in which to study the hot gas content of a galaxy is through ultraviolet (UV) absorption line observations of the Li-like oxygen ion (O i\(^{+5} \) or O vi), which has a doublet of transitions at 1031.926 and 1037.617 Å. The O vi ion principally arises in hot, collisionally ionized gas in galactic environments since the ionization potential for its production (\( IP_{\text{O vi}} = 114 \) eV) is high enough to preclude a significant photoionized component.
TABLE 1
SIGHT LINE AND STELLAR PROPERTIES FOR FUSE LMC TARGETS

| Star   | Alternate Name | \( \alpha \) (J2000) | \( \delta \) (J2000) | \( V \) (mag) | Spectral Type | Reference| \( v_\infty \) (km s\(^{-1}\)) | Reference |
|--------|----------------|----------------------|----------------------|-------------|---------------|---------|------------------|---------|
| Sk – 67°05° ...... | HD 268605 | 04 50 18.9 | –67 39 38.2 | 11.34 | O9.7 Ib | 1 | 1665 | 1 |
| Sk – 67°20° ...... | HD 32109 | 04 55 31.5 | –67 30 01.0 | 13.87 | WN4b | 2 | 2900 | 2 |
| Sk – 66°51° ...... | HD 31333 | 05 03 10.2 | –66 40 54.0 | 12.69 | WN8h | 2 | 850 | 3 |
| Sk – 67°69° ...... | 05 14 20.2 | –67 08 03.5 | 13.09 | O4 III(f) | 3 | 2600 | 4 |
| Sk – 68°80° ...... | HD 36521 | 05 26 30.4 | –68 50 26.6 | 12.40 | WC4 + OB | 4 | ... |
| Sk – 70°91° ...... | LH 62-1 | 05 27 33.7 | –70 36 48.3 | 12.78 | O6.5 V | 5 | 3000 | 5 |
| Sk – 66°100° ...... | 05 27 35.6 | –66 55 15.0 | | O6 II(f) | 6 | 2075 | |
| Sk – 67°144° ...... | HD 37026 | 05 30 12.2 | –67 26 08.4 | 14.30 | WC4 | 4 | 2600 | 7 |
| Sk – 71°45° ...... | HD 269676 | 05 31 15.5 | –71 04 08.9 | 11.47 | O4–5 III(f) | 1 | 2500 | 5 |
| Sk – 69°191° ...... | HD 37680 | 05 34 19.4 | –69 45 10.0 | 13.35 | WC4 | 4 | 2800 | 7 |
| Sk – 67°211° ...... | HD 269810 | 05 35 13.9 | –67 33 27.0 | 12.26 | O2 II*(f) | 7 | 3750 | 8 |
| Sk – 66°172° ...... | 05 37 05.6 | –66 21 35.7 | 13.13 | O2 II*(f) + OB | 6 | 3250 | 8 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\( a \) Stellar wind terminal velocity. The terminal velocities for the W-R stars often have larger uncertainties than those for the O stars.

\( b \) References for the adopted wind terminal velocities: (1) Patriarchi & Perinotto 1992; (2) Koesterke et al. 1991; (3) Crowther & Smith 1997; (4) Leitherer 1988; (5) D. Massa et al. 2002, in preparation; (6) Priinja & Crowther 1998; (7) Gräfener et al. 1998; (8) Walborn et al. 2002, in preparation.

\( c \) References for the adopted spectral classification: (1) Walborn 1977; (2) Smith, Shara, & Moffat 1996; (3) Garmay & Walborn 1987; (4) Smith et al. 1990; (5) Conti, Garmay, & Massey 1986; (6) Walborn et al. 1995; (7) Walborn 1982.

\( d \) References for the adopted wind terminal velocities: (1) Patriarchi & Perinotto 1992; (2) Koesterke et al. 1991; (3) Crowther & Smith 1997; (4) Leitherer 1988; (5) D. Massa et al. 2002, in preparation; (6) Priinja & Crowther 1998; (7) Gräfener et al. 1998; (8) Walborn et al. 2002, in preparation.

Such observations are currently plausible using the Far Ultraviolet Spectroscopic Explorer (FUSE), a dedicated spectroscopic observatory operating in the wavelength range 905–1187 Å at high resolution \( (R \equiv \lambda/\Delta \lambda \approx 15,000–20,000) \). FUSE can easily observe stars in the Galactic halo, stars in the Magellanic Clouds, and distant extragalactic sources with sufficient signal to noise to produce reliable \( \text{O}\text{VI} \) column density and line profile measurements.

Here we present FUSE spectra of \( \text{O}\text{VI} \) absorption toward 12 early-type stars in the LMC, the properties of which are summarized in Table 1. In this work we show that the LMC contains a large amount of highly ionized gas distributed in a patchy manner across its face. The \( \text{O}\text{VI} \) column densities in the LMC along the directions studied in this work are as high as those observed through the halo of the Milky Way (Savage et al. 2000). We show that the hot material traced through \( \text{O}\text{VI} \) is present at significantly different velocities than the bulk of the low-ionization material arising in the disk of the LMC, a phenomenon that was also seen in Hubble Space Telescope (HST) observations of \( \text{C}\text{IV} \) absorption (Walcker et al. 1998). We will argue that the available evidence suggests much of the observed LMC absorption arises in an extended halo or corona, perhaps very similar to that observed in the Milky Way. These results are important since the LMC is the only other disk galaxy beyond the Milky Way that can be studied in this manner.

In § 2 we discuss the reduction of the FUSE data employed in this work, while § 3 discusses the methods used in analyzing the data. We discuss the gross distribution of \( \text{O}\text{VI} \) column densities in the LMC in § 4, and the rough kinematic properties of the hot material in § 5. In § 6 we discuss the implications of our observations, and we summarize our work in § 7.

2. FUSE OBSERVATIONS AND DATA REDUCTION

The FUSE mission, its planning, and its in-orbit performance are discussed by Moos et al. (2000) and Sahnow et al. (2000). Briefly, the FUSE observatory consists of four co-aligned prime-focus telescopes and Rowland-circle spectrographs feeding two microchannel plate (MCP) detectors with helical double delay line anodes. Two of the telescope/spectrograph channels have SiC coatings providing reflectivity over the range ~905–1105 Å, while the other two have Al:LiF coatings for sensitivity in the ~1000–1187 Å range. We make use of only the latter, the LiF channels, in this work. Light from each mirror passes through an aperture onto a holographically ruled spherical grating. The resulting spectra are projected onto the MCP detectors, with spectra from one LiF and one SiC channel imaged in parallel onto each detector.

The data used in this work were all obtained with the source centered in the 30'' × 30'' (LWRS) aperture of the LiF1 spectrograph channel. In many cases, the LiF2 channel was co-aligned well enough with the LiF1 channel that a second set of spectra covering the 1000–1187 Å wavelength range was obtained. Total exposure times ranged from 3.6 to 33 ks for the LMC stars used in this work. A log of the observations used for this investigation is given in Table 2.

The raw data sets consist of tables of time-tagged photon event locations within each 16,384 × 1024 detector array. The individual exposures for a set of observations were merged into a single spectrum by concatenating the individual photon event lists. These combined time-tagged photon event lists were processed with version 1.8.6 or 1.8.7 of the standard FUSE calibration pipeline (CALFUSE) available at The Johns Hopkins University (see Oegerle, Murphy, & Kriss [2000] for a detailed description of the CALFUSE pipeline). The differences between these two versions of the

\( ^6 \) The Sk – 67°05° data were obtained as part of in-orbit checkout activities that required multiple exposures with the object at different locations within the aperture. The processing of this observation required special care to ensure that the individual exposures were shifted and summed properly. The analysis of this sight line is discussed by Friedman et al. (2000).

\( ^7 \) Bright targets make use of the spectral image mode wherein the photons arriving at each pixel are simply summed and read out at the end of the exposure. This mode does not preserve the time-tagged nature of the data.
pipeline are inconsequential for our purposes. The photon lists were screened for valid data with constraints imposed for earth limb angle avoidance and passage through the South Atlantic Anomaly. Corrections for detector backgrounds, Doppler shifts caused by spacecraft orbital motions, and geometrical distortions were applied (Sahnow et al. 2000). No corrections were made for optical astigmatism aberrations, and no flat-field corrections are yet applied in the FUSE calibration process. Given the existence of significant fixed-pattern noise structure introduced by the FUSE detectors, the latter omission can be particularly important. We compared the LiF1 and LiF2 spectra whenever possible to determine the significance of the observed features.

The processed data have a nominal spectral resolution of \( \lesssim 20 \text{ km s}^{-1} \) (FWHM), with a relative wavelength dispersion solution accuracy of \( \sim 6 \text{ km s}^{-1} \) (1 \( \sigma \)). The zero point of the wavelength scale for each individual observation is poorly determined. In a few cases International Ultraviolet Explorer (IUE) or Space Telescope Imaging Spectrograph (STIS) data allowed us to constrain the velocity zero point of observations of LMC stars. These include the sight line toward Sk \(-71^\circ 45\) with STIS and Sk \(-67^\circ 211\) with IUE. We have also investigated the velocity offsets of several stars not presented in this work and find that a consistent shift of \( \approx -45 \) to \(-50 \text{ km s}^{-1} \) from the CALFUSE wavelength solution was often appropriate to bring the FUSE data into the LSR frame (with the exception of the Sk \(-67^\circ 05\) data sets; see Friedman et al. 2000). This is consistent with the average shift of \( -47 \pm 5 \text{ km s}^{-1} \) derived for FUSE LMC/SMC observations calibrated with STIS echelle-mode observations by Danforth et al. (2002). We note that this shift includes an implicit correction for the sign error in the application of the heliocentric velocity correction in all CALFUSE versions prior to v2.0, though the magnitude of this error is small for LMC sight lines (of order \( \sim 5 \text{ km s}^{-1} \)).

In those cases where other data are not available, we have adopted a \(-50 \text{ km s}^{-1} \) shift to the FUSE velocity scale.

Figure 1 shows portions of the final FUSE spectra of two stars near the O \textsc{vi} doublet: Sk \(-67^\circ 211\) and Sk \(-71^\circ 45\). These spectra represent only data from the LiF1 channel for each star. Several prominent ionic absorption lines are marked, with ticks showing the location of the Milky Way and LMC absorption components. The positions of the Milky Way and LMC ticks are determined by the velocity of the Si \textsc{ii} line at 1020.699 \AA. We have not marked the position of interstellar Ly\( \beta \) absorption. Telluric emission lines from Ly\( \beta \) and O \textsc{i} can be seen to varying degrees in the data.

