PROBING HALOS OF GALAXIES AT VERY LARGE RADII USING BACKGROUND QSOs

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ABSTRACT

Gaseous halos of nine nearby galaxies (with redshifts \( z < 6000 \) km s\(^{-1} \)) were probed at large galactocentric radii using background quasars observed with the Hubble Space Telescope Goddard High Resolution Spectrograph and the Space Telescope Imaging Spectrograph. The projected quasar-galaxy separations range from 55 to 387 h\(^{-1}\) kpc. Ly\( _{\alpha} \) absorption lines were successfully detected in the spectra of five quasars, at impact parameters of up to \( \sim 170 \) h\(^{-1}\) kpc from the center of the nearby galaxy, and in each case at wavelengths consistent with the galaxy’s redshift. Our observations include the lowest redshift Ly\( _{\alpha} \) lines detected to date. H \( i \) velocity fields were obtained at the Very Large Array for three of the galaxies in our sample (in one case the velocity field was available from the literature) to derive their rotation curves. When comparing the inner rotation curves of the galaxies with the velocity at large radius provided by the Ly\( _{\alpha} \) line, it is apparent that it is very difficult to explain the observed Ly\( _{\alpha} \) velocity as due to gas in an extended rotating disk. In most cases, one would need to invoke large warps in the outer gas disks and also thick gas disks to reconcile the observed velocities with the predicted ones. Indeed, in one case, the Ly\( _{\alpha} \) line velocity indicates, in fact, counterrotation with respect to the inner disk rotation. In light of these results, we conclude that in a typical galaxy there is no longer detectable atomic gas corotating in an extended disk at radii greater than \( 35 \alpha^{-1}\) kpc, where \( \alpha^{-1} \) is the stellar disk exponential scale length. The cosmic web is the most likely origin for the detected Ly\( _{\alpha} \) lines. Our observations confirm the recent Bowen et al. correlation of equivalent widths with the local volume density of galaxies around the sight line, and the observed equivalent widths of the lines are consistent with expectations of the cosmic web.

Subject headings: galaxies: halos — galaxies: ISM — galaxies: spiral — quasars: absorption lines

1. INTRODUCTION

Rotation curves are the best tool to study the dark matter halos of galaxies, and the most extended ones better constrain the dark matter halo parameters. Rotation curves derived from neutral hydrogen (H\( i \)) observations enable us to probe the dark matter potential to distances of at most \( (20–25)\alpha^{-1} \) (where \( \alpha^{-1} \) is the optical disk exponential scale length), for gas-rich late-type spiral galaxies with particularly extended H\( i \) (e.g., NGC 2841 from Begeman 1987 or NGC 2915 from Meurer et al. 1996). But it is not possible to obtain any kinematical data with 21 cm emission farther out than the radius at which the gas density falls to levels of a few times \( 10^{12} \) atoms cm\(^{-2}\), even with very sensitive observations, as the H\( i \) column falls sharply beyond this point (e.g., the H\( i \) edge observed in NGC 3198; van Gorkom 1991). This sharp truncation of the H\( i \) distribution is believed to be the result of ionization of the atomic gas by the extragalactic UV radiation field (as predicted by Silk & Sunyaev 1976). At lower column densities, the neutral fraction is therefore predicted to drop dramatically in comparison with the total (ionized) hydrogen column (see Maloney 1993). Some studies have attempted to detect the faint ionized gas just beyond the H\( i \) limit from recombination emission in H\( \alpha \). Depending on the volume density of the plasma at the critical column density at which the outer disk becomes optically thin to this radiation (about \( N_{H_\alpha} \sim 3 \times 10^{19} \) cm\(^{-2}\) for NGC 3198), the emission measure based on recombination radiation expected to be emitted by this ionized gas is only \( 0.025–0.25 \) cm\(^{-6}\) pc (Maloney 1993). The only reported detection of recombination radiation so far is that of NGC 253, for which sensitive Fabry-Perot observations by Bland-Hawthorn et al. (1997) managed to extend the H\( i \) rotation curve from \( 1.2R_{25} \) to \( 1.4R_{25} \), with measured surface brightness values in H\( \alpha \) from 80 to 40 mR (in millirayleighs, where 1 R = \( 10^8/4\pi \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\).
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or 2.78 cm$^{-6}$ pc at H$\alpha$). But at this level, as pointed out by the authors, the emission is probably not due to recombination after ionization by the metagalactic background but rather to hot young stars near the center of the galaxy that ionize the warped outer H i disk.

