Probing the Extended Gaseous Regions of M31 with Quasar Absorption Lines

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ABSTRACT

We present Hubble Space Telescope - Cosmic Origins Spectrograph spectra of ten quasars located behind M31, selected to investigate the properties of gas associated with its extended disk and high velocity clouds (HVCs). The sightlines have impact parameters ranging between \( b = 13 \) kpc and 112 kpc. No absorption is detected in the four sightlines selected to sample any extended disk (or halo) gas that might be present in the outer regions of M31 beyond an impact parameter of \( b > 57 \) kpc. Of the six remaining sightlines, all of which lie at \( b < 32 \) kpc and within the \( N_{\text{HI}} = 2 \times 10^{18} \) cm\(^{-2}\) boundary of the H\(_{\text{I}}\) disk of M31, we detect low-ionization absorption at M31 velocities along four of them (three of which include Mg\(_{\text{II}}\) absorption). We also detect Mg\(_{\text{II}}\) absorption from an HVC. This HVC sightline does not pass through the 21 cm disk of M31, but we detect additional Mg\(_{\text{II}}\) absorption at velocities distinct from the HVC that presumably arises in the halo. We find that along sightlines where both are detected, the velocity location of the low-ion gas tracks the peak in 21 cm emission. High-ionization absorption is detected along the three inner sightlines, but not along the three outer sightlines, for which C\(_{\text{IV}}\) data exist.

As inferred from high-resolution 21 cm emission line maps of M31’s disk and extended regions, only one of the sightlines may be capable of harboring a damped Ly\(\alpha\) system, i.e., with \( N_{\text{HI}} \geq 2 \times 10^{20} \) cm\(^{-2}\). This sightline has impact parameter \( b = 17.5 \) kpc, and we detect both low- and high-ion absorption lines associated with it.

The impact parameters of our observed sightlines through M31 are similar to the impact parameters of galaxies identified with Mg\(_{\text{II}}\) absorbers at redshifts \( 0.1 < z < 1.0 \) in a 2011 study by Rao et al. However, even if we only count cases where absorption due to M31 is detected, the Mg\(_{\text{II}}\) \( \lambda 2796 \) rest equivalent width values are significantly smaller. In comparison, moderate-to-strong Mg\(_{\text{II}}\) absorption from Milky Way gas is detected along all ten sightlines. Thus, this study indicates that M31 does not present itself as an absorbing galaxy which is typical of higher-redshift galaxies inferred to give rise to moderate-strength quasar absorption lines. M31 also appears not to possess an extensive large gaseous cross section, at least not along the direction of its major axis.

Key words: galaxies: individual: M31 - quasars: absorption lines

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1 INTRODUCTION

The standard paradigm for metal-line absorption systems in quasar spectra is that they arise in the extended gaseous halos/disks of galaxies well beyond their observable optical radii. However, with the exceptions afforded by gravitationally-lensed quasars, rarely is there more than one sightline passing in the vicinity of a galaxy. As such, the study of quasar absorption lines arising in extended gas associated with the great spiral galaxy in Andromeda (M31) represents a unique opportunity. M31’s large extent on the sky means that many quasar sightlines should intercept its extended gas. For example, the $N_{HI} = 1.9 \times 10^{18}$ atoms cm$^{-2}$ 21 cm emission contour around M31, as derived from the data discussed by Thilker et al. (2004), is approximately 5.0 $\times$ 1.5 square degrees on the sky (see Figure 1). We list some properties of M31 in Table 1. Quasar surveys have shown that there are as many as 18 quasars per square degree brighter than $R_{opt} = 20$ at $z < 2.6$ (Richards et al. 2009, Abraham et al. 2012). Thus, there are likely to be on the order of 135 such quasars behind M31 within the boundaries of its observed 21 cm emission, and a factor of several more in its extended gaseous disk and halo regions. However, until now, quasar absorption lines have never been successfully used to study the extended gas of M31 because of the lack of sufficiently-bright, identified quasars.

Two of the most recognizable signatures of metal lines in quasar spectra are the Mg II $\lambda\lambda$2796,2803 and C IV $\lambda\lambda$1548,1550 doublets, which have been studied in numerous quasar absorption-line surveys. The first comprehensive study which demonstrated that galaxies at large impact parameters exist along the sightlines to low-redshift Mg II absorbers was by Bergeron and collaborators, e.g., Bergeron & Boissé (1991). They estimated that the average Mg II radius of a spherical gaseous envelope surrounding an $L^*$ galaxy is $R^* \sim 3.5 \times 5.0 R_H(\sim 55 \text{ to } 80 \text{ kpc})$ at $z \sim 0.3$ for rest equivalent widths $W_{0,2796}^{\lambda\lambda} \gtrsim 0.3 \text{ Å}$, where $R_H$ is the Holmberg radius. Others had made similar estimates (e.g., Lanzetta et al. 1987, Lanzetta & Bowen 1990, Steidel 1993). The recent survey of galaxies associated with Mg II absorbers at $0.1 < z < 1.0$ by Rao et al. (2011) showed that the gaseous extent of Mg II-selected absorbing galaxies could be as large as 100 kpc. At $z < 0.5$, Chen et al. (2010) find that the mean covering fraction for Mg II absorbers with $W_{0,2796}^{\lambda\lambda} \gtrsim 0.3 \text{ Å}$ within $\sim 130 \text{ kpc}$ of a 2$L^*$ galaxy (for $h = 0.7$) is $\sim 70\%$. Therefore, if cross sections have remained constant since $z \sim 0.5$, then we might expect that gas giving rise to Mg II is likely to be present in the extended gaseous regions of M31 out to a radius of $\sim 100 \text{ kpc}$ or more, assuming it is a typical absorbing galaxy.

As described in §2, we obtained Hubble Space Telescope (HST) - Cosmic Origins Spectrograph (COS) spectra of ten quasars located behind M31 in order to investigate the properties of the gas in its extended disk and high velocity clouds (HVCs). We searched for Mg II, C IV, and other absorption lines to do this. In §3 we describe the results obtained from each spectrum. We discuss the results in §4 and end with a summary and conclusions in §5. This study indicates that M31 does not present itself as an absorbing galaxy which is typical of the higher-redshift galaxies inferred to give rise to moderate-strength quasar absorption lines.

### Table 1. M31 properties

| Property | Value | Reference$^a$ |
|----------|-------|---------------|
| RA (2000) | 00$^b$42$^m$44$^s$ | 1 |
| Dec (2000) | $+41^\circ 16' 08''$ | 1 |
| Distance | 752 $\pm$ 27 kpc | 2 |
| Inclination | 78$^\circ$ | 3 |
| $v_{sys}$ | $\sim$ 306 km/s | 3 |
| $R_{opt}$ | 22.3 kpc | 4 |
| $m_B$ | 4.16 | 4 |
| $L_B$ | $2.0L_B^*$ | 4,5 |
| $R_{21cm}$ | 33 kpc | 3 |
| $M_{virial}$ | $0.8 - 1.1 \times 10^{12}M_\odot$ | 6 |

$^a$References: 1. Evans et al. (2010); 2. Riess et al. (2012); 3. Corbelli et al. (2010); 4. de Vaucouleurs et al. (1991); 5. Cood et al. (2012); 6. Tamm et al. (2012)

$^b$Optical radius at $B$-band surface brightness $\mu_B = 25 \text{ magnitudes per square arcsec}$.

$^c$Assuming $M_B^* = -19.92$ (Cool et al. 2012).

$^d$From the $N_{HI} = 1.9 \times 10^{18}$ atoms cm$^{-2}$ contour (Figure 1).

2 OBSERVATIONS

2.1 Existing H I: 21 cm Emission Observations

Since M31 is the nearest large spiral galaxy close to the Milky Way, it has been the subject of many observational studies. Specifically for this work, we will make reference to several results over the past decade from radio observational studies of M31’s H I 21 cm emission. These are: the Green Bank Telescope (GBT) study of Thilker et al. (2004), which identified high-velocity clouds (HVCs) but at lower spatial resolution than later studies; the Westerbork Synthesis Radio Telescope (WSRT) study of Braun and Thilker (2004) which discovered the M31-M33 H I bridge, and of Westmeier et al. (2005), which focused on obtaining higher spatial resolution observations of HVCs; the WSRT study of Braun et al. (2009), which obtained observations over a wide field at high spatial resolution; and the study of Corbelli et al. (2010), which smoothed the data to lower spatial resolution in order to fit a tilted-ring model to M31’s warped disk and study its rotation curve. At some level, all of this work was collaborative by various members of the same group, and in later studies they made use of results that could be derived from earlier data sets.