These two sight lines represent two extremes of molecular hydrogen absorption for our sample of stars. The sight line toward Sk \(-71^\circ 45\) shows a rich spectrum of H\(_2\) absorption from both Milky Way and LMC gas. The expected positions of the H\(_2\) lines (for \( \lambda \gtrsim 1018 \) \AA and \( J \lesssim 4 \) only) in both the Galaxy and LMC toward Sk \(-71^\circ 45\) are marked under the spectrum of that star. The sight line toward Sk \(-67^\circ 211\), however, shows only very weak H\(_2\) absorption [e.g., the Lyman (5–0) \( R(3) \) transition at 1041.16 \AA]. We discuss the importance of H\(_2\) contamination of the interstellar O \textsc{vi} profiles in \$3.2. The properties of the H\(_2\) absorption within the LMC are discussed by Tumlinson et al. (2001).

It should be noted from Figure 1 that the absorption from the weaker O \textsc{vi} transition at 1037.617 \AA is almost always heavily confused by absorption from C \textsc{iv} and H\(_2\) when studying the LMC. This is the case even for Sk \(-67^\circ 211\), which exhibits only very weak H\(_2\) absorption.

3. ANALYSIS OF INTERSTELLAR O \textsc{vi} ABSORPTION

This section discusses the details of our analysis of the interstellar O \textsc{vi} absorption. Of particular importance is the estimation of the stellar continuum, which is determined by the specifics of the outflowing stellar wind for the stars in
3.1. Estimation of the Stellar Continuum

The single greatest uncertainty in an analysis of the interstellar O\textsc{vi} absorption from the LMC is the determination of the stellar continuum in the regions immediately surrounding the interstellar features. As discussed by Massa et al. (2002, in preparation), the shape of the local stellar continuum in the O\textsc{vi} spectral region of early-type stars is dominated by resonance absorption (and scattering) of the stellar continuum emission by O\textsc{vi} ions in the outflowing stellar wind. The principle source of O\textsc{vi} within the stellar winds of the O stars is likely ionization by X-rays produced in strong shocks propagating through the wind (Puls, Owocki, & Fullerton 1993). The radiative transfer of photons from the photosphere through the expanding wind yields a characteristic P Cygni–like profile (see Lamers & Cassinelli 1999). Because of the stochastic nature of the shock formation process, the shape of the O\textsc{vi} P Cygni profiles can be significantly different for individual OB and W-R stars and can even be temporally variable (e.g., Lehner et al. 2001).

Our approach to studying the interstellar O\textsc{vi} in this first study of the LMC is to use only stars whose stellar continua are straightforward to approximate. Furthermore, we have compared our fits of the stellar continua with the Sobolev Exact Integration (SEI; see Massa, Prinja, & Fullerton 1995) modeling of the radiative transfer of photospheric photons through the outflowing stellar wind from Massa et al. (2002, in preparation). We have insured that there are no significant systematic inconsistencies between the stellar continua determined when viewing the stellar wind on a relatively local scale (i.e., within a few hundred km s$^{-1}$ of the ISM absorption) and the information derived from self-consistent radiative transfer models of the entire stellar wind profiles (with the provisos discussed by Massa et al. 2002, in preparation).

We have limited our sample to W-R stars and O stars with spectral types O7 and earlier. The use of only the earliest spectral types implies that we are using stars with large mass-loss rates (and often large terminal velocities as well), which tend to show more fully developed (i.e., simpler) O\textsc{vi} P Cygni profiles and are less susceptible to difficulties caused by wind variations (see discussion below). To this end we have examined the existing \textit{FUSE} PI team spectra of all
stars meeting these spectral class requirements. From this sample we have chosen to study 12 sight lines: 11 new sight lines and one (Sk – 67°05) studied by Friedman et al. (2000). The properties of these 12 stars are summarized in Table 1.

Figure 2 shows the adopted stellar continua for the O stars (left column) and W-R stars (right column) studied in this work. For each star we estimated the shape and level of the local stellar continuum near the interstellar O vi λ1031.926 absorption by fitting low-order (≤5) Legendre polynomials to adjacent spectral regions free from interstellar lines. This fitting followed the techniques described by Sembach & Savage (1992), including the estimation of the uncertainties in the Legendre polynomial fitting coefficients. This allows us to include an estimate for continuum fitting uncertainties in our equivalent width and column density measurement error estimates (see below). In each case we adopted the lowest order polynomial that could reasonably approximate the stellar continuum. Though we applied an F-test to assess the significance of additional polynomial terms, the final decision on the order of the fit was subjective.

A few general comments regarding the placement of stellar continua for early-type stars are necessary. The separation of the two members of the O vi doublet is ~1650 km s\(^{-1}\). Thus, for stars whose winds have terminal velocities, \(v_\infty\), in excess of this velocity, the absorption from the red member of the doublet will overlap that of the blue member. From the standpoint of understanding the stellar continuum in the region of interstellar O vi, stars with stellar wind terminal velocities within a few hundred km s\(^{-1}\) of the 1650 km s\(^{-1}\) separation of the O vi doublet are often problematic. Given that the terminal velocity is often manifested as a relatively sharp gradient in the absorption strength of the wind profile, stars with such terminal velocities can have relatively complex stellar continua in the region of interest for interstellar studies.

For terminal velocities 1650 \(\lesssim v_\infty \lesssim 2000\) km s\(^{-1}\) the absorption edge of the 1031.926 Å transition lies in the deep interstellar Ly \(\beta\) trough or the 1037 Å transition overlaps the 1031.926 Å rest velocity. In both of these cases, the overlap with other transitions can make it very difficult to obtain a reliable SEI fit because the models typically try to simultaneously fit both lines of the doublet. With the exception of Sk – 67°05, the terminal velocities for the O stars in Table 1 are in excess of these values. The terminal velocities for the W-R stars are all outside of this range (though we did not make use of SEI modeling of these stars). Our exclusion of lower terminal velocity O stars is not because of the difficulty of the SEI modeling, but rather because stars with lower terminal velocities often display more complex continua in the region of interstellar O vi absorption. However, studies of the ISM toward later spectral type stars will need to consider the difficulties in the SEI modeling when comparing such models to their data.

Another concern regarding the general shape of the stellar wind absorption in the region of the O vi ISM lines is the probable variability of the stellar wind O vi absorption profiles. Lehner et al. (2001) have discussed such variations and their effects on continuum placement for interstellar studies. Using multiple FUSE observations of the O vi spectral region in Galactic and LMC stars, these authors showed that, even in sparsely sampled time series of two to three spectra, a large fraction (≥60%) exhibited some spectral variability over the time periods probed (days to months). In general the variability in the O vi P Cygni profiles happened at velocities much higher than those of the interstellar absorption toward these stars. Furthermore, the scale over which the O vi varies was typically several hundred km s\(^{-1}\), significantly broader than most of the interstellar absorption lines in the Galaxy. Lehner et al. (2001) found that even though the shape of the stellar continuum can vary significantly with time, the derived O vi column densities and equivalent widths for Galactic absorption were typically not significantly different.

The situation for absorption in the LMC is less encouraging. Because the full extent of the absorption from the Galactic halo and the LMC typically extends over ~300–400 km s\(^{-1}\), the expectation that changes in the P Cygni profiles should occur over scales larger than that of the ISM absorption profile is no longer valid. Because the Milky Way absorption in these directions occurs at velocities of a few hundred km s\(^{-1}\) with respect to the rest frame of the stars, it is also no longer the case that most of the variation should occur at velocities well beyond the interstellar absorption. Indeed, the column densities and equivalent widths estimated toward the one LMC star in the study by Lehner et al. were significantly different between the two times sampled.

At this point we are unable to quantitatively assess the affects of stellar wind variability on the column densities derived along the sight lines to the LMC stars discussed in this work (see below). We note, however, that our choice of the earliest spectral type stars may help in this regard. Hot stars with large mass-loss rates are desirable as background
probes since their O vi wind lines are usually saturated. Nearly all of the flux observed in a saturated wind line is due to scattered light from throughout the wind. Therefore, substantial changes in the line-of-sight wind optical depth cannot have much of an impact on the flux profile because the transmitted flux is a small fraction of the total flux. The stellar wind profiles of these stars are therefore less susceptible to variations. The LMC star studied by Lehner et al. (2001) has a significantly lower terminal velocity and is of a later spectral type than the stars studied in this work. The continuum placement for this star is much more difficult than for any star in the present sample. This is important insofar as the column densities and equivalent widths of interstellar O vi can be accurately determined along the sight line to that star, irrespective of whether or not any variation in the wind profile is present.

Given the above discussion of wind variability and its effects on the derivation of O vi column densities, the reader should bear in mind that the column densities reported in this work have not been corrected for any stellar wind absorption features that may reside at velocities similar to the ISM features. Future reobservations of some of these stars are planned and may reveal some such features. However, the presence of discrete stellar wind absorption features at interstellar velocities can never be ruled out since one can only identify their presence if they change.

We should also note that for this work we have chosen to consider targets having relatively unambiguous separation between the stellar and interstellar features and well-delineated stellar continua, with the exception of Sk −67°05. The continuum placement and uncertainties for this star, which also falls outside the range of spectral types we have investigated, are discussed in detail by Friedman et al. (2000). In general the stellar continua are more complicated as one looks to later spectral types because the O vi P Cygni profiles of later type stars tend to be less well developed than those of the early O stars. As our understanding of the stellar winds of the later spectral-type stars improves, we may be able to make use of the larger sample of FUSE observations of late O and B stars in the LMC for studying interstellar O vi.

3.2. Assessing the Contamination from Molecular Hydrogen

Absorption from molecular hydrogen in both the Milky Way and the LMC can overlap the O vi absorption along the observed sight lines. Absorption from the (6–0) P(3) and R(4) transitions of H2 at 1031.19 and 1032.35 Å, respectively, can contaminate the O vi absorption from the Milky Way halo and in some cases the O vi absorption from the LMC (e.g., see Fig. 1). These lines absorb at −214 and +123 km s−1 relative to the rest frame of O vi λ1031.926. Rather than derive the detailed characteristics of the entire H2 absorption spectrum, we have taken a more pragmatic approach to estimating the contamination of the interstellar O vi profiles by molecular hydrogen.