If indeed spiral galaxies have extended (mostly ionized) gas disks, then it should be possible to detect them in absorption in the spectrum of a bright background quasar, down to H i column densities of only $\sim 10^{13}$ atoms cm$^{-2}$. With such a suitably placed UV-bright background object, one could obtain kinematical information on that galaxy’s outer rotation curve out to (30–40)$\alpha^{-1}$ or more. At such radii, the data could reveal the extent of the dark matter halo and constrain the mass profile out to such large galactocentric radii. This could then provide strong tests of cosmological galaxy formation scenarios. For example, according to the rotation curves predicted by cold dark matter–dominated N-body simulations (e.g., Navarro et al. 1996), in low-mass dwarf galaxies we should be able to detect a turndown in the rotation curve if we could get data points just 15% or 20% farther out in radius than currently mapped by H i observations. This matching of a Ly$\alpha$ absorption-line velocity with the kinematics of the nearest galaxy has already been attempted, originally by Barcons et al. (1995), who found that for two galaxies at $z = 0.075$ and 0.09 the Ly$\alpha$ velocities, as measured from background QSO spectra at impact parameters 64$ h_{75}^{-1}$ kpc ($=16\alpha^{-1}$) and 83$ h_{75}^{-1}$ kpc ($=35\alpha^{-1}$), were consistent with gas in extended gaseous halos corotating with the inner stellar disks (with $h_{75}^{-1} = H_0/75$, where $H_0$ is the Hubble constant and $q_0 = 0$). On the other hand, Hoffman et al. (1998) found that the dwarf galaxy MCG +00-32-16, which is the closest galaxy to the low-redshift Ly$\alpha$ system in the sight line of 3C 273, has an H i disk that would be counterrotating compared with the Ly$\alpha$ velocity. In this case, however, the impact parameter is 204 kpc, which for the dwarf galaxy represents about 153$\alpha^{-1}$, in other words, an excessively large radius for us to expect the extended gas halo to reach. More recently, Steidel et al. (2002) have obtained long-slit spectra of five intermediate-redshift galaxies (0.44 $\leq z \leq 0.66$) in the proximity of Mg ii absorber sight lines (with projected separations from 19 to 95 $h_{75}^{-1}$ kpc) and succeeded in reasonably matching the Mg ii absorbers’ velocities with the galaxies’ rotation curves, but only when setting various disk thicknesses and velocity scale heights (describing the velocity falloff with z-height above the plane) case by case.

Our approach here is the reverse. Instead of identifying and analyzing the galaxies found near the line of sight of a quasar exhibiting a known Ly$\alpha$ line, we start by selecting nearby galaxies, normal and well behaved kinematically and hence easy to subsequently model dynamically, and searching for bright background quasars at some particular impact parameter away, i.e., at the interesting radii beyond the galaxy’s H i envelope and up to about 50$\alpha^{-1}$. We then observe these quasars with the Hubble Space Telescope (HST), first to attempt to detect a Ly$\alpha$ line arising from the extended galaxy’s disk and then to use this Ly$\alpha$ line velocity to probe the outer dynamics of the galaxy.

Our study does not aim to elucidate the overall nature of all Ly$\alpha$ forest lines (other studies are better designed for this, by surveying all lines along several QSO sight lines and getting numerous spectra of galaxies in the surrounding fields; e.g., Penton et al. 2002; Morris et al. 2002). Indeed, while it is now generally accepted that most metal line absorption systems found in QSO spectra are associated with gaseous galaxy halos, the situation for the Ly$\alpha$ absorption systems has long been debated. Some studies claim that (at least the stronger) Ly$\alpha$ lines are associated with extended halos of galaxies, while most believe that the majority of the lines occur in the intergalactic medium, tracing the cosmic web (see van Gorkom et al. 1996), the intricate network of filaments and sheets of gas predicted by hydrodynamical simulations (e.g., Davé et al. 1999). Some convincing arguments of the latter are the fact that several Ly$\alpha$ lines have been detected in voids (McLin et al. 2002), which is also confirmed by deep H i observations that would have detected dwarf galaxies and other low surface brightness galaxies (Shull et al. 1998). In addition, observations of double QSO sight lines find Ly$\alpha$ lines common to both spectra on scales of typically a megaparsec (Dinshaw et al. 1997, 1998). Here we are testing the simple conjecture that gaseous galactic disks extend beyond those that can be probed in emission in H i, by searching for a corresponding Ly$\alpha$ line. More important, a successful detection can be used as a dynamical probe of the outer halo of the galaxy.