H I emission spectra were extracted from the Thilker et al. (2004) and Braun et al. (2009) datacubes along the sightlines toward our target quasars. These data, originally in units of Jy/beam, were converted to $N_{HI}$ under the assumption of negligible H I opacity. This conventional assumption, while recently questioned by Braun et al. (2009) and Braun (2012) in the dense gaseous environment of the traditional optical disk and slightly beyond, is expected to be satisfied in the outer disk and halo environment. A more significant concern regarding the $N_{HI}$ from observations of emission is the vastly different scale probed by the GBT and WSRT relative to COS. The maximum linear spatial resolution of the high resolution 21 cm observations is $\sim 50 - 100 \text{ pc}$ at the distance of M31. This scale is of order $\sim 10^3$ times larger than the linear spatial scale sampled in quasar “pencil-beam”
absorption-line observations, where the pencil-beam has the scale of the UV continuum emitting region of the background quasar. Thus, \( N_{HI} \) values derived from 21 cm emission observations are averaged over a much larger spatial scale in comparison to those derived from quasar absorption-line spectra. Nevertheless, using 21 cm observations to derive average \( N_{HI} \) values along our sightlines, and noting the velocity range of detected emission, provides some important information.

As an aside, we note that it would be interesting if \( N_{HI} \) results derived from M31’s 21 cm emission data could someday be compared with \( N_{HI} \) determinations from Lyman series absorption seen in the UV spectra of background quasars. One could then get an H I column density measurement averaged over less than a milli-parsec region in M31, in comparison to the \( \sim 50 \) pc linear spatial scale offered by the radio observations. This would provide information on the homogeneity and size scale of H I absorbing regions in M31.

2.2 Optical Discovery Spectra of Quasars behind M31

We started this project by developing a list of quasars in especially desirable locations (see below) relative to M31. These were initially quasar candidates, since existing catalogs generally did not include quasars behind M31. The quasar candidates were selected from special plates of the SDSS, which were obtained specifically to find quasars behind the extended regions of M31 (Adelman-McCarthy et al. 2006). Of the 219 candidates, 108 were confirmed as quasars. Twenty-three of the 108 were spectroscopically confirmed during our October 2003 NOAO 2.1 m Gold Camera run at Kitt Peak. To make follow-up observations with HST-COS (§2.3 and §3) more feasible, we concentrated on finding brighter quasars. We also focused our search behind M31’s extended major axis to probe possible disk gas that could sample its outer rotation curve. See Figures 1 and 2, and Tables 1 and 2, for information on their locations relative to M31 and the discovery spectra. Quasars labeled 1 through 4 would sample any extended disk gas (or possibly halo gas) that is undetected in 21 cm emission; quasars 5, 6, 8, and 9 lie near the edge of detected 21 cm emission; the sightline towards quasar 7 passes through a high velocity cloud (HVC) in the circumgalactic environment of M31; and quasar 10 lies behind the 21 cm emission H I disk as well as two other HVCs. Importantly, owing to M31’s systemic velocity of \(-306 \) km s\(^{-1}\) (Corbelli et al. 2010) and its direction of rotation, absorption originating on the southwest side of M31 will not be confused with Galactic absorption. Consequently, quasars 1 through 4 offer the best opportunities for observing extended disk gas and measuring M31’s rotation curve much farther out than possible with 21 cm emission observations. Unfortunately, while obtaining information on M31’s rotation curve at large galactocentric distance was one of the primary motivations for observing quasars 1 through 4, no M31 absorption near the expected velocity was detected in their UV spectra (§2.3 and §3). We note, however, that higher quality observations might yet be able to detect gas at these locations. Observing quasars on the extended northeast side of M31 was avoided because of potential confusion with Galactic absorption.

2.3 HST-COS UV Spectroscopy

The HST-COS spectroscopic data were obtained during the period July-October 2010. Table 2 gives details of the quasars and the HST-COS observations. We decided to make a broad initial absorption-line survey in order to maximize the observed number of metal-line transitions we could reasonably cover within our allocation of 39 HST orbits. The aim was to reach a signal-to-noise ratio which would enable us to detect Mg II and C IV absorption rest equivalent widths commonly seen in prior, large moderate-resolution quasar absorption-line surveys. Therefore, we did not use higher-resolution COS gratings. However, it would indeed be worthwhile to perform follow-up spectroscopy of a number of our detections at higher spectral resolution and signal-to-noise ratios.

The COS gratings used in this study along each sightline are specified in Table 2. The near ultraviolet (NUV) G230L grating has a resolution of 2 pixels or \( \sim 0.82 \) Å at the wavelength of the Mg II \( \lambda \lambda 2796,2803 \) doublet, which corresponds to \( \sim 87 \) km s\(^{-1}\) on a velocity scale. The far ultraviolet (FUV) G140L grating has a resolution of 7 pixels or \( \sim 0.55 \) Å at the wavelength of the C IV \( \lambda \lambda 1548,1550 \) doublet, which corresponds to \( \sim 106 \) km s\(^{-1}\). Given the redshifts of the quasars, we should note that in certain wavelength regions there is the possibility of contamination by Lyα forest absorption. For example, Lyα forest absorption would potentially be visible near any Galactic or M31 Mg II absorption when the quasar’s redshift is higher than \( z_{em} \sim 1.3 \) (i.e., in quasar 4) and near any Galactic or M31 C IV absorption when the quasar’s redshift is higher than \( z_{em} \sim 0.27 \) (i.e., in all quasars except quasar 9). However, according to Weymann et al. (1998), the incidence of Lyα forest absorption lines with rest equivalent widths \( \geq 0.24 \) Å at these relatively low redshifts is typically only about one line per 30 Å (about one line per 3200 km s\(^{-1}\)), so we did not necessarily anticipate too much confusion due to overlapping Lyα forest absorption. There might also be overlapping absorption due to unidentified metal-line systems. In §3 we note instances where Lyα forest absorption or other overlapping unidentified absorption appears to be a confusing factor.

Seven quasars were observed with both the NUV and FUV gratings, while three were targeted with the NUV grating alone. These three had low FUV fluxes based on the GALaxy Evolution eXplorer (GALEX) telescope measurements, and so they were not observed. The NUV grating covers Fe II, Mn II, Mg II and Mg I transitions, while the FUV grating covers C IV, Si IV and several lower-ion transitions, as described in §3.

Pipeline flux-calibrated and wavelength-calibrated spectra were used for all the measurements, and no additional calibrations or re-calibrations were carried out. The wavelength scale is heliocentric, and measured velocity offsets relative to a transition of interest are made on a velocity scale. The far ultraviolet (FUV) G140L grating has a resolution of 7 pixels or \( \sim 0.55 \) Å at the wavelength of the C IV \( \lambda \lambda 1548,1550 \) doublet, which corresponds to \( \sim 106 \) km s\(^{-1}\). Given the redshifts of the quasars, we should note that in certain wavelength regions there is the possibility of contamination by Lyα forest absorption. For example, Lyα forest absorption would potentially be visible near any Galactic or M31 Mg II absorption when the quasar’s redshift is higher than \( z_{em} \sim 1.3 \) (i.e., in quasar 4) and near any Galactic or M31 C IV absorption when the quasar’s redshift is higher than \( z_{em} \sim 0.27 \) (i.e., in all quasars except quasar 9). However, according to Weymann et al. (1998), the incidence of Lyα forest absorption lines with rest equivalent widths \( \geq 0.24 \) Å at these relatively low redshifts is typically only about one line per 30 Å (about one line per 3200 km s\(^{-1}\)), so we did not necessarily anticipate too much confusion due to overlapping Lyα forest absorption. There might also be overlapping absorption due to unidentified metal-line systems. In §3 we note instances where Lyα forest absorption or other overlapping unidentified absorption appears to be a confusing factor.