To estimate the contribution to the O vi profiles from the (6–0) P(3) and R(4) lines of molecular hydrogen, we have fitted Gaussian profiles to a number of J = 3 and 4 transitions of H2 with line strengths, log λf, very similar to the contaminating 6–0 band transitions. The H2 transitions used in this approach are given in Table 3. For comparison, the properties of the contaminating (6–0) P(3) and R(4) lines are also given. We have used only lines that appear in the LiF1 channel. This helps to minimize the effects of changes in the breadth and shape of the instrumental line spread function, which occur when comparing lines in different channels and detector segments. Because of blending with other species and varying line strengths, the transitions available from Table 3 varied for each sight line.

The fitting process yields a peak apparent optical depth, a breadth, and a central velocity for each of the transitions. We have scaled the peak apparent optical depth for each fit by which the peak optical depths are scaled is small. In general we have found that the scaled peak optical depths and varying line strengths, the transitions available from Table 3 varied for each sight line.

The fitting process yields a peak apparent optical depth, a breadth, and a central velocity for each of the transitions. We have scaled the peak apparent optical depth for each fit by which the peak optical depths are scaled is small. In general we have found that the scaled peak optical depths and varying line strengths, the transitions available from Table 3 varied for each sight line.
Fig. 3.—Continuum normalized interstellar O vi absorption profiles for the sight lines being considered in this work. For each star two panels are shown: the normalized O vi profiles with a model for the contaminating H2 absorption overplotted (top) and the normalized profiles after division by the H2 absorption model (bottom). These profiles are plotted after rebinning to 20 mA, or ~6 km s⁻¹ per pixel.

panel shows the continuum-normalized profiles with the H2 model divided out. The models include the Milky Way P(3) and LMC R(4) components, which were estimated using the same approach as the contaminating LMC P(3) and Milky Way R(4) absorption. Though these outlying components do not overlap the O vi absorption in which we are interested, they demonstrate the quality of our procedure for estimating the H2 absorption strength.

For most of the sight lines studied in this work, the contamination of the O vi profile by molecular hydrogen absorption does not significantly affect the LMC absorption component. Notable exceptions include the sight lines...
toward Sk $-68^\circ 80$, Sk $-71^\circ 45$, and, to lesser extents, Sk $-67^\circ 20$, and Sk $-69^\circ 191$.

The (6–0) $R(0)$ transition of the HD molecule at 1031.912 Å is almost coincident with the rest wavelength of the strong O vi transition. For the sight lines toward the LMC stars studied here, contamination of O vi by this line is unimportant because the H$_2$ column densities, which are expected to be $\sim 10^{10} - 10^{12}$ times stronger, are low (see Tumlinson et al. 2001). Furthermore, several HD lines of similar strength to the 6–0 band transition exist in the FUSE bandpass (see Sembach 1999) but are not seen in the spectra. We have, therefore, made no correction for HD contamination of the O vi absorption.

3.3. Interstellar Absorption Line Measurements

We measured equivalent widths and column densities of the interstellar O vi $\lambda 1031.926$ following Sembach & Savage (1992). We estimated interstellar column densities using the apparent optical depth method (Savage & Sembach 1991). The apparent optical depth, $\tau_a(v)$, is an instrumentally blurred version of the true optical depth of an absorption line, given by

$$
\tau_a(v) = -\ln[I(v)/I_0(v)],
$$

where $I_0(v)$ is the estimated continuum intensity and $I(v)$ is the observed intensity of the line as a function of velocity. This is related to the apparent column density per unit velocity, $N_a(v)$ [atoms cm$^{-2}$ (km s$^{-1}$)$^{-1}$], by

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

where $\lambda$ is the wavelength in Å, and $f$ is the atomic oscillator strength. In the absence of unresolved saturated structure the $N_a(v)$ profile of a line is a valid, instrumentally blurred representation of the true column density distribution as a function of velocity, $N(v)$. In the case of interstellar O vi absorption, the absorption profiles are typically broad enough to be fully resolved by the FUSE spectrographs (e.g., see Savage et al. 2000). In the few cases where the weaker O vi 1037.617 Å line is clean enough to allow a comparison with the stronger line, no evidence for unresolved saturation has been found.

Table 4 lists the derived O vi the equivalent widths and column densities for the LMC material. The error estimates in Table 4 include contributions from statistical (photon) uncertainties and uncertainties in the continuum polynomial coefficients (see Sembach & Savage 1992). The effects of a 2% flux zero-level uncertainty are $\sim 0.01$ dex.

| Identification | Star | $W'_{21}$ (mA) | log $N$(Ovi) | $v_\cdot v_o$ |
|---------------|------|----------------|--------------|--------------|
| 1             | Sk $-67^\circ 05$ | 87 ± 5 | 13.89 $\pm 0.07$ | +180, +325 |
| 2             | Sk $-67^\circ 20$ | 180 ± 10 | 14.26 $\pm 0.09$ | +175, +335 |
| 3             | Sk $-66^\circ 51$ | 199 ± 21 | 14.31 $\pm 0.07$ | +180, +365 |
| 4             | Sk $-67^\circ 69$ | 249 ± 11 | 14.48 $\pm 0.03$ | +160, +345 |
| 5             | Sk $-68^\circ 80$ | 331 ± 7 | 14.61 $\pm 0.03$ | +140, +330 |
| 6             | Sk $-68^\circ 20$ | 279 ± 9 | 14.65 $\pm 0.07$ | +175, +375 |
| 7             | Sk $-66^\circ 100$ | 164 ± 15 | 14.26 $\pm 0.06$ | +175, +315 |
| 8             | Sk $-67^\circ 144$ | 220 ± 16 | 14.41 $\pm 0.07$ | +175, +335 |
| 9             | Sk $-69^\circ 191$ | 205 ± 18 | 14.38 $\pm 0.05$ | +185, +350 |
| 10            | Sk $-71^\circ 45$ | 223 ± 5 | 14.38 $\pm 0.05$ | +185, +350 |
| 11            | Sk $-67^\circ 211$ | 164 ± 6 | 14.21 $\pm 0.04$ | +185, +375 |
| 12            | Sk $-66^\circ 172$ | 191 ± 14 | 14.31 $\pm 0.06$ | +195, +365 |

* Equivalent widths for the LMC material along the observed sight lines with 1 $\sigma$ error estimates. The error estimates include the effects of shifting the lower velocity integration limit by $\pm 20$ km s$^{-1}$.

* O vi column densities for LMC material along the observed sight lines with 1 $\sigma$ error estimates. In all cases these column densities have been derived using observations of the 1031.926 Å transition assuming no unresolved saturation is present. We adopt an $f$-value of $f = 0.1352$ from the theoretical calculations of Yan, Tambasco, & Drake 1998.

* Velocity range over which the LMC profile was integrated.

* The O vi column densities toward Sk $-67^\circ 05$ are taken from Table 2 of Friedman et al. 2000 assuming their “upper” continuum placement.

the LMC O vi column densities, we have also derived these column densities at velocities $\pm 20$ km s$^{-1}$ from the assumed lower velocity limit. The difference between the columns derived with these limits and that derived using the limits quoted in Table 4 is then treated as a 1 $\sigma$ uncertainty and added in quadrature to the statistical and continuum placement uncertainties discussed above. The estimated uncertainties derived using these $\pm 20$ km s$^{-1}$ integration limits were in the range 0.02–0.09 dex ($\approx 5\%$–23$\%$), with an average of $\sim 0.05$ dex ($\sim 12\%$).

4. CONTENT AND DISTRIBUTION OF O VI WITHIN THE LMC

In this section we discuss the total column densities and distribution of interstellar O vi within the LMC. The stars in this work were chosen to have early spectral types and well-behaved O vi P Cygni profiles. Many of the stars in the sample were observed in order to study their stellar properties. As such we have not selected these sight lines based solely upon the properties of the LMC ISM in these directions. Even so, these sight lines probe a variety of physical regions within the LMC. We discuss the physical environments of the individual sight lines and compare the general distribution of O vi absorption with that of the gas traced by H$\alpha$ and X-ray emission.

4.1. Total Line-of-Sight O vi Column Densities

The integrated LMC O vi column densities span the range log $N$(O vi) $\sim 13.9$–14.6 (in units of atoms cm$^{-2}$), i.e., a factor of $\sim 5$. We have detected O vi absorption along all of the sight lines presented in this work. This is suggestive of a high
surface covering factor of O\textsc{vi} in the LMC. We are hesitant to place too much emphasis on this result given that we have selected only early O and W-R stars as background probes. The effects of the high wind luminosities of these stars on their local environments could in principle provide some of the observed O\textsc{vi} column densities. Figure 4 shows the column density of LMC O\textsc{vi} as a function of the spectral type of the background star. While there is no evidence for a dependence on spectral type, we sample a limited range of spectral types.

The statistics of the O\textsc{vi} column densities along the sight lines presented in this work are summarized in Table 5, including the straight and weighted means, standard deviation, and median of the sample. We give these statistics for the full sample of 12 stars shown in Table 4 and for the sample without the star Sk $-67^\circ05$. The sight line to this star was discussed by Friedman et al. (2000). Because of its late spectral type (O9.7 Ib) and relatively complex stellar continuum, we would not have included it in our sample had it not been discussed in detail previously. The medians and unweighted means of the two samples are very similar. We will henceforth discuss the values from the entire sample, with the caveat that one of our twelve sight lines may suffer from different systematic effects than the others.

As shown in Table 5, the average of the LMC column density measurements is $\log(N(O\textsc{vi})) = 14.37$ with a standard deviation of $\pm 0.13$ dex. The logarithm of the median of the measurements is 14.38. There is significant variation in the column densities between the individual sight lines. The separations of the background probes used here range from 0.5 to 5.1 (5450–4550 pc). Over the four smallest separations probed (450–510 pc), the absolute differences in the logarithmic column densities are 0.15, 0.17, 0.20, and 0.37 dex, corresponding to linear ratios of 1.41, 1.48, 1.58, and 2.34. The last value is for the Sk $-67^\circ05$/Sk $-67^\circ20$, pair, which we point out because of the potential uncertainties associated with the former star. We will discuss the distribution of O\textsc{vi} column densities more fully in § 4.2.

An obvious point of comparison for interpreting the column densities of O\textsc{vi} in the LMC is the Milky Way. Savage et al. (2000) reported the first FUSE observations of interstellar O\textsc{vi} absorption in the disk and halo of the Milky Way as seen in the spectra of 11 active galactic nuclei (AGNs). These authors report a patchy distribution of O\textsc{vi} within the Milky Way halo. Defining the column density of O\textsc{vi} projected onto the plane of the Galaxy by $N_\perp(O\textsc{vi}) \equiv N(O\textsc{vi}) \sin \beta$, the sample of column densities in the Savage et al. (2000) sample has a mean $\log(N_\perp(O\textsc{vi})) = 14.29 \pm 0.14$ (standard deviation), with a median of 14.21 and a full range log $N_\perp(O\textsc{vi}) = 13.80$ to 14.64 (a factor of $\approx 7$ range). In a plane-parallel exponentially stratified layer the quantity $N_\perp$ is simply the product of the midplane density, $n_e$, and the exponential scale height, $h$, of the distribution. Adopting a midplane density of $n_e(O\textsc{vi}) = 2 \times 10^{-6}$ cm$^{-3}$ based on Copernicus observations (Jenkins 1978), Savage et al. find implied exponential scale heights in the range $h_{O\textsc{vi}} \approx 1.0$–7.0 kpc. Assuming an irregular distribution of absorbing clouds they derive a scale height for the clouds of $\approx 2.7 \pm 0.4$ kpc.

In order to compare the observed column densities in the LMC with those observed looking out from our position in the Galactic disk toward distant AGNs, it is useful to convert the LMC values to column densities projected perpendicular to the plane of the LMC, $N_\perp$, similar to the $N \sin \beta$ treatment of Savage et al. (2000). In the case of the LMC, that requires correcting the observed column densities for the inclination of the LMC. The inclination of the LMC is typically defined in terms of the angle of the disk plane from the plane of the sky, with values in the literature typically near $i \approx 33^\circ$ (e.g., Westerlund 1997). Hence, the correction factor is not the sine, but rather the cosine of the inclination from the plane of the sky. We find $\log(N_\perp(O\textsc{vi})) = \log(N(O\textsc{vi}) \cos i = 14.29 + 0.14 \pm 0.21$ with the log of the median value being 14.30.

Throughout this work we adopt the canonical distance of 50 kpc to the LMC.

---

**TABLE 5**

**Statistical Properties of Interstellar O\textsc{vi} in the LMC**

| Quantity            | Column Density Statistics |
|---------------------|---------------------------|
|                     | Linear  | Logarithmic |
| Full Sample         |         |            |
| Mean                | $2.34 \times 10^{14}$   | 14.37    |
| Weighted mean       | $1.80 \times 10^{14}$   | 14.25    |
| Standard deviation  | $+0.89 \times 10^{14}$  | $-0.21$  |
| Median              | $2.37 \times 10^{14}$   | 14.38    |
| New Observations$^b$|         |            |
| Mean                | $2.49 \times 10^{14}$   | 14.40    |
| Weighted mean       | $2.22 \times 10^{14}$   | 14.35    |
| Standard deviation  | $+0.78 \times 10^{14}$  | $-0.12$  |
| Median              | $2.37 \times 10^{14}$   | 14.38    |

$^a$ All quantities quoted were derived from the linear column densities.

$^b$ Statistics for the sight lines excluding that toward Sk $-67^\circ05$. This star, described in detail by Friedman et al. 2000, has continuum placement uncertainties that likely exceed those of the rest of our sample.
The average column density of O vi projected onto the plane of the LMC in our sample of 12 sight lines is identical to that projected onto the disk of the Milky Way, with the same degree of variation. We note that the same calculations excluding the sight line toward Sk –67°05 yield an average column density higher by 0.03 dex (7%) with a lower standard deviation. We will discuss the implications of this comparison of the hot gas content of the Milky Way and LMC more fully in § 6.

4.2. Comparison with Other Views of the LMC

The ISM of the LMC has been studied extensively over a range of wave bands. Given its proximity, these studies have provided a wealth of information on the warm (∼10⁴ K) ionized gas traced through its Hα emission and hot (≥10⁶ K) ionized material traced through its X-ray emission. Surveys of the former, in particular, have been used to identify large-scale structures in the ISM of the LMC that trace the feedback of energy from massive stars into the ISM (Henize 1956; Davies et al. 1976; etc.). Hα imaging observations have revealed the presence of ionized structures on almost all scales, including H ii regions, supernova remnants (SNRs), superbubbles, and “supergiant shells” (SGSs). The latter two classes of Hα-emitting structures are the most prominent with projected diameters of ∼100 to ∼1000 pc.

4.2.1. Comparison with Hα Distribution

Many of the stars in our FUSE sample are projected onto prominent Hα-emitting structures. Table 6 lists the identification of any nebulosity and describes the general interstellar environments for each sight line. The identifications and descriptions rely heavily on previous studies. Examining Table 6 one can see a range of the general interstellar environments probed, including sight lines that are projected onto very faint Hα emission associated with diffuse H ii regions as well as objects that are projected onto prominent shells that have been identified as superbubbles. Several sight lines also probe the SGS LMC 4. Thus, while our sample of sight lines is small, it seems to probe a wide variety of physical regions.

Figure 5 presents a representation of the interstellar O vi column densities as a function of position on the sky overlaid on an Hα image of the LMC (Gaustad et al. 2001). The directions probed by our O vi measurements are marked with circles whose radii are linearly proportional to the integrated LMC O vi column densities along these lines of sight. Hence, Figure 5 shows a “map” of the O vi column density across the face of the LMC. A number is given next to each circle that denotes each sight line with the identification given in Table 4, and the circle in the upper right of the figure gives the scale for N(O vi) = 10¹⁴ cm⁻². More detailed views of the Hα-emitting gas projected near these sight lines can be found in Danforth et al. (2002).

Figure 5 gives an interesting view of the O vi distribution within the LMC. This figure demonstrates that relatively strong O vi absorption is present in regions where the ISM traced by Hα is relatively quiescent. For example, the lines of sight to Sk –67°20, Sk –66°51, and Sk –67°69 (nos. 2-4 in Fig. 5) all probe regions of only relatively diffuse Hα emission in quiescent regions of the galaxy (the bright spot near the last of these is due to an incompletely subtracted foreground star), though their O vi column densities exceed 10¹⁴ cm⁻².

It can also be seen from Figure 5 that several stars (e.g., Sk –66°100, Sk –67°144, and Sk –66°172—nos. 7, 8, and 12) probe the periphery or interior of the SGS LMC 4, a 1400 pc diameter ring delineated by H ii regions and encompassing an H i void (Kim et al. 1998) centered at α 2000 ≈ 05h31m33s; δ 2000 ≈ –66°40’28”. Furthermore, those lines of sight south of δ 2000 = –68° are all projected onto previously identified “superbubbles” in Hα and X-ray studies (e.g., Dunne, Points, & Chu 2001). While two of these four sight lines exhibit the largest column densities in our sample (Sk –68°80 and Sk –71°45—nos. 5 and 9, which probe N144 and N206, respectively), the other two have column densities consistent with the median of the sample.

The O vi column densities observed along our 12 sight lines seem to have little relation to the observed morphological structure of Hα emission (Gaustad et al. 2002; Danforth et al. 2002) in these directions. Furthermore, there is no relationship between the observed O vi column densities and the local star formation rate as traced by the intensity of the

| Identificationa | Star     | Nebulosityb | Description                      |
|-----------------|----------|-------------|----------------------------------|
| 1..................| Sk –67°05| N3/DEM7     | Diffuse, faint H ii region       |
| 2..................| Sk –67°20| Field star  |                                   |
| 3..................| Sk –66°51| DEM56       | Faint H ii region                |
| 4..................| Sk –67°69| DEM107      | Faint H ii region on periphery of SGS LMC 4 |
| 5..................| Sk –68°80| N144/DEM199 | Superbubble projected onto LMC 3 |
| 6..................| Sk –70°91| N204/DEM208 | Superbubble                      |
| 7..................| Sk –66°100|             | Interior of LMC 4               |
| 8..................| Sk –67°144|             | Periphery of LMC 4              |
| 9..................| Sk –71°45| N206/DEM221/KDSB GS70 | Superbubble                 |
| 10.................| Sk –69°191| N154/DEM246/KDSB GS72 | Superbubble                   |
| 11.................| Sk –67°211| N59A/DEM241 | Bright H ii region               |
| 12.................| Sk –66°172| N64B/DEM252 | Bright H ii region on periphery of LMC 4 |

a Identifications corresponding to the labels in Figs. 5–8.
b The designations N and DEM refer to entries in the catalogs of Henize 1956 and Davies et al. 1976, respectively. The designation KDSB GS refers to an entry in the Kim et al. 1999 catalog of “giant shells” identified in the Kim et al. 1998 H i mosaic of the LMC.
Figure 6 shows the observed O\textsc{vi} column densities as a function of the relative H\textalpha surface brightness integrated over 6\textquoteleft 6 \times 6\textquoteleft 6 (100 \times 100 \text{pc}^2) regions surrounding the target stars. The range in H\textalpha surface brightness measurements is much larger than the range in O\textsc{vi} column densities.

The sight lines probing superbubbles and supergiant shells have O\textsc{vi} column densities quite similar to those projected onto more quiescent regions of the galaxy, and our derived O\textsc{vi} column densities have no observable relationship to the local H\textalpha intensity within the LMC. Thus, there is no evidence for large enhancements in the O\textsc{vi} column densities associated with large-scale structures or high levels of local star formation. As discussed in § 6, this is consistent with a scenario in which much of the observed O\textsc{vi} resides in an extended, but patchy, distribution such as a galactic “corona.”

4.2.2. Comparison with X-Ray Distribution

Hot ionized material in galaxies can also be revealed through observations of its X-ray emission. The general distribution of X-ray emission in the LMC has been studied with several instruments including the \textit{Einstein Observatory} (Wang et al. 1991) and ROSAT (Snowden & Petre 1994). These studies have discussed the observations in the context...
of the diffuse, hot ISM in the LMC. Many studies detailing various aspects of individual regions of the LMC have also been published. The most relevant for comparison with this work are recent summaries of X-ray emission from superbubbles (Dunne et al. 2001) and large-scale diffuse regions, including SGSs (Points et al. 2001). These works include discussions of diffuse X-ray emission from some of the structures (regions) probed by our absorption line measurements.

In general it is difficult to study the soft X-ray emission from the LMC given the relatively large foreground photoelectric opacity. Unfortunately, this is the wave band that is most likely to correspond to the material being traced by our O vi absorption-line measurements. However, the harder X-ray emission traces gas at relatively high temperatures ($10^6$–$10^7$ K), which will presumably cool through the temperatures ($\lesssim 3 \times 10^5$ K) at which O vi is expected to be most abundant. Therefore, one might expect at least a loose connection between these two tracers of hot ionized matter. Figure 7 shows the ROSAT PSPC mosaic of the LMC from Snowden & Petre (1994) with the O vi columns from this work displayed as in Figure 5. The X-ray mosaic makes use of the R4–R7 filters of the PSPC, which are sensitive to $\sim 0.5$–2.0 keV photons, and has been adaptively smoothed, as discussed in Snowden & Petre. This energy range is non-uniformly affected by photoelectric absorption by LMC and Milky Way gas. Point sources (e.g., X-ray binaries and background AGNs) have not been removed.