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Pipeline flux-calibrated and wavelength-calibrated spectra were used for all the measurements, and no additional calibrations or re-calibrations were carried out. The wavelength scale is heliocentric, and measured velocity offsets relative to a transition of interest are made on a velocity scale. Before making absorption-line measurements, the FUV spectra were re-binned to two pixels per resolution element and all spectra were normalized using an interactive algorithm which fitted splines to a quasar’s observed continuum plus broad emission lines to derive a pseudo-continuum.

1 Parallel imaging data were also obtained. These will be discussed in Thilker et al. (in prep.).
Figure 1. Location of the ten quasars that were observed with HST-COS. An optical image of M31 is shown in the background along with 21 cm emission maps showing the disk gas and HVCs. The red contour is 21 cm emission at 1 Jy km/s, or an H\textsc{i} column density of $N_{\text{HI}} = 1.9 \times 10^{18}$ cm$^{-2}$. Higher column density contours interior to this are not shown. High velocity cloud contours from Thilker et al. (2004) are shown in green. The scale at the distance of M31 is 13.2 kpc deg$^{-1}$. The innermost (8. 0043+4016) and outermost (1. 0018+3412) quasars are at projected distances (impact parameters) of $b = 13.4$ kpc and $b = 111.9$ kpc from M31’s center. See Tables 1 and 2.
Figure 2. KPNO 2.1m Gold Camera discovery spectra of the ten quasars that were observed with HST-COS. The quasar name and emission redshift are noted in each panel.
We used the pipeline-provided standard deviation in flux to calculate the 1σ error in the normalized flux. When reporting errors in equivalent width measurements, we do not include (propagate) any errors that might arise during the process of defining a pseudo-continuum.

### 3 RESULTS

Figures 3 – 12 show the pseudo-continuum-normalized spectra near the predicted locations of metal lines along the ten sightlines, and Table 3 gives the measured metal-line absorption rest equivalent widths or upper limits for both M31 and Galactic lines. To make these measurements, heliocentric velocity locations for the absorbing gas had to be determined. The procedure for this is discussed below and the results on velocity offsets are given in Table 4.

For the low-ion transitions, the narrow Mn II lines (when present) allow for a more accurate determination of the velocity centroid of Galactic gas since they are well-fitted by single Gaussians. Therefore, the velocity offsets of low-ion Galactic absorption lines are defined by the centroids of Galactic Mn II λ2576 absorption for sightlines 2, 8, 9, and 10. The centroids of Galactic Mg II λ2796 are used to define the velocity offsets of absorption along other sightlines. The wavelength interval covered by the COS-FUV spectra includes transitions due to Si II, O I, C I, C II*, Fe II, and Al II. The centroids of these low-ion lines were fixed at the velocities determined from either the Mn II λ2576 line or Mg II λ2796 as indicated above. In the panels for each figure, dash-dot vertical lines are drawn at the determined velocity offsets of M31 and Galactic gas.

The only high-ion transitions detected in our spectra are due to C IV and Si IV*. The velocity centroids of Gaussians fitted to the C IV λ1548 lines were allowed to vary since low-ion and high-ion absorption lines are not a priori required to have the same velocity centroids or line widths. The C IV λ1550 line and Si IV lines were then constrained to have the same velocity locations and widths as the C IV λ1548 line, within the uncertainties and resolution of the data. Inspection of the final fits suggests that this was a reasonable constraint.

The 1σ error in the normalized flux is shown in the figures as a black dotted line. M31 and Galactic absorption transitions that are identified at a level of significance > 2σ are indicated in the figures by red profiles. A > 2σ rest equivalent width detection threshold is an appropriate criterion for identifying absorption because we already know the approximate velocity location of M31 absorption (e.g., from M31’s 21 cm emission). We also searched for significant absorption in a wider velocity window. Gaussian profiles are fitted to detected absorption. If more than one Gaussian is required to fit the data, we show the individual Gaussians as red dashed profiles, visible above the solid red profile. In the absence of multiple Gaussians, the red solid profile will lie on top of the red dashed profile, and the red dashed profile will not be visible. However, the measurements indicated by the red dashed profiles are what we report in Tables 3 and 4. As noted earlier, the positions of most low-ion lines are fixed by the centroid of either the Mn II λ2576 or the Mg II λ2796 line; however, their widths are allowed to vary in order to obtain the best fit. In a few cases, even the velocity offsets had to be allowed to vary up to one resolution element in order to obtain a satisfactory fit. Also, while performing the fits, we identified some absorption in the spectra which were likely blends resulting from a real M31 or Galactic absorption line plus overlapping or nearby absorption due to, for example, Lyα forest absorption, some other unrelated absorption, or even related absorption such as C II λ1334.5 and C II* λ1335.7. When this happened, we fitted Gaussians to these nearby absorption components in order to better isolate the M31 and Galactic absorption transition of interest. We refer to this as deblending. However, when we report results in Tables 3 and 4, as noted earlier, only
absorption taken to be due to the designated transition of interest in M31 or the Galaxy is reported and shown on the figures. Other nearby absorption lines which were fitted in order to isolate M31 and Galactic gas are shown as green dashed Gaussian profiles. The identifications and measurements of M31 and Galactic lines in the presence of confusing overlapping or nearby absorption should be considered less secure.

When a line is not detected (i.e., the detection is $<2\sigma$) at its expected velocity offset, or nearby absorption not due to the transition of interest appears to be present, a red dotted Gaussian profile with FWHM equal to the spectrograph resolution (i.e., $\sim 0.82$ Å or $\sim 87$ km s$^{-1}$ for the NUV lines and $\sim 0.55$ Å or $\sim 106$ km s$^{-1}$ for the FUV lines) is shown on the figures to indicate the reported upper limit. If no overlapping or nearby confusing absorption is present, this is just the $2\sigma$ upper limit on equivalent width generated from the error in normalized flux. However, if overlapping or nearby absorption is present, the upper limit is determined from the strength of this overlapping or nearby absorption. Lacking evidence that a low-oscillator-strength transition should be present along a particular sightline, we would attribute any significant detected absorption as due to overlapping absorption, and list it as an upper limit.

In cases where the velocity of an M31 absorption line overlaps with the velocity of a different Galactic absorption line, for example, the M31 C iv $\lambda 1550$ and the Galactic C iv $\lambda 1548$ lines, or the M31 Si ii $\lambda 1304$ and the Galactic O i $\lambda 1302$ lines along sightlines 1, 3, and 4 (Figures 3, 5, and 6), we assign the absorption to the Galactic absorption system. The measurement is listed in Table 3 only for the Galactic absorption line.

The bottom panels for sightlines 5 through 10 (Figures 7–12) show H i 21 cm emission profiles extracted from the GBT data of Thilker et al. (2004). The intensities are scaled to accentuate the very weak emission signal from M31. The dash-dot horizontal line drawn in each 21 cm panel marks the location of zero intensity. The H i 21 cm emission disk of M31 extends out to $\sim 33$ kpc as determined from the $N_{HI} = 1.9 \times 10^{18}$ cm$^{-2}$ column density contour (Figure 1), and no H i 21 cm measurements exist at the positions of quasars 1 through 4. Therefore, to estimate equivalent width upper limits for these four sightlines, we have assumed that M31’s 21 cm rotation curve is flat at large galactocentric distances and we extrapolate the sightline 21 cm emission velocity out to the positions of quasars 1 through 4 to predict a probable velocity location of absorbing gas. Note that M31 is nearly edge-on and inclined $\sim 78$ deg on the plane of the sky. Thus a small inclination correction is needed since $\sin(78) = 0.978$. Then the assumption of a flat rotation curve suggests that if metal-line absorption is present in M31’s outer regions, we might find it near a heliocentric velocity location of $\sim 525$ km s$^{-1}$. This is where we determine M31 equivalent width upper limits for sightlines 1 through 4. We note that the choice of where to measure potential absorption in the four outer sightlines is purely an algorithmic decision given that flat rotation curves exist. We also considered the Tamm et al. (2012) study which derives a rotation curve out to a galactocentric radius of $\sim 500$ kpc. They employ, among other diagnostics, observations of stellar streams (Fardal et al. 2006) and satellite galaxies (Tollerud et al. 2012) which yield rotational velocities of $\sim 160$ km s$^{-1}$ near the position of our outermost sightline. This translates to a heliocentric velocity of $\sim 466$ km s$^{-1}$ since our outer sightlines lie on the approaching, SW, side of M31. This is well within one resolution element (§2.3) of our assumed velocity location of $\sim 525$ km s$^{-1}$. Therefore, we are confident that we have not missed any absorption from gas in M31 along the outer four sightlines that is above our detection limits.