The main purpose of presenting this mosaic in comparison with our O vi measurements is to demonstrate that the sight lines probed in this work do not, in fact, probe regions of the LMC that are unusually X-ray bright. Our sample includes observations of a star projected onto the superbubble N144 and three sight lines projected onto the SGS LMC 4. Recent work on archival ROSAT PSPC data have shown that these regions do not have excessively high X-ray surface...
toward Sk/C0. The dashed line corresponds to a linear one-to-one relationship between the circles denote directions toward identified superbubbles (see Table 6). Each point correspond to the identifications listed in Tables 4 and 6. Open boxes) for the sight lines studied in this work. The numbers given beside <ray surface brightnesses were calculated for boxes 6

ROSAT keV PSPC surface brightness (averaged over 100 × 100 pc² (6/6 × 6/6) boxes) for the sight lines studied in this work. The numbers given beside each point correspond to the identifications listed in Tables 4 and 6. Open circles denote directions toward identified superbubbles (see Table 6). The dashed line corresponds to a linear one-to-one relationship between the O vi column density and X-ray surface brightness. Note that the sight line toward Sk –67°211 is not covered by the ROSAT mosaic and, therefore, is not represented in this figure. The lowest O vi column density is seen toward Sk –67°05 (no. 1). The continuum placement for this star is less certain than for the other objects (see Friedman et al. 2000).

Figure 8 shows the observed O vi column densities compared with the relative X-ray surface brightness from ROSAT (Snowden & Petre 1994) for each sight line. The X-ray surface brightnesses were calculated for boxes 6/6 (100 pc) on a side, centered on the star of interest. No correction for overlying photoelectric opacity has been made in deriving the X-ray brightnesses. A linear relationship of slope unity between the two data sets is shown with the dashed line in the plot. We note that if the lowest point is left out (representing the sight line toward Sk –67°05), this diagram becomes a scatter plot with no discernible relationship between the O vi column density and X-ray surface brightness measurements. Indeed, a Spearman rank-order correlation test (Press et al. 1992) cannot rule out the null hypothesis that the O vi columns and X-ray surface brightnesses are uncorrelated at the 2σ level. The significance of any correlation between the quantities is small. Given the very different way in which these measurements are made, the differing systematics to which they are subject, and the different gas traced by each approach, it would be surprising to find a significant correlation.

The four sight lines in our sample probing superbubbles are denoted with open circles in Figure 8, while the other sight lines are marked with filled circles. The superbubble sight lines have the highest four X-ray surface brightnesses, though their O vi column densities are not so easily separated from the other measurements. This may suggest that local effects are more important for determining the hard X-ray brightness than they are for determining the O vi column densities. However, the ROSAT “beam” is much larger than that probed by our absorption line measurements, and we do not know that the stars used as background probes do indeed lie behind the gas associated with the superbubbles.

5. GROSS KINEMATIC PROPERTIES OF O VI WITHIN THE LMC

Figure 3 demonstrates two items of note regarding the kinematics of the observed O vi absorption: (1) There is a large degree of variation in the observed kinematic profiles of the Milky Way/LMC absorption complex; and (2) Separating the Milky Way and LMC components is nontrivial in some cases. The identification of O vi absorption in the velocity range 150 km s⁻¹ ≤ v ≤ 200 km s⁻¹ with either of the two galaxies is particularly difficult. At lower velocities, profiles such as those seen toward Sk –66°100, Sk –67°69, and Sk –67°211 strongly suggest a Milky Way (including high- and intermediate-velocity cloud) origin. However, there is not easily identifiable separation between Milky Way and LMC absorption profiles such as those toward Sk –70°91 and Sk –67°20. This ambiguity between the absorption from the two galaxies makes it difficult to definitively discuss the kinematics of the absorption from the LMC. In particular, some of the material in this intermediate range could be caused by outflows from the LMC with velocities of ~100–150 km s⁻¹. If this is the case, it is an important aspect of the LMC O vi kinematics, although one that cannot be addressed by the current observations.

Even in the presence of such ambiguities, there is useful information on the kinematics of the LMC O vi within the observed absorption profiles. We discuss two particular aspects of the LMC O vi kinematics in this section: a comparison of the O vi velocity profiles with those of the lower ionization material traced by Fe ii; and the kinematic properties of the O vi in directions where there is a clear separation between the Milky Way and LMC absorption.

Figure 9 shows a comparison of the O vi λ1031.926 absorption line profiles (cleaned of H₂) with the Fe ii λ1125.448 profiles. The latter trace low-ionization gas associated with the relatively high column density warm neutral and warm ionized media in the Milky Way and LMC. Presumably most of the material in these cooler phases (~10³–10⁴ K gas) resides in or near the disk of each galaxy. Examining the Fe ii profiles, one can see clear signatures of Milky Way, intermediate- and high-velocity clouds (IVCs and HVCs), and LMC absorption. All of the sight lines in our sample show evidence for either IVC and/or HVC absorption. Though these components are not always readily visible in the Fe ii λ1125.448 profiles, the stronger Fe ii 1144.938 and O i 1039.230 A transitions show this to be the case (see the profiles presented in Danforth et al. 2002). The LMC often exhibits multiple components or complex absorbing structure. The stronger Fe ii 1144.938 A transition often shows much lower column density components that are not visible in the Fe ii λ1125.448 profiles.

The individual Fe ii components are more easily separated than those in the O vi profiles because the widths of typical Fe ii absorption complexes is significantly lower.
velocities in this direction, much of this effect could also be caused by the larger vertical extent of O vi compared with Fe ii.

Several sight lines show enough separation between the Milky Way and LMC O vi absorption that the detailed kinematic properties of the LMC absorption can be ascertained. We have fitted Gaussian components to the apparent optical depth profiles for several lines of sight, deriving the average velocity, breadth, and peak optical depth for the LMC absorption seen toward these stars. We assume that the LMC absorption can be approximated by a single Gaussian component. In most cases this gives a reasonable approximation to the observed absorption profiles. In these cases we have also fitted the Milky Way absorption to account for any minor blending with the LMC absorption. We do not report the Milky Way results here, particularly because there is a large degree of ambiguity when fitting the O vi profiles with multiple Gaussians.

The absorption profiles fitted in this way include those toward the stars Sk −67°69, Sk −66°100, Sk −67°211, and Sk −66°172. Further decomposition of the profile toward Sk −71°45 is discussed by Lauroesch et al. (2002, in preparation). The most important aspect of these fits is the derived dispersion of the LMC O vi absorption. For the sight lines listed we derive $\sigma = 37, 30, 41, \text{and } 48 \text{ km s}^{-1}$, respectively. The corresponding FWHM ($\Gamma$) values are $\Gamma = 87, 71, 96, \text{and } 113 \text{ km s}^{-1}$. This range of widths implies temperatures for the absorbing regions $T \leq 2 \times 10^5$ to $\leq 5 \times 10^5$ K. If the observed gas is closer to the temperature at which the abundance of O$^{+5}$ peaks in collisional ionization equilibrium ($T \approx 3 \times 10^5$ K), most of the observed breadths of these profiles must be caused by nonthermal broadening mechanisms, including turbulence, multiple velocity components, and large-scale dynamical effects.

Given the smoothness of the profiles observed at high signal-to-noise ratios, it seems likely that if this breadth is due to multiple absorbing components along the line of sight then several such components may be required.

Savage et al. (2002, in preparation) have measured the apparent breadths of the absorption from the O vi within the halo (or thick disk) of the Milky Way as seen toward a large number ($\sim 85$) of extragalactic sources. These authors find $\sigma = 16–65 \text{ km s}^{-1} (\Gamma \approx 37–153 \text{ km s}^{-1})$ with a median of $\sigma \approx 39 \text{ km s}^{-1}$. The observed breadths toward lower latitude sources may be affected by Galactic rotation, although many of their sight lines are at high enough Galactic latitudes that such effects are unimportant. The median breadth from these large number of measurements through the Galactic halo is essentially equivalent to that of the four LMC measurements (median $\sigma = 39 \text{ km s}^{-1}$). For comparison, Jenkins (1978) has discussed the breadths of nearby ($d \lesssim 1000 \text{ pc}$) disk O vi absorption as observed by Copernicus; he found an average dispersion of $\sigma \approx 29 \text{ km s}^{-1}$.

We have also fitted Gaussian profiles to the observed Fe ii absorption for the four sight lines listed above to determine the central velocities of the LMC Fe ii. Of interest in these cases is the relative difference between the average velocities of the O vi and Fe ii absorption. For this small sample of sight lines, we find that an average velocity difference, $\Delta v = v_{O\text{vi}} - v_{Fe\text{ii}} = -32 \text{ km s}^{-1}$. The central velocity of the O vi is on average shifted by $-32 \text{ km s}^{-1}$ relative to central velocity of the Fe ii along these lines of sight. Because the O vi is significantly broader than the Fe ii, much of the O vi absorption occurs at velocities significantly lower than the
bulk of the Fe ii absorption (which can be seen in Fig. 9). This average velocity separation may not be typical of all of the sight lines since we have examined only those directions that show a clear separation between the Milky Way and LMC O vi absorption.

We note that our observations cannot be used to test the existence of high-velocity outflows from the disk of the LMC. Material separated from the LMC disk velocity by \( v - v_{\text{disk}} \lesssim -75 \text{ km s}^{-1} \) is confused with Galactic ISM, IVC, and HVC absorption. In almost all of the sight lines there is O vi absorption at velocities shortward of the Fe ii absorption associated with the LMC disk (but longward of the \(+150 \text{ km s}^{-1}\) separation between LMC and HVC material). O vi absorption is usually not detected at positive velocities relative to the Fe ii from the LMC disk. The two exceptions to this are Sk -68°80 and perhaps Sk -70°91. The Fe ii profile toward the latter object shows several LMC components with similar strength, making the identification of the “disk” component somewhat ambiguous. Toward Sk -68°80 O vi absorption extends to velocities \(+60 \text{ km s}^{-1}\) higher than the Fe ii 1125.448 Å absorption. A very weak component can be seen in the Fe ii 1144.938 Å line at \( v \approx +275 \text{ km s}^{-1} \), though the bulk of the Fe ii absorption in this direction is centered at \( v \approx +240 \text{ km s}^{-1} \). The extended high positive velocity absorption seen in the O vi profile toward Sk -68°80 may be evidence for infalling material along this sight line. However, at least 10 of the 12 sight lines studied in this work reveal no such absorption, suggesting infalling highly ionized material is rare in the LMC.

6. DISCUSSION: THE HOT CORONA OF THE LMC

Our observations of interstellar O vi associated with the LMC reveal that this tracer of hot, collisionally ionized gas is present in relatively large quantities across the whole face of the LMC, though with a large degree of patchiness. Lines of sight projected onto superbubbles and supergiant shells have much the same column densities as lines of sight projected onto quiescent regions (as indicated by Hα emission). The velocity distribution of the LMC O vi absorption is significantly different than that of lower ionization gas (e.g., Fe ii), being both much broader and present at lower absolute velocities.

The average column density projected onto the plane of the LMC \( N_z \) is equivalent to that projected onto the plane of the Milky Way, as determined by measurements of the Galactic halo toward extragalactic sources (Savage et al. 2000). The dispersion in the measurements of \( N_z \) in the LMC and Milky Way is also the same. The kinematics of the highly ionized gas traced by O vi in the LMC seems to be very similar to that seen through the halo of the Milky Way, although our ability to accurately measure the kinematic profiles of the LMC absorption is limited.

There are several possible interpretations of these salient aspects of the LMC O vi absorption observed toward our sample of 12 stars. However, given the striking similarities between the properties of the LMC O vi and the Galactic halo O vi, the relatively small impact of superbubbles on the total O vi column densities, the existence of significant quantities of O vi along sight lines with little evidence for local sources of highly ionized material, and the general decoupling of the O vi kinematics from the disk material traced by Fe ii, we favor an interpretation in which the LMC O vi absorption arises in a vertically extended halo or corona similar to that seen about the Milky Way (see Savage et al. 2000).

6.1. Alternative Interpretations

Before exploring the O vi corona interpretation in more detail, it is worth mentioning alternatives to this scenario. Sembach et al. (2000) have presented observations of O vi in the HVC system surrounding the Galaxy. Most (if not all) sight lines that pass through known H i HVCs show O vi absorption, including the Magellanic Stream (MS), material tidally expelled from the LMC/SMC system. If the MS has a component projected between the Sun and the LMC, the observed O vi at LMC velocities (or at the IVC and HVC velocities) could be associated with this tidal structure. For this to be true, however, the ionization state of the Stream in these directions would be significantly different than other directions probing this structure (and than most other HVCs). Given that the observed Fe ii absorption can be associated with LMC disk material (see, e.g., Danforth & Chu 2000) and is typically centered well away from the center of the O vi absorption, relatively little low-ionization material could be associated with such a putative Stream component.

Another possibility is that the O vi absorption traces the interaction between the gaseous coronae of the LMC and Milky Way. The presence of O vi in the MS strongly suggests the Milky Way halo extends to the distance of that structure, which is roughly \( \sim 25-75 \text{ kpc} \) from the Sun (see the discussion by Sembach et al. 2000). It is therefore reasonable to expect that the Galactic corona extends to the 50 kpc distance \( (z \sim 25 \text{ kpc}) \) of the LMC. Interactions between the LMC corona (or other portions of this galaxy) with the low-density, highly ionized medium associated with the extended distribution of hot gas of the Milky Way could, in principle, provide for instabilities that cool the gas through the transition temperatures at which O^+^2 is abundant. (De Boer et al. [1998] have similarly suggested that the motion of the LMC through the Galactic halo can trigger star formation through the compression of LMC material along the leading edge of the LMC by the low-density Milky Way material.) Given the large number of unknowns regarding the structure of the ISM of the LMC and the extended Galactic halo, this model remains largely unconstrained. Unfortunately, at this point, it is difficult to falsify either of these alternative models.

6.2. The Origins of O vi in the Corona of the LMC

The scenario we prefer is one in which the O vi within the LMC is distributed within the thin disk as well as in a more vertically extended thick disk or halo of the LMC. Since our lines of sight probe large path lengths through the halo component, this dominates over material associated with the disk, in a manner analogous to observations of extragalactic sources from within the disk of the Milky Way (Savage et al. 2000). The presence of a possible corona about the LMC has been discussed in the literature for several years. Early observations of C iv absorption toward LMC stars with the IUE observatory revealed highly ionized material at velocities consistent with an LMC origin (Savage & de Boer 1979, 1981; de Boer, Koo H, & Savage 1980; de Boer & Savage 1980). The early IUE measurements of LMC material were interpreted as absorption from an extended hot
corona. That interpretation was subsequently called into question (Chu et al. 1994; Feitzinger & Schmidt-Kaler 1982) because of the strong possibility that the high ions observed were produced in the local environments of the observed stars. Wakker et al. (1998) used HST observations of C iv toward stars in quiescent regions of the LMC to argue that the LMC did indeed contain a highly ionized corona. The data to date, however, have been too sparse to firmly detail the properties of the highly ionized material in the LMC.

The O vi absorption in this coronal scenario traces material at relatively large distances from the disk that has been heated and ejected from the disk by some form of feedback between massive stars and the ISM. Most calculations suggest this requires the collective actions of multiple, correlated supernovae (particularly to raise the material far above the plane). There are several possible microphysical origins for the O vi within an extended corona about the LMC. Highly ionized halo gas may trace material cooling from higher temperatures through the transition temperatures (a few times $10^4$ K) at which O vi is abundant or material created in the interactions between cooler (e.g., $10^4$ K) and hotter (e.g., $>10^6$ K) gases (e.g., in conductive interfaces or turbulent mixing layers). These two broad types of models have significantly different predictions for the O vi columns through a hot corona. As such, the interpretation of the observed O vi column density depends upon which microphysical situation is most applicable. We discuss the details of each of these models below.

6.2.1. Radiative Cooling Models

Edgar & Chevalier (1986) have calculated the column densities of highly ionized species for gas cooling from temperatures $T \gtrsim 10^6$ K. They show that for cases where the cooling is dominated by metal line emission, the expected column density of O vi and the other high-ions is independent of metallicity. The expected column density of a metal ion, $Z'$, in a column of cooling material is $N(Z') \propto A_Z N_{\text{cool}}$, where $A_Z$ is the abundance of the element Z with respect to hydrogen, $N$ is the flux of cooling material (in ionized hydrogen atoms cm$^{-2}$ s$^{-1}$), and $t_{\text{cool}}$ is the cooling time. The cooling time is inversely proportional to the abundance of metals, making $N(Z') \propto 1/A_Z$ independent of $A_Z$. This is important for the LMC because the abundance of oxygen is $A_O \approx 2.2 \times 10^{-4}$ (Russell & Dopita 1992; see also Appendix of Welty et al. 1999), a factor of $\sim 2.5$ below the recently updated solar value of $A_O \approx 5.4 \times 10^{-4}$ (Holweger 2001).

Because $t_{\text{cool}} \propto n_{\text{HI}}^{-1}$, where $n_{\text{HI}}$ is the initial ionized hydrogen density of the cooling material, the column density of highly ionized metals in the radiatively cooling flows discussed by Edgar & Chevalier (1986) is proportional to $N/n_{\text{HI}}$, which, by conservation of mass, is simply a velocity, $v$. The Edgar & Chevalier calculations predict a column density of $N(\text{O} \text{ vi}) \approx 4 \times 10^{14}$ ($v/100$ km s$^{-1}$). This value is sensitive to the peak temperature from which the gas cools, which is assumed to be $1 \times 10^6$ K. If the peak temperature is $3 \times 10^6$ K, the column density is increased by a factor of $\sim 2$. Using the mean value of $N(\text{O} \text{ vi})$ from Table 5, the expected velocity associated with an Edgar & Chevalier–like flow is in the range $v \sim 30$–$60$ km s$^{-1}$. The lower portion of this range (which corresponds to higher initial cooling temperatures) is crudely consistent with the observed velocity separation between the O vi and Fe ii absorption.

Since models of radiatively cooling gas predict the column density of O vi to be independent of metallicity, they provide a natural explanation for the similarities between the values of $N_{\perp}$ in the Milky Way and the LMC. For the Edgar & Chevalier models, so long as the ratio $v \equiv N/n_{\text{HI}}$ is similar in the two systems, the column densities of the observed O vi absorption should also be similar.

In the context of a cooling flow like that described by Edgar & Chevalier (1986), the column density of O vi is related to the mass flow rate out of the disk, $M$:

$$M \approx (\mu m_H) n_{\text{HI}} \Omega \left(\frac{N}{n_{\text{HI}}}\right).$$

In this expression $\mu m_H$ is the mean mass per atom and $\Omega$ is the surface area of the flow region, which we take to be the disk of the LMC assuming a diameter of $\sim 7.3$ kpc, the diameter of the H 1 disk (Kim et al. 1998). For gas cooling under isobaric conditions from $1 \times 10^6$ K, Edgar & Chevalier find $N/n_{\text{HI}} \sim 2.5 \times 10^{6} [N_{\perp}(\text{O} \text{ vi})/10^{14} \text{ cm}^{-2}]$. These values yield an estimate for the mass-flow rate from the near side of the plane of the LMC:

$$\dot{M} \sim 1 \left(\frac{n_{\text{HI}}}{10^{-2} \text{ cm}^{-3}}\right) M_\odot \text{ yr}^{-1}. \quad (4)$$

The initial density of the cooling gas, $n_{\text{HI}}$, is an unknown. Points et al. (2001) estimate electron densities of the X-ray emitting gas in the range $n_e \gtrsim (0.3–2) \times 10^{-2} \text{ cm}^{-3}$ in their study of the X-ray emission from supergiant shells and diffuse gas in the LMC. Dunne et al. (2001) estimate electron densities of X-ray-emitting gas in LMC superbubbles in the range $n_e \gtrsim (1–10) \times 10^{-2} \text{ cm}^{-3}$. These estimates depend upon the assumed volume occupied by the X-ray–emitting material, and a filling factor of unity for the material is assumed (the predicted densities increase as the assumed filling factor decreases). The O vi column densities themselves can also be used to crudely estimate density limits for the hot ionized material. If we assume that the path length through LMC material probed by our observations is no greater than the 7.3 kpc diameter of the LMC assumed above, the average density of O vi ions is $\langle n_{\text{O vi}} \rangle \equiv N_{\perp}(\text{O} \text{ vi})/d \sim 10^{-3} \text{ cm}^{-3}$. This corresponds to average ionized hydrogen densities of $\langle n_{\text{HI}} \rangle \gtrsim 2 \times 10^{-4} \text{ cm}^{-3}$ assuming the fraction of oxygen in the form of O vi is at its maximum expected value of $\sim 0.2$ (Sutherland & Dopita 1992). The true density of ionized hydrogen in the O vi–bearing gas will likely be substantially larger since the fraction of space occupied by this material is likely to be small. We note, however, that the densities suggested by this crude treatment of the O vi column densities and the X-ray analyses (which are biased toward high-density material that is more likely to be in the plane of the LMC) probably bound the physical ionized hydrogen density in the O vi–bearing gas.