Tables 3 and 4 summarize all of the measurements and upper limits, both for M31 and the Milky Way Galaxy. A discussion of individual sightlines follows (see Figures 3–12), with emphasis on what they reveal about M31 gas. The discussions are presented in order of increasing sightline right ascensions. This ordering generally follows decreasing impact parameter, $b$, except for the last three sightlines which all have $13 < b < 18$ kpc. At the beginning of each discussion we indicate the maximum wavelength at which Ly$\alpha$ forest absorption might cause blending and confusion, $\lambda_{\text{forest}} \sim 1216(1 + z_{\text{em}})$ Å.

1. **0018+3412** ($b = 111.9$ kpc, $\lambda_{\text{forest}} < 1760$ Å, Fig. 3): No significant M31 absorption is detected along this sightline, and H i 21 cm emission maps of M31 do not extend this far out. Therefore, rest equivalent width upper limits on absorption were measured at $\sim 525$ km s$^{-1}$ as described earlier. At this velocity location, the red dotted Gaussian lines show the velocity positions and rest equivalent widths of hypothetical unresolved absorption lines with $\pm 2$ km s$^{-1}$ of significance, and these are the upper limits reported in Table 3. Galactic absorption is clearly present. Suspected confusion (blending) due to overlapping Ly$\alpha$ forest absorption is apparent for the Si ii $\lambda 1260$, Si ii $\lambda 1304$, O i $\lambda 1302$, C ii $\lambda 1334$, and C iv $\lambda 1550$ Galactic absorption lines. The method we used to measure such cases was discussed above.

2. **0024+3439** ($b = 98.6$ kpc, $\lambda_{\text{forest}} < 2216$ Å, Fig. 4): As in the previous sightline, no significant M31 absorption is detected, and H i 21 cm emission maps do not extend this far out, so upper limits were measured at a velocity location of $\sim 525$ km s$^{-1}$. Only NUV spectra of this quasar were obtained. Therefore, for example, the C iv region was not observed. A Galactic Mn ii $\lambda 2576$ line is detected at a level of significance of $\sim 3\sigma$, however the two weaker members of the triplet are not detected at $> 2\sigma$. Galactic Mg ii and Fe ii absorption are clearly detected.

3. **0030+3700** ($b = 64.4$ kpc, $\lambda_{\text{forest}} < 2720$ Å, Fig. 5): Again, no significant absorption lines from M31 are detected at or near $\sim 525$ km s$^{-1}$, and the 21 cm emission maps do not extend out this far. Among the significant Galactic absorption lines that are detected, the measurements of Si ii $\lambda 1260$, Si iv $\lambda 1393$, C iv $\lambda 1548$ and Fe ii $\lambda 2586$ were made in the presence of overlapping unrelated absorption using the method described earlier. While only the stronger members of the Galactic Si iv and C iv doublets are detected, the rest equivalent width upper limits of the weaker members of these doublets are consistent with their expected strengths based on $f\lambda$ values. In addition to the detected Galactic metal absorption lines, at least two partial Lyman limit absorption systems are present in the spectrum. One at $z \sim 0.5$ is clearly visible in the FUV observation (not shown). Based on the difference in flux level between the FUV and NUV observations, and the presence of some strong Ly$\alpha$ forest absorption near and just shortward of the
Lya broad emission line, at least one other Lyman limit absorption system is likely to be present at $1.21 < z < 1.24$. However, it is not directly visible in our observations because it falls in the wavelength gap between the FUV and NUV spectra.

4. 0031+3727 ($b = 57.6$ kpc, $\lambda_{\text{forest}} < 2797$ Å, Fig. 6): As with the first three sightlines, no significant absorption lines from M31 gas are seen, and the 21 cm emission map does not extend out this far. M31 upper limits were estimated at $-525$ km s$^{-1}$ for both the high and low ions. Galactic absorption is clearly detected for some transitions, but the measurements of Si$^\text{II}$ λ1260, C$^\text{II}$ λ1334, Si$^\text{II}$ λ1526, Fe$^\text{II}$ λ1608, and Fe$^\text{II}$ λ2600 required deblending due to the presence of unrelated overlapping absorption.

5. 0032+3946 ($b = 31.5$ kpc, $\lambda_{\text{forest}} < 2600$ Å, Fig. 7): Only NUV spectra were obtained for this quasar. An M31 Mg$^\text{II}$ λ2796 absorption line with a significance of $2\sigma$ at a heliocentric velocity of $-453$ km s$^{-1}$ appears to be present (see Table 3), however a corresponding 2-pixel-wide absorption feature near the expected position of Mg$^\text{II}$ λ2803 has a significance $< 2\sigma$. If present, this absorption may originate at the southwest edge of M31’s disk (see Figure 1). Apart from strong Galactic emission, the GBT 21 cm data along this sightline (bottom panel of Figure 7) shows evidence for M31 emission between $-509$ and $-459$ km s$^{-1}$. Although the resolution of the NUV spectrum is $\sim 0.82$ Å ($\sim 87$ km s$^{-1}$) at the position of Mg$^\text{II}$, the centroid of the absorption line can be estimated with an uncertainty of $\sim 6$ km s$^{-1}$ (see §4). Thus, the identified Mg$^\text{II}$ λ2796 feature at $-453$ km s$^{-1}$ is near the maximum velocity of observed 21 cm emission. Keeping in mind the limitations of using H1 21 cm emission observations to determine H1 column densities ($\S 2.1$), we find $N_{\text{H1}} \approx 2.5 \times 10^{18}$ atoms cm$^{-2}$ along this sightline. Very significant Galactic Mg$^\text{II}$ and Fe$^\text{II}$ absorption is detected along this sightline, but the Galactic Fe$^\text{II}$ λ2586 line was deblended to separate it from unrelated nearby absorption.

6. 0037+3908 ($b = 30.5$ kpc, $\lambda_{\text{forest}} < 2590$ Å, Fig. 8): Only NUV spectra were obtained for this quasar. Absorption from M31 gas is not detected. However, apart from the strong Galactic emission, the GBT data along this sightline reveal M31 21 cm emission between $-542$ and $-475$ km s$^{-1}$ (bottom panel of Figure 8), with an integrated column density of $N_{\text{H1}} = 2.5 \times 10^{18}$ atoms cm$^{-2}$ (see §2.1). The $2\sigma$ upper limits on M31 absorption are made at the central velocities predicted by the observed M31 21 cm emission. Very significant Galactic Mg$^\text{II}$ and Fe$^\text{II}$ absorption is detected along this sightline. The Galactic Fe$^\text{II}$ λ2586 and Fe$^\text{II}$ λ2600 lines were deblended to separate them out from unrelated nearby absorption.

7. 0040+3915 ($b = 26.9$ kpc, $\lambda_{\text{forest}} < 2552$ Å, Fig. 9): Only the velocity profiles in the vicinity of Mg$^\text{II}$ and Mg$^\text{I}$ are visible in our observations for two reasons. First, the quasar spectrum exhibits intrinsic broad absorption lines.
(BALs) and the N\textsc{v} BAL trough overlaps the Mn\textsc{ii} and Fe\textsc{ii}
absorption-line regions. This prevents useful measurements of M31 and Galactic lines in those regions. Second, the FUV spectrum shows no useful continuum flux, possibly due to strong shorter-wavelength BALs and/or overlapping intervening Lyman limit absorption. Mg\textsc{ii} $\lambda$2796 due to M31 gas appears as two absorption components in the NUV spectrum. The noise characteristics of the spectrum are worse in the corresponding Mg\textsc{ii} $\lambda$2803 region, and two absorption components are not seen (a single Gaussian was fitted to the absorption), but we give this lower weight due to the higher noise. The two vertical dash-dot lines at $-389$ km s$^{-1}$ and $-513$ km s$^{-1}$ mark the velocity positions of the two M31 Mg\textsc{ii} $\lambda$2796 absorption components. The sightline passes through an HVC (see Figure 1), whose 21 cm emission profile can clearly be seen in the bottom panel of the figure peaking at $\sim -500$ km s$^{-1}$. The GBT data reveal that this 21 cm emission extends between $-542$ and $-442$ km s$^{-1}$. Thus, the two Mg\textsc{ii} absorption components at $-389$ km s$^{-1}$ and $-513$ km s$^{-1}$ may correspond to M31 halo gas and HVC gas, respectively, with the halo component showing no apparent 21 cm emission. From the WSRT 21 cm emission data, the integrated H\textsc{i} column density in the HVC is estimated to be $N_{\text{HI}} = 9.5 \times 10^{19}$ atoms cm$^{-2}$ (see §2.1). Very significant Galactic Mg\textsc{ii} absorption is present along this sightline.

8. $0043+4016$ ($b = 13.4$ kpc, $\lambda_{\text{forest}} < 2545$ Å, Fig. 10): This is the lowest impact parameter sightline. M31 low-ion absorption from Si\textsc{ii} $\lambda$1260 and C\textsc{ii} $\lambda$1334 is detected, and high-ion absorption from C\textsc{iv} $\lambda$1548 is detected, but the Si\textsc{ii} $\lambda$1260 and C\textsc{iv} $\lambda$1548 lines had to be deblended from overlapping unrelated absorption. Given that the 21 cm emission extends over a large range in velocity, we cannot rule out that all the absorption features within the C\textsc{iv} $\lambda$1548 blend are due to C\textsc{iv} $\lambda$1548 absorption over a wide velocity range. Confirmation would require a higher signal-to-noise spectrum; here, we identify the lowest velocity component with the M31 C\textsc{iv} $\lambda$1548 absorption line. The low-ions are centered at $\sim -336$ km s$^{-1}$ and the high-ions are centered at $\sim -340$ km s$^{-1}$. However, Mg\textsc{ii}
Figure 5. Same as Figure 3, but for 0030+3700.

Figure 6. Same as Figure 3, but for 0031+3727.
and Fe II absorption lines from M31 gas were not detected. The GBT data show that 21 cm emission from M31 exists along this sightline between $-559$ km s$^{-1}$ and $-326$ km s$^{-1}$ with a total integrated column density of $N_{\text{HI}} = 1.2 \times 10^{19}$ atoms cm$^{-2}$. We note that the absorption-line velocities are coincident with the peak in the 21 cm emission-line spectrum (bottom panels of Figure 10). Many significant Galactic absorption lines are present. Galactic Si II $\lambda 1260$ and C IV $\lambda 1550$ had to be deblended to separate them out from unrelated overlapping absorption.

9. 0043+4234 ($b = 17.4$ kpc, $\lambda_{\text{forest}} < 1448$ Å, Fig. 11): The sightline to this quasar passes “above” the H I 21 cm
Figure 8. Same as Figure 7, but for 0037+3908. No FUV spectra were obtained for this quasar.

emission disk of M31 on the receding, northwest, side (see Figure 1). Due to the location of the sightline, the detected M31 and Galactic absorption lines needed to be deblended from each other. We used two-component Gaussian fits with fixed velocity components to do this. Measurements of the Si\textsc{ii} $\lambda 1260$, C\textsc{ii} $\lambda 1334.5$ (and C\textsc{ii}$^*$ $\lambda 1335.7$), Si\textsc{iv} $\lambda 1393$, and Al\textsc{ii} $\lambda 1670$ absorption lines are further complicated by other overlapping absorption. For low-ion absorption the velocity centroid for the Galactic lines was fixed using Mn\textsc{ii} $\lambda 2576$, while allowing the position of the M31 low-ion velocity centroid to vary until the best least-squares solution was found. Deblending indicates that the detected M31 low-ion gas, which gives rise to transitions of Si\textsc{ii}, C\textsc{ii}, Al\textsc{ii}, Fe\textsc{ii} and Mg\textsc{ii}, is located at $-234$ km s$^{-1}$, and the Galactic low-ion gas is located at $-73$ km s$^{-1}$. It is notable that along this sightline there is a detection of Galactic
Figure 9. Same as Figure 7, but for 0040+3915. The M31 HVC that is detected in 21 cm at \(-513\) km/s, is also detected in the $\text{Mg}\,\text{II}$ $\lambda 2796$ line. The two $\text{Mg}\,\text{II}$ $\lambda 2803$ components are too weak to be resolved with these data. The FUV data are not shown because the spectrum had no flux presumably due to an intervening Lyman limit system.

$\text{CII}^\ast$ $\lambda 1335.7$. The M31 high-ion gas, which gives rise to transitions of Si$\text{IV}$ $\lambda 1393$ and C$\text{IV}$ $\lambda 1548$, are also members of a multi-component blend with Galactic lines. Using a procedure similar to the one used for the low-ions, we find that the M31 high-ion gas is at $-191$ km s$^{-1}$ and the Galactic high-ion gas is at $-1$ km s$^{-1}$. GBT data reveal M31 21 cm emission between $-259$ km s$^{-1}$ and $-93$ km s$^{-1}$, with a total integrated column density of $N_{\text{HI}} = 8 \times 10^{18}$ cm$^{-2}$ (see §2.1). The higher velocity edge of the M31 21 cm emission is uncertain since it may overlap with Galactic 21 cm emission.