The estimated mass-circulation rate from the LMC is a factor of $\sim 10$ lower than the values typically estimated for the Milky Way assuming the same initial densities. The main cause of this difference is the much different surface areas assumed for the disks of the two galaxies. The mass-flow rate per unit area of the disk for the LMC is

$$\dot{M} \sim 2 \times 10^{-2} \left(\frac{n_{\text{HI}}}{10^{-2} \text{ cm}^{-3}}\right) M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}. \quad (5)$$
which should be closer to the Milky Way value for the same assumed densities.

6.2.2. Interface Models

Models in which the O \(\text{vi}\) ions occur in conductive interfaces or turbulent mixing layers (TMLs) make different predictions for the behavior of O \(\text{vi}\) column density with abundance. In the TML models, for example, the column density of O \(\text{vi}\) is related both to the specific properties of the mixing (e.g., the velocity shear and fraction of hotter material mixed into the turbulent layer) and the abundance of the oxygen in the material (Slavin, Shull, & Begelman 1993). Therefore, in these models, the similarity in the Galactic and LMC values of \(N_\text{vi}\) may simply be a coincidence dictated by the lower abundance of the latter modified by a greater amount of transition temperature material in the LMC compared with the Milky Way.

Increased amounts of gas in the O \(\text{vi}\)–producing temperature range may be related to different energy input into the ISM by massive stars (and their corresponding supernovae), or to differences in the interaction between hot and cool gas between the two galaxies (determined by unknown mechanisms, which may include the metallicity or differences in the magnetic fields). If we assume that the physics of the mixing between the galaxies is similar, the increased quantities of hot gas in the interface models requires a higher energy input into the ISM in the LMC compared with the Milky Way.

A larger local energy input from massive stars in the LMC has some observational support. Tumlinson et al. (2001) have studied the excitation and photodissociation of H\(_2\) in the LMC. Their models predict that the near-ultraviolet (NUV) flux per unit area of the LMC is a factor of \(\sim 10\) higher than in the solar neighborhood of the Milky Way. If the NUV radiation field in the LMC is taken to be an indicator of the current density of massive stars, then this would argue for a correspondingly larger kinetic energy input into the ISM in the LMC compared with the Milky Way.

Measures of the current star formation rate (SFR) and its surface density (which is more closely related to the energy input per unit area of the disk) also suggest the LMC should have a greater energy input into the ISM than the Milky Way. The SFR in the Milky Way is of order 2–5 \(M_\odot\) yr\(^{-1}\) (McKee & Williams 1997; McKee 1989; Mezger 1987), with average SFR per unit area of \((2–8) \times 10^{-3} M_\odot\) yr\(^{-1}\) kpc\(^{-2}\), depending on the adopted SFR and area over which the average is determined. For the LMC, the SFR is estimated to lie between 0.25 and 1 \(M_\odot\) yr\(^{-1}\) (Kennicutt et al. 1995 and Klein et al. 1989, respectively). The former measurement is derived from H\(\alpha\) observations while the latter is from the thermal component of radio continuum measurements. Given the probable effects of dust on the former, the higher value is somewhat preferred. Kim et al. (1998) determine that the bulk of the H\(\alpha\) column of the LMC (which should correspond to the bulk of the star formation) occurs within a disk of diameter \(\sim 7.3\) kpc. This implies a current SFR per unit area of \((6–24) \times 10^{-3} M_\odot\) yr\(^{-1}\) kpc\(^{-2}\) (with the higher value preferred). This also suggests a larger energy input per unit area in the LMC than in the local Milky Way, which would presumably lead to larger amounts of highly ionized gas.

Distinguishing between the radiatively cooling outflow and hot/cool gas interaction models as the origins of the observed O \(\text{vi}\) absorption will shed light on the structure and physics of a putative corona about the LMC and about the dependence of the feedback efficiency in galaxies on metallicity and stellar energy input. However, the current observations give little leverage for rejecting either class of models. The ratios of highly ionized atoms in the gas can discriminate between pure radiatively cooling and TML-type models (see Spitzer 1996). Currently there are few reliable observations of the other high-ion transitions (e.g., of C \(\text{iv}\), Si \(\text{iv}\), or N \(\text{v}\)) in the LMC. Bomans et al. (1996) have presented \textit{HST} observations of C \(\text{iv}\) toward two stars projected within LMC 4, while Wakker et al. (1998) have presented \textit{HST} observations of C \(\text{iv}\) absorption seen toward five stars within the “field.” None of these objects are included in the current sample of \textit{FUSE} observations.

6.3. Kinematics of the LMC Corona

The kinematic profiles of Fe \(\text{ii}\) and O \(\text{vi}\) along the sight lines in this work suggest that the O \(\text{vi}\) is kinematically decoupled from the thin interstellar disk of the LMC. The O \(\text{vi}\) is, on average, observed to be centered at velocities \(\sim -30\) km s\(^{-1}\) from the Fe \(\text{ii}\) centroids. There are two straightforward explanations for this kinematic offset of the O \(\text{vi}\) to more negative velocities: (1) rotation of a thickened disk or halo and (2) outflow of highly ionized material from the thin disk. Both of these explanations are compatible with our interpretation of the observed O \(\text{vi}\) properties of the LMC, i.e., that the O \(\text{vi}\) is indeed tracing a widely distributed thick disk or halo of hot material.

A thickened disk of hot material that roughly rotates with the underlying thin interstellar disk of the LMC could produce the observed kinematic differences between the O \(\text{vi}\) and the Fe \(\text{ii}\). The ray from the Earth to a star in the disk of the LMC intersects the thin disk (traced by Fe \(\text{ii}\) absorption) at essentially only the location of the star; however, because it is vertically extended, the hot material (traced by O \(\text{vi}\) absorption) is sampled over a greater range of radial positions within the galaxy. Under the assumption of approximate corotation of disk and halo gas, this implies the O \(\text{vi}\) absorption will be observed over a greater range of velocities. In particular, assuming the H \(\text{i}\) velocity field (Kim et al. 1998) traces the rotation of the thin interstellar disk, the O \(\text{vi}\) is expected to occur at velocities generally lower than the Fe \(\text{ii}\) in such a scenario. The maximum velocity of the O \(\text{vi}\) should be approximately equal to that expected of the thin disk at the position of the star, i.e., equal to the central velocity of the Fe \(\text{ii}\) absorption. This is consistent with the velocity structure seen in Figure 9 (with a few exceptions).

A low-velocity outflow of highly ionized material from the disk of the LMC could also explain the observed kinematic differences between the O \(\text{vi}\) and Fe \(\text{ii}\) absorption profiles. If we assume that the outflow is purely perpendicular to the plane of the LMC, then the outflow velocity is \(v_\perp \equiv \Delta v \sec i\), where \(\Delta v\) is the observed outflow velocity and \(i\) is the inclination of the LMC from the plane of the sky. Our observations then imply \(\langle v_\perp \rangle \sim 40\) km s\(^{-1}\). The outflow of material from the disk is predicted in all models for the production of an interstellar galactic corona or thick disk. However, it is not clear whether one expects to observe O \(\text{vi}\) associated with the outflow or the subsequent infall of material in various models. Models that produce O \(\text{vi}\) in radiatively cooling material require that the material ejected from the disk cool sufficiently from the very high temperatures at
which the gas originates to temperatures where O \text{ vi} is expected to be abundant. The observation of O \text{ vi} in the outflowing material of a fountain flow would imply that the cooling time of the material was less than or of the order the sound crossing time of the halo (Houck & Bregman 1990). If the cooling time is sufficiently long (e.g., for low densities or very high initial temperatures), cooling through the temperatures at which O \text{ vi} is abundant will not occur until the material ejected from the disk reaches its highest point and begins to infall.

For all of the sight lines probed by our observations there is O \text{ vi} absorption at velocities that could imply the outflow of highly ionized (O \text{ vi}–bearing) gas from the thin disk of the LMC. However, in only two cases (toward Sk $-68^\circ80$ and Sk $-70^\circ91$) is there O \text{ vi} absorption at velocities that might imply the infall of highly ionized material. If a large-scale circulation of material through a corona about the LMC is occurring the majority of the gas must cool in the outflow phase of the circulation. We note that the velocities of the observed O \text{ vi} absorption are low enough relative to the disk of the LMC that the material will not escape the galaxy altogether.

7. SUMMARY

We have presented observations of 12 early type stars within the Large Magellanic Cloud obtained with the FUSE observatory. These observations reveal strong absorption from interstellar O \text{ vi} within the LMC. The main conclusions of our work are as follows.

1. Strong interstellar O \text{ vi} at LMC velocities is present along all of the sight lines studied in this work. The observed stars probe a range of interstellar environments from stars within supernovae shells or superbubbles (e.g., Sk $-71^\circ45$, Sk $-68^\circ80$) to those in the field (e.g., Sk $-67^\circ20$, Sk $-67^\circ05$). A wide range of kinematic profiles for O \text{ vi} within the LMC is also observed.

2. The column density of interstellar O \text{ vi} at LMC velocities ranges from $\log N(\text{O \text{ vi}}) = 13.9$ to $14.6$ in atoms cm$^{-2}$ with a mean of $\log \langle N(\text{O \text{ vi}}) \rangle = 14.37$ (with a dispersion of $\sim 40\%$). The average column density projected perpendicular to the disk of the LMC is $\log \langle N(\text{O \text{ vi}}) \rangle = 14.29$, which is identical to the value derived from observations of the Milky Way halo even though the metallicity of the LMC is $\sim 2.5$ times lower than that of the Milky Way. The dispersions of the individual $N(\text{O \text{ vi}})$ measurements about the mean for each galaxy are also indistinguishable.