10. 0046+4220 ($b = 17.5$ kpc, $\lambda_{\text{forest}} < 1588$ Å, Fig. 12): To infer what gaseous structures exist along this sightline we are guided by the observed GBT H$\text{I}$ 21 cm emission velocity profile, which is shown in the bottom panels of Figure 12. An inset in the bottom left panel shows the entire 21 cm profile. Most notably, the weaker 21 cm peak near $-5$ km s$^{-1}$ represents Galactic emission, while the stronger 21 cm emission peak near $-55$ km s$^{-1}$ represents M31’s disk; however, such a velocity separation cannot be distinguished in the COS G140L and G230L absorption-line spectra. More generally, the entire 21 cm velocity profile and the detected low-ion absorption lines have allowed us to infer the existence of five gaseous structures along this sightline: one near $-5$ km s$^{-1}$ (Galactic gas), one near $-55$ km s$^{-1}$ (M31 disk gas), one near $-195$ km s$^{-1}$ (M31 halo gas), one near $-334$ km s$^{-1}$ (a M31 HVC), and one near $-409$ km s$^{-1}$ (a second M31 HVC). As with sightline 9, detected Galactic and M31 absorption lines needed to be deblended from each other, but the blending along this sightline is more severe. In particular, the low-ion absorption detected near $-40$ km s$^{-1}$ must be a blend of Galactic gas and M31 disk gas, with most of the absorption being due to M31 disk gas. This Galactic+M31 blended component is included under the heading of "Milky Way Absorption Lines" in Table 3 but with a footnote. Absorption due to $\text{CII}^\ast$ $\lambda 1335.7$ is among the many transitions detected in this component (see Table 3). A weak (barely significant) blended Galactic and M31 high-ion absorption component is located near $-35$ km s$^{-1}$. The 21 cm emission profile allows us to estimate that the Galactic component peaking near $-5$ km s$^{-1}$ has $N_{\text{HI}} = 4.0 \times 10^{20}$ atoms cm$^{-2}$ and the M31 disk component peaking near $-55$ km s$^{-1}$ has $N_{\text{HI}} = 1.5 \times 10^{21}$ atoms cm$^{-2}$. Aside from this first blended absorption component, a second low-ion absorption component is seen displaced toward lower velocities by $\sim 155$ km s$^{-1}$, close to the edge of the H$\text{I}$ 21 cm emission profile, which we take as evidence for halo gas. However,
measurements of the Si\(\text{II}\) \(\lambda 1260\), O\(\text{I}\) \(\lambda 1302\), Si\(\text{II}\) \(\lambda 1304\), C\(\text{II}\) \(\lambda 1334.5\) (and C\(\text{II}^*\) \(\lambda 1335.7\)), Si\(\text{II}\) \(\lambda 1526\), C\(\text{IV}\) \(\lambda 1548\), and Al\(\text{II}\) \(\lambda 1670\) absorption lines are complicated by overlapping or nearby absorption. Deblending indicates that the M31 low-ion halo gas component is near \(-195\) km s\(^{-1}\), and this gives rise to absorption due to Si\(\text{II}\), O\(\text{I}\), C\(\text{II}\), Al\(\text{II}\), Fe\(\text{II}\), and Mg\(\text{II}\). Deblending also indicates that a high-ion absorption component is located near \(-152\) km s\(^{-1}\); it is clearly present in C\(\text{IV}\) but possibly not Si\(\text{IV}\). The 21 cm emission allows us to estimate that the M31 halo component peaking near \(-195\) km s\(^{-1}\) has \(N_{\text{HI}} = 7 \times 10^{19}\) atoms cm\(^{-2}\). The velocity locations of the above described absorption components for the low ions and high ions are shown as vertical dot-dashed lines in the panels, including the lower left inset panel. In addition, the GBT 21 cm observations also reveal gas from two M31 HVCs near \(-334\) km s\(^{-1}\) (between \(-342\) km s\(^{-1}\) and \(-326\) km s\(^{-1}\)), and near \(-409\) km s\(^{-1}\) (between \(-426\) km s\(^{-1}\) and \(-392\) km s\(^{-1}\)). The total integrated column densities along the sightlines to these HVCs are \(N_{\text{HI}} = 2 \times 10^{18}\) atoms cm\(^{-2}\) and \(N_{\text{HI}} = 2.5 \times 10^{18}\) atoms cm\(^{-2}\), respectively. We do not detect metal-line absorption near the velocities of these HVCs, so we have not used vertical lines to mark their velocity locations in Figure 12. Thus, using standard quasar absorption line jargon, we conclude that, given the estimated \(N_{\text{HI}}\) values for the four detected M31 velocity components, we have detected a
DLA system (M31 disk gas), a sub-DLA system (M31 halo gas), and two Lyman limit systems (two M31 HVCs). Finally, we point out that the blended low-ion absorption near $-40 \text{ km s}^{-1}$ in sightline 10 is the only system which reaches DLA $\text{H}\text{i}$ column densities (i.e., $N_{\text{HI}} \geq 2 \times 10^{20}$ atoms cm$^{-2}$). As described above, it is due to a blend of Galactic gas and M31 disk gas. DLAs are the quasar absorption-line systems used to track the evolution of neutral gas in the Universe at low (Rao et al. 2006) and high (e.g., Noterdaeme et al. 2012) redshift. The strength of the Mg$\text{II} \lambda 2796$ and Fe$\text{II} \lambda 2600$ absorption lines in this component are consistent with criteria used in Mg$\text{II}$-selected DLA searches (Rao et al. 2006).

4 SUMMARY AND DISCUSSION OF RESULTS FOR M31

4.1 Overview on the Detection of Low-Ion and High-Ion Absorption Lines

The detections of M31 gas presented in the previous section and reported in Tables 3 and 4 can be summarized as follows.

Low-ion Mg$\text{II}$ absorption due to M31 gas is detected along four of the 10 observed sightlines (5, 7, 9, and 10). These sightlines have impact parameters ranging between $b \approx 17$ and 32 kpc. We also detect other low-ion gas (e.g., due to Si$\text{II}$, O$\text{I}$, C$\text{II}$, Fe$\text{II}$, or Al$\text{II}$) along three of the four sightlines with Mg$\text{II}$ detections; sightline 5 was not observed.
in the FUV, where most of these transitions occur. In addition, we detect C\textsc{ii} absorption at M31 velocities along sightline 8 (b = 13.4 kpc). Sightline 6 (b = 30.5 kpc) is the only “inner” sightline which does not show evidence for M31 low-ion absorption (W_{\alpha 2796} < 0.41 \AA); however, no FUV spectra were obtained along this sightline. Among these “inner” sightlines, except for the blended Galactic and M31 line in sightline 10, the Mg\textsc{ii} rest equivalent widths ranged between W_{\alpha 2796} \approx 0.34 \text{ and } 0.71 \AA, with the strongest detection being a two-component absorber with W_{\alpha 2796} \approx 0.30 \text{ and } 0.41 \AA. The four outer sightlines (1 through 4), with impact parameters ranging between b \approx 57 \text{ to } 112 \text{ kpc}, do not show Mg\textsc{ii} absorption down to 2\sigma rest equivalent upper limits ranging between W_{\alpha 2796} \approx 0.21 \text{ and } 0.46 \AA.

High-ion C\textsc{iv} absorption due to M31 gas is detected along three of six sightlines (8, 9, and 10) which have usable FUV spectra. These three detections are all in “inner” sightlines, with impact parameters ranging between b \approx 13 \text{ and } 18 \text{ kpc}, and rest equivalent widths ranging between W_{\alpha 1548} \approx 0.17 \text{ and } 0.65 \AA. Some Si\textsc{iv} absorption and low-ion absorption is also detected along these three “inner” sightlines. The three C\textsc{iv} non-detections are in outer sightlines (1, 3, and 4), with impact parameters ranging between b \approx 57 \text{ and } 112 \text{ kpc}, and with 2\sigma rest equivalent width upper limits ranging between W_{\alpha 1548} \approx 0.18 \text{ and } 0.30 \AA.

We should point out that many of the detections summarized above were near the limit of our sensitivity threshold, despite the fact that our rest equivalent width upper limits are typical of those in large optical quasar absorption-line surveys. Another concern is confusion from overlapping or nearby absorption, but we believe we have dealt with this appropriately.

Also, Rich et al. (private communication) has observed three sightlines in the halo of M31 with COS. They do not cover the Mg\textsc{ii} region, but detect C\textsc{iv} from M31 in some of these sightlines. There are other HST archival observations in the M31 halo, but these do not show any detections.

### 4.2 Implications

As elaborated further in §4.3, a clear picture does emerge. The absorption lines that arise in M31 gas are found to be relatively weak in comparison to those often identified in optical quasar absorption-line surveys, and even more so in
comparison to absorption lines which arise in the ISM of the Milky Way Galaxy (e.g., Table 3). Moreover, none of the detected M31 absorption lines are found at large impact parameters. This could also be viewed as unexpected since the bulk of intervening low- to moderate-redshift metal-line absorbers seen in quasar spectra are identified with large-impact-parameter galaxies in followup imaging studies (e.g., Rao et al. 2011, Chen et al. 2010). However, all of the large-impact-parameter sightlines we observed were generally along M31’s major axis, so one scenario which might explain the lack of absorption in those cases would be to hypothesize that extended gaseous absorption originates in galactic fountains and preferentially avoids extended regions along the direction of the disk (e.g., Bordoloi et al. 2011, Bouček et al. 2012). Using the observed distribution of HVCs around the Milky Way and M31, Richter (2012) finds an exponential decline in the mean filling factor of HVCs with a characteristic radial extent of ~50 kpc. If HVCs alone are responsible for absorption lines, then one would not expect to find any absorption along our four outer sightlines. Alternatively, M31 may simply be typical of a class of luminous galaxies that don’t possess large gaseous core sections which are capable of giving rise to moderate-strength quasar absorption lines. Our findings for M31 may in some way be connected to the observed relative decrease in the incidence of stronger Mg II systems with decreasing redshift (e.g., Nestor et al. 2005).

In the past several years there has been speculation that M31 is a galaxy that lies in the “green valley” (e.g., Mitch et al. 2011, Davidge et al. 2012). The idea is that it exhibits properties that put it between the red cloud and blue cloud populations that have been identified in large galaxy surveys. Such galaxies may be in a stage of transition and their star formation may nearly cease in less than 5 Gyrs. While this may be the case for M31, we note that the data we have discussed here should not be taken to offer any clues about this. For example, our data do not allow us to draw any conclusions about the strength of star formation or even the column densities of metal-line absorption. This is because the lines we have identified are likely to be mostly saturated. Thus, the weakness of the metal-line absorption in M31 most likely indicates that the effective gas velocity spread is low; it may either be truly low relative to the spectral resolution and/or there may be a small number of velocity components within the spectral resolution element.

### Table 3. Rest Equivalent Width Measurements

| Line (Å) | SiII2600 | AlII1670 | MgII2796 | FeII2600 |
|----------|----------|----------|----------|----------|
|REW (Å)   | ≤ 0.113  | ≤ 0.222  | ≤ 0.134  | ≤ 0.134  |
|REW (Å)   | ≤ 0.300  | ≤ 0.302  | ≤ 0.311  | ≤ 0.311  |

*Table 3. Rest Equivalent Width Measurements

Note: a) Upper limits are tabulated for non-detections.

b) In sightline 10, Milky Way absorption lines are blended with M31 disk gas. See the description in §3.

c) The two measurements are M31 HVC and disk components, respectively. See Figure 9.

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Quasar Sightlines Through M31
4.3 Mg II Rest Equivalent Width ($W_{\lambda 2796}^i$) versus Impact Parameter ($b$)

Figure 13 is a plot of M31 Mg II $\lambda 2796$ rest equivalent width ($W_{\lambda 2796}^i$) detections (or $2\sigma$ upper limits) versus sightline impact parameter ($b$). The measurement shown for sightline 7, which has $b = 26.9$ kpc, was made by fitting a single Gaussian to both absorption components reported in Table 3, i.e., it is not a simple sum of the results from the two individual Gaussian fits reported in Table 3. Since the impact parameters of sightlines 9 and 10 are very similar, they are displaced from each other in the figure for clarity. Note that the upper limits are $2\sigma$ upper limits, while the error bars are the $1\sigma$ uncertainties. The four outermost data points are suggestive of an overall decrease of $W_{\lambda 2796}^i$ with increasing impact parameter. Quasar absorption line studies of large samples of absorber-galaxy pairs have shown this to be true as well (Chen et al. 2010; Rao et al. 2011).

For comparison, Figure 14 includes results from the Rao et al. (2011) sample of absorbing galaxies which have been identified for Mg II-selected DLAs, subDLAs, and Lyman limit systems (LLSs). The mean redshift of the Rao et al. sample is $z \sim 0.5$, with redshifts in the range $0.1 \lesssim z \lesssim 1.0$. The identified absorbing galaxies in the Rao et al. sample also have a range of luminosities, mostly $0.1 \lesssim L \lesssim 1.0L^*$, but there is not a significant correlation between luminosity and impact parameter. Rao et al. found only a marginal ($1.8\sigma$) correlation between $W_{\lambda 2796}^i$ and $b$. The solid black circles in Figure 14 are DLAs and the open circles are subDLAs and LLSs. The data from this current M31 study are in red. Sightlines 5 through 10 have averaged integrated 21 cm emission H1 column densities in the subDLA regime, with the exception of the Galactic and M31 blended component along sightline 10. (See §3.) H1 21 cm emission maps are not available as far out as the four outermost sightlines, but since the $N_{HI} = 1.9 \times 10^{18}$ cm$^{-2}$ edge of the H1 disk of M31 is at $b \approx 33$ kpc (Figure 1), these sightlines are not expected to have averaged integrated H1 column densities in the DLA or subDLA regime.

Thus, as noted in §4.1 and §4.2, it is clear that the sightlines passing near M31, or through its gaseous disk seen in 21 cm emission, do not give rise to the moderate-to-strong Mg II absorption lines which are often identified in moderate-to-high-redshift quasar absorption-line surveys. For comparison, all of the Galactic detections reported in Table 3 have $W_{\lambda 2796}^i > 0.5$ A, and 4 of the Galactic sightlines have $W_{\lambda 2796}^i \sim 1$ A (sightline 10 is a blend of Galactic and M31 gas). In the HST Key Project sample of Galactic sightlines (Savage et al. 2000) the median value is $W_{\lambda 2796}^i = 1.17$ A, and the strongest line has $W_{\lambda 2796}^i = 2.2$ A.

Of course, our sightlines through M31 are biased sightlines in the context of traditional absorption line surveys, in that the galaxy was pre-selected in order to study the properties of its low-ion and high-ion gas. Therefore, for M31 the probability of occurrence of Mg II absorption as a function of $W_{\lambda 2796}^i$ is not properly estimated from the observed incidence of Mg II absorption in unbiased quasar absorption-line surveys. Instead, however, this experiment does show that a gas-rich, $\sim 2L^*$, spiral galaxy like M31 need not give rise to moderate-to-strong Mg II absorption along sightlines which pass through its H1 21 cm emission disk, or even through a putative extended gaseous halo.

4.4 Comparison of 21 cm Emission and Absorption-Line Velocities

The range of velocities that exhibit 21 cm emission for sightlines 5 through 10 are shown as cyan and orange vertical bars as a function of impact parameter in Figure 15. Cyan bars correspond to 21 cm emission velocities from M31 gas and orange bars represent HVC velocities. Also plotted are the velocities of the low-ion (red stars) and high-ion (blue triangles) absorption lines from Table 4. The Galactic and M31 blended low-ion absorption line along sightline 10 is shown as the encircled star. For the two inner disk sightlines (9 and 10 at $\approx 17.5$ kpc), it appears that the velocity of the high-ion absorption is better correlated with the 21 cm emission velocity range. Along sightline 8, the low and high-ion absorption lie at an outer velocity edge of where 21 cm emission is detected. As noted in §3, this velocity corresponds to the peak in 21 cm emission along this sightline. For sightlines 7 (at $b = 26.9$ kpc) and 5 (at $b = 31.5$ kpc), the low-ion gas again coincides with the peak of 21 cm emission which is near near the edge of the 21 cm profile (see Figures 7 and 9). Thus, in nearly all cases, the low ions occur near the edge of the 21 cm profiles (two are near the low velocity edge and three are near the high velocity edge), and for sightlines 5, 7, and 8, are coincident with the peak in 21 cm emission.

Given the resolution of the NUV and FUV data ($\sim 87$ km s$^{-1}$ at $\sim 2800$ Å and $\sim 106$ km s$^{-1}$ at $\sim 1550$ Å), one might question if these differences are significant. However, it is well-known that in data with sufficient signal-to-noise, a Gaussian fit to an absorption line can be used to determine the centroid location of the line to an accuracy much better than the line’s FWHM. In order to determine how accurately absorption-line locations can be determined, we ran 10,000 realizations of lines with equivalent widths drawn from the data. Figure 16 shows the distributions of equivalent widths. Noise was added to the Gaussian profiles generated with these equivalent widths so that the resulting signal-to-noise ratios matched the data. Line centroids were then estimated by refitting Gaussian profiles to the noise-up absorption lines. The resulting distributions of centroid velocities relative to the input values are shown in Figure 17. For both the original as well as the simulated data, the spectra were rebinned to two pixels per resolution element before measurements were made. The signal-to-noise ratios of NUV spectra were, in general, higher than in FUV spectra. Thus, the accuracy with which the line centroids can be measured is higher for the Mg II lines. Specifically, the centroid standard deviation of the Mg II distribution is $\sim 6$ km s$^{-1}$ compared to $\sim 16$ km s$^{-1}$ for CIV. These uncertainties indicate that the separations in velocities of the low and high ions are significant towards sightlines 9 and 10 at approximately the $2\sigma$ level.

The 21 cm emission studies of M31 (e.g., §2.1) show that for this nearly edge-on galaxy, the sightline velocities of gas giving rise to 21 cm emission can span a large range (e.g., see the lower panels in Figures 7 - 12). Corbelli et al. (2010) fitted a tilted ring model to M31’s H1 21 cm emission data from 8 to 37 kpc to study the details of its rotation, finding that M31’s disk warps beyond galactocentric distances of $\sim 25$ kpc and that it becomes more inclined with respect to our sightline. As we have shown above, the Mg II absorption regions are almost always at the peak of the 21
cm emission profile, which occurs near the edge of the 21 cm emission velocity range. Thus, when detected, the low-ion gas appears to trace the 21 cm gas. Interestingly, neither low- nor high-ion absorption lines are detected at the 21 cm velocity locations of the HVCs along sightline 10 ($b = 17.5$ kpc). Low-ion absorption is also not detected at the 21 cm disk velocity location towards sightline 6 ($b = 30.5$ kpc). However, the observed low-ion absorption along sightline 7 originates in the HVC detected in 21 cm emission, but at the velocity location of the other absorption component, there is no detected 21 cm emission. This component, at $-389$ km s$^{-1}$, is likely to be M31 halo gas. Thus, it appears that the sightlines through M31 are passing through very different physical and kinematic conditions within its ISM.