3. While our observations probe several sight lines projected onto superbubbles or other large-scale structures, any enhancements in the O \text{ vi} column densities over those observed for field stars are minor ($\lesssim 50\%$–$100\%$). The column density variations over the smallest scales probed by our observations ($\sim 450$–$510$ pc) are the same as those seen between sight lines toward and away from large-scale structures. Thus there is little evidence for enhanced O \text{ vi} column densities toward superbubbles or other large-scale structures.

4. The average velocities of the LMC O \text{ vi} absorption are different than those of the Fe \text{n} absorption, which traces low-ionization material associated with the disk of the LMC. The O \text{ vi} velocities are on average shifted by $\sim -30$ km s$^{-1}$ from the peak low-ionization absorption. This systematic displacement of the O \text{ vi} to lower velocities may be the signature of a low-velocity outflow from the disk or of a rotating thickened disk.

5. Our measurements are not able to test for the existence of high negative velocity O \text{ vi} in the LMC because of the overlap of Milky Way, IV C, HVC, and LMC absorption. The observations of all of the sight lines considered here are consistent with the presence of O \text{ vi} outflowing from the LMC disk at relatively low velocities ($< 75$ km s$^{-1}$). Material at positive velocities relative to the LMC disk, which could trace infalling material, is only allowed along the sight lines toward Sk $-68^\circ80$ and possibly Sk $-70^\circ91$. The former sight line shows gas which may be infalling at velocities $\sim 70$ km s$^{-1}$ relative to the LMC disk.

6. The velocity dispersion of the O \text{ vi} absorption is much greater than that of Fe \text{n} and other low-ionization species seen along the same lines of sight. The former is difficult to measure due to overlap between Milky Way and LMC absorption along many sight lines, but where measurable gives Gaussian dispersions of $\sigma \sim 30$–$50$ km s$^{-1}$. These breadths are much broader than the expected thermal broadening ($\sigma_{\text{thermal}} \sim 12$ km s$^{-1}$ for $T \sim 3 \times 10^5$ K), suggesting the presence of several absorbing components within the LMC O \text{ vi} profiles.

7. We discuss the observed properties of interstellar LMC O \text{ vi} in the context of a galactic “halo” or “corona” similar to that of the Milky Way. The striking similarity in the O \text{ vi} columns and variations and in the observed velocity dispersions between the LMC absorption and that observed in the halo of the Milky Way motivate such a model. The observations are consistent with models of radiatively cooling galactic fountain flows, although turbulent mixing layers and other types of interfaces are not ruled out. The radiatively cooling fountain scenario is attractive since the predicted column density of O \text{ vi} is not dependent on the metallicity of the cooling material.

8. If the O \text{ vi} is produced in a galactic fountain flow, then the mass flow from one side of the disk of the LMC is estimated to be $M \sim 1 M_{\odot}$ yr$^{-1}$, or alternatively, the mass flow rate per unit area of the disk is estimated to be $M/\Omega \sim 2 \times 10^{-2}$ $M_{\odot}$ yr$^{-1}$ km$^{-2}$. The cooling of this ejected material occurs before the gas begins to return to the disk. The average density of ionized hydrogen associated with the O \text{ vi}–bearing gas likely exceeds $n_{\text{H}^+} \gtrsim 2 \times 10^{-4}$ cm$^{-3}$; studies of X-ray emission in the LMC suggest $n_{\text{H}^+} \sim 10^{-2}$ cm$^{-3}$, though this may sample denser gas than the O \text{ vi}–bearing material. Better estimates of the physical state of the gas could be made with O \text{ vi} emission line measurements toward the sight lines probed by our absorption line measurements.

We thank J. Gaustad and collaborators for the use of their H$\alpha$ image of the LMC. This image is from the Southern H-Alpha Sky Survey Atlas (SHASSA), which is supported by the National Science Foundation. We also thank Y.-H. Chu for help with the ROSAT X-ray mosaic. This work is based on data obtained for the Guaranteed Time Team by the NASA-CNES-CSA FUSE mission operated by the Johns Hopkins University. Financial support to US participants has been provided by NASA contract NAS 5-32985. J. C. H. and K. R. S. also recognize support from NASA Long Term Space Astrophysics grant NAG 5-3485 through the Johns Hopkins University.
REFERENCES

Bomans, D. J., de Boer, K. S., Koornneef, J., & Grebel, E. K. 1996, A&A, 313, 101
Bregman, J. N. 1980, ApJ, 236, 577
Brinks, E., & Bajaja, E. 1986, A&A, 169, 14
Chu, Y.-H., Wakker, B. P., Mac Low, M.-M., & García-Segura, G. 1994, ApJ, 408, 1696
Conti, P. S., Garmann, C. D., & Massey, P. 1986, AJ, 92, 48
Crowther, P. A., & Smith, L. J. 1997, A&A, 320, 500
Danforth, C. W., & Ercolani, F. Y.-H. 2000, ApJ, 552, L155
Danforth, C. W., Houck, J. C., Fullerton, A. W., Blair, W. P., & Sembach, K. R. 2002, ApJS, 138, 81
Davies, R. D., Elliott, K. H., & Meaburn, J. 1976, MmRAS, 81, 89
De Avillez, M. A. 2000, MNRAS, 315, 479
De Boer, K. S., Braun, J. M., Vallenari, A., & Mebold, U. 1998, A&A, 329, 49
De Boer, K. S., Koornneef, J., & Savage, B. D. 1980, ApJ, 236, 769
De Boer, K. S., & Savage, B. D. 1980, ApJ, 238, 86
Deul, E. R., & den Hartog, R. H. 1990, A&A, 229, 362
Dunne, B. C., Points, S. D., & Chu, Y.-H. 2001, ApJS, 136, 119
Edgar, R. J., & Chevalier, R. A. 1986, ApJ, 310, 506
Feitzinger, J. V., & Schmidt-Kaler, Th. 1982, ApJ, 257, 457
Friedman, S. D., et al. 2000, ApJ, 538, L31
Garmany, C. D., & Walborn, N. R. 1987, PASP, 99, 240
Gaustad, J. E., McCullough, P. R., Rosing, W., & Van Buren, D. 2001, PASP, 113, 1326
Graefener, G., Hamann, W.-R., Hillier, D. J., & Koesterke, L. 1998, A&A, 329, 190
Heiles, C. 1990, ApJ, 345, 483
Henize, K. G. 1956, ApJS, 2, 135
Hofmeister, C. M. 1991, in Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (Melville: AIP), 23
Houck, J. C., & Bregman, J. N. 1990, ApJ, 352, 506
Jenkins, E. B. 1978, ApJ, 220, 107
Kennicutt, R. C., Bresolin, F., Bomans, D. J., Bothun, G. D., & Thompson, I. B. 1995, AJ, 118, 2797
Kim, S., Dopita, M. A., & Staveley-Smith, L., & Bessell, M. S. 1999, AJ, 118, 280
Klein, U., Wielebinski, R., Haynes, R. F., & Malin, D. F. 1989, A&A, 211, 128
Koesterke, L., Hamann, W.-R., Schmutz, W., & Wessolowski, U. 1992, A&A, 248, 166
Lamers, H. J. G. L. M., & Cassinelli, J. P. 1999, Introduction to Stellar Winds (Cambridge: Cambridge Univ. Press)
Lehner, N., Fullerton, A. W., Sembach, K. R., Massa, D. L., & Jenkins, E. B. 2001, ApJ, 556, L103
Leitherer, C. 1988, ApJ, 334, 626
Mac Low, M.-M., & McCray, R. 1988, ApJ, 324, 776
Massa, D., Prinja, K. P., & Fullerton, A. W. 1995, ApJ, 452, 842
McKee, C. F. 1989, ApJ, 345, 782
McKee, C. F., & Williams, J. P. 1997, ApJ, 476, 144
Mezger, P. G. 1987, in Starbursts and Galaxy Evolution, ed. T. X. Thuan, T. Montmerle, & J. Tran Thanh Van (Paris: Editions Fronti`eres), 3
Moos, H. W., et al. 2000, ApJ, 538, L1
Norman, C. A., & Ikeuchi, S. 1989, ApJ, 345, 372
Oegerle, W. R., Murphy, E. M., & Kriss, G. A. 2000, The FUSE Data Handbook (Baltimore: Johns Hopkins Univ.)
Oey, M. S. 1996, ApJ, 467, 666
Patriarchi, P., & Perinotto, M. 1992, A&A, 258, 285
Points, S. D., Chu, Y.-H., Snowden, S. L., & Smith, R. C. 2001, ApJS, 138, 99
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C: The Art of Scientific Computing (Cambridge: Cambridge Univ. Press)
Prinja, R. K., & Crowther, P. A. 1998, MNRAS, 300, 828
Puche, D., Westpfahl, D., Brinks, E., & Roy, J.-R. 1992, AJ, 103, 1841
Puls, J., Owocki, S. P., & Fullerton, A. W. 1993, A&A, 279, 457
Russell, S. C., & Dopita, M. A. 1992, ApJ, 384, 508
Sahnow, D., et al. 2000, ApJ, 538, L7
Savage, B. D., & Sembach, K. R. 2000, ApJ, 538, L27
Savage, B. D., & de Boer, K. S. 1979, ApJ, 230, 177
———. 1981, ApJ, 243, 460
Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245
Sembach, K. R. 1999, in ASP Conf. Ser. 166, Stromlo Workshop on High-Velocity Clouds, ed. B. K. Gibson & M. E. Putman (San Francisco: ASP), 243
Sembach, K. R., & Savage, B. D. 1992, ApJS, 83, 147
Sembach, K. R., et al. 2000, ApJ, 538, L31
Slavin, J. D., Shull, J. M., & Begelman, M. C. 1993, ApJ, 407, 83
Smith, L. F., Shara, M. M., & Moffat, A. F. J. 1990, ApJ, 358, 229
———. 1999, MNRAS, 281, 163
Smith, R. C. 1999, in IAU Symp. 190, New Views of the Magellanic Clouds, ed. Y.-H. Chu, N. Suntzeff, J. Hesser, & D. Bohlender (San Francisco: ASP), 28
Snowden, S. L., & Petre, R. 1994, ApJ, 436, 123
Sutherland, W., & Dopita, M. A. 1993, 88, 253
Spitzer, L. 1996, ApJ, 458, L29
Tumlinson, J., et al. 2001, ApJ, submitted
Welty, D. E., Frisch, P. C., Sonneborn, G., & York, D. G. 1999, ApJ, 512, 636
Westerlund, B. E. 1997, The Magellanic Clouds (Cambridge: Cambridge Univ. Press)
Yan, Z.-C., Tambasco, M., & Drake, G. W. F. 1998, Phys. Rev. A, 57, 1652