5 CONCLUSIONS

A conventional study relating quasar absorption-lines to the galaxies that cause them begins with the detection of an intervening absorption-line system in a spectrum followed by imaging work to identify the galaxy. The experiment with M31 described here is a quasar absorption-line survey conducted in reverse. We probed ten sightlines with vastly different impact parameters through a single spiral galaxy with a luminosity of $\sim 2L^*$. As summarized in §4.1, we detected some type of absorption from M31 gas in five of the six inner sightlines ($13 < b < 32$ kpc), but no absorption in any of the four outer sightlines ($57 < b < 112$ kpc). We also reported the first detection of metals in a M31 HVC.

In §4.3 we compared our M31 results to the findings in the conventional Rao et al. (2011) survey. Rao et al. found only a marginal anticorrelation between $W_{\lambda 2796}$ and $b$, and indeed we find the same qualitative trend in M31, but the values of $W_{\lambda 2796}$ are far smaller in M31 (Figure 14). And while Rao et al. found that there were fewer systems with moderate-to-strong $W_{\lambda 2796}$ at large-$b$ ($b > 50$ kpc), we found none arising in M31. In §4.4 we compared the velocity locations of low-ion and high-ion gas in M31 to that of M31’s 21 cm emission and found that the high-ion gas is better aligned with the velocities of observed 21 cm emission along two of three sightlines where it is detected. The velocity of the low-ion gas is correlated with the peak of 21 cm emission and is often near the edge of the 21 cm emission velocity range. In one case Mg ii is detected at a velocity location that shows no 21 cm emission.

Broadly, our results indicate that:

(i) Despite the fact that M31 is a gas-rich, $\sim 2L^*$ spiral galaxy, it produces relatively weak Mg ii and C iv absorption lines in comparison to those found in moderate-to-high redshift quasar absorption-line surveys. For Mg ii, this may indicate that M31 is typical of a class of luminous galaxies that don’t possess gaseous cross sections capable of giving rise to moderate-strength quasar absorption lines even at impact parameters $b \lesssim 32$ kpc. This finding might also be
Figure 14. Same as Figure 13, but data points from Rao et al. (2011) have been added. These represent identified galaxy impact parameters for Mg\textsc{ii} systems with H\textsc{i} column density measurements at $z \sim 0.5$. Solid black circles are the DLAs as measured in UV spectra (Rao, Turnshek, & Nestor 2006) and open black circles are subDLAs and LLSs.

Table 4. Heliocentric velocity offsets of low- and high-ion absorption lines$^a$

| Quasar   | M31 | Milky Way |
|----------|-----|-----------|
|          | Low ion (km s$^{-1}$) | High ion (km s$^{-1}$) | Low ion (km s$^{-1}$) | High ion (km s$^{-1}$) |
| 1. 0018+3412 | ... | ... | -18 | -61 |
| 2. 0024+3439 | ... | ... | -6 | ... |
| 3. 0030+3700 | ... | ... | -21 | -53 |
| 4. 0031+3727 | ... | ... | -33 | ... |
| 5. 0032+3946 | -453 | ... | -42 | ... |
| 6. 0037+3908 | -508 | ... | -42 | ... |
| 7. 0040+3915 | -513,-389$^b$ | ... | -38 | ... |
| 8. 0043+4016 | -336 | -340 | 6 | 42 |
| 9. 0043+4234 | -234 | -191 | -73 | -1 |
| 10. 0046+4220 | -195,-40$^c$ | -152,-35$^c$ | -40 | -35 |

$^a$The velocity centroid of the Milky Way absorption system is determined from the Mn\textsc{ii} $\lambda2576$ line, if detected, or from the Mg\textsc{ii} $\lambda2796$ line if no Mn\textsc{ii} is present, or from the C\textsc{ii} $\lambda1334$ if neither is present in the spectrum. The velocity centroid of the C\textsc{iv} $\lambda1548$ line was determined independent of the low-ion velocity, and was used to constrain the positions of the high-ionization lines. The uncertainties in the low- and high-ion velocities are 6 km s$^{-1}$ and 16 km s$^{-1}$, respectively.

$^b$The two measurements are M31 HVC and halo components, respectively. See Figure 9.

$^c$The two measurements are M31 halo and disk components, respectively. The disk component is blended with the Milky Way line.

related to the observed relative decrease in the incidence of stronger Mg\textsc{ii} systems with decreasing redshift.

(ii) M31 appears not to possess an extensive large gaseous cross section at impact parameters $b > 57$ kpc that is capable of giving rise to moderate-strength quasar absorption lines (e.g., with $W_0^{\lambda1548} > 0.2$ Å or $W_0^{\lambda2796} > 0.3$ Å), at least not along the direction of its major axis.

(iii) For the relatively weak absorption that we did detect at $b \leq 32$ kpc, we found the low-ion gas to be associated with the peak in the 21 cm emission profile, near one edge of the 21 cm emission velocity range. Two of three sightlines
Figure 15. Velocities of detected lines in M31 as a function of impact parameter. Cyan and orange vertical bars represent velocity ranges of 21 cm emission from M31’s disk and HVCs, respectively. (See the bottom panels of Figures 7-12 for an indication of the velocity regimes which contain the most gas.) Red stars are low-ion (Mn\textsc{ii}, Mg\textsc{ii}, or C\textsc{ii}) line centroids, and blue triangles are high-ion (C\textsc{iv}) line centroids from Table 4. The uncertainty in the velocity measurement is shown as the vertical bar in the upper left corner. Sightlines 9 and 10 are displaced for clarity. Three distinct velocity ranges are apparent towards sightline 10: the wide component arises in M31, and is partly blended with Milky Way gas. The encircled star at $-40$ km s$^{-1}$ is the blended Galactic and M31 disk absorption-line velocity centroid, and the red star at $-195$ km s$^{-1}$ is from M31’s halo. (See description of sightline 10 in §3.) The two narrower orange components originate in M31 HVCs. No metal lines are detected at these velocities. The two red stars along sightline 7 are the two components of the Mg\textsc{ii} line shown in Figure 9. 21 cm emission is detected only from the HVC along this sightline but not at the velocity of the Mg\textsc{ii} component at $-389$ km s$^{-1}$. We therefore surmise that this gas resides in the halo and not in the disk of M31. We caution that the velocities plotted in this figure are not a measurement of M31’s rotation curve since, except for sightline 10, the inner sightlines, i.e., 5-9, do not lie along the major axis of M31. See Figure 1.

Figure 16. Distribution of rest equivalent widths, Mg\textsc{ii} $W_{\lambda 2796}$ (left) and C\textsc{iv} $W_{\lambda 1548}$ (right), from 10,000 realizations of the data.
showed high-ion gas to be centrally located within the 21 cm emission profile, with the third being coincident with an edge. It is also likely that we have detected low-ion halo gas through two of the sightlines.

Future UV spectroscopy of quasars behind M31 can build on these findings by: (1) acquiring higher signal-to-noise data to probe down to weaker rest equivalent width values, (2) acquiring higher resolution data to better study the velocity locations of the gas relative to 21 cm emission velocities, and/or (3) probing a larger number of sightlines including ones in M31’s extended halo region.

It would be interesting if \( N_{\text{HI}} \) results derived from M31’s 21 cm emission data could be compared with \( N_{\text{HI}} \) determinations from Lyman series absorption seen in the UV spectra of background quasars. One could then get an \( \text{H} \) column density measurement averaged over less than a milliparsec region in M31, in comparison to the \( \sim 50 \) pc linear spatial scale offered by the radio observations. This would provide information on the homogeneity and size scale of \( \text{H} \) absorbing regions in M31.

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