In § 2 we explain the selection of our targets. Section 3 describes the observations (HST and radio), and then § 4 discusses the results of matching the Ly$\alpha$ velocities with the galaxies’ rotation curves and the implications.

2. SELECTION OF TARGETS

Our list of galaxy-QSO pairs suitable for our purpose was compiled by cross-correlating all 646 quasars with $V < 17.0$ in the sixth edition of the Véron-Cetty & Véron catalog (1993) with the H i Catalog of Galaxies (Huchtmeier & Richter 1989). This magnitude limit was imposed to make sure that the background QSO observations would be feasible with HST within a reasonable time. Our criteria for selection were the following:

1. The projected distance between the QSO and the galaxy was less than roughly 10 times the optical diameter ($D_{25}$) of the galaxy. This was to find QSOs in the interesting region beyond the galaxy’s H i emission extent but where the column density of neutral gas would still be high enough to be detected in absorption (assuming that galaxies have extended gaseous disks out to large radii, as suggested, e.g., Chen et al. [2001]).

2. The galaxy systemic velocity was $\geq 550$ km s$^{-1}$. This ensured that the associated Ly$\alpha$ detection stayed clear from the geocoronal Ly$\alpha$ emission at 1216 Å (from the Earth’s exosphere). Moreover, this also ensured that the Ly$\alpha$ detection’s velocity would not fall in the range covered by the damped Ly$\alpha$ wing of our Galaxy, which can extend to $\approx 1220$ Å toward some sight lines, depending on the total H i column density present in that direction. If a galaxy’s systemic velocity is too low, any associated line will get lost in the wing of the Galactic damped line, where the continuum against which this absorption line would be detected is seriously depleted.

3. The galaxy was not interacting and was relatively isolated. This means that an observed Ly$\alpha$ line would be fairly unambiguously assigned to that object; i.e., galaxy-QSO pairs in the middle of clusters, such as in 3C 273, were discarded (but one target, NGC 5033, was later found to be surrounded by several dwarf galaxies; see § 4.1).

4. The galaxy’s optical diameter was at least $\geq 1''$, so that a detailed kinematical study using H i rotation curves is feasible (since in the best cases, the H i radio beams are about a dozen arcsec). In some cases, the rotation curves were already available in the literature. For the same reason, the galaxy also had to appear “well behaved,” with no obvious distortions or morphological asymmetries—in other words, as normal as possible.

We observed a sample of nine galaxy-QSO pairs with HST, chosen to cover a range of morphological types (Sa–Sd), with a
range of magnitudes \(-20 < M_B < -15.1\). Assuming successful detection of \(L_{\text{Ly}\alpha}\) absorption lines, this would allow testing of scaling relations across a wide range of galaxy properties. For example, Chen et al. (1998), in their study of 26 galaxy-absorber pairs with separations ranging from 16 to 209 \(h^{-1}\) kpc, find that the strength of the absorption depends not only on the impact parameter separation but also on the \(B\)-band luminosity of the galaxy. Hence, to investigate these possible trends, galaxies with a wide range of properties were chosen for our sample. Table 1 lists the properties of our selected target galaxies. Note that the impact parameters of the galaxy-QSOs are based on distances estimated using \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\). In the case of NGC 2841, there is a Cepheid distance of 14.1 ± 1.5 Mpc (Macri et al. 2001). Its velocity simply estimated with \(H_0 = 75\) would give a distance of 8.5 Mpc, which is only 60% of this “true” distance. Hence this gives an idea of the large uncertainties possible in these impact parameter estimates.

3. OBSERVATIONS AND REDUCTIONS

3.1. HST Observations of QSOs

Spectroscopy of our nine target QSOs was obtained with the \(HST\) Goddard High Resolution Spectrograph (GHRS) through the Small Science Aperture with the G140L grating, as well as with the \(HST\) Space Telescope Imaging Spectrograph (STIS) Far-Ultraviolet MAMA through the 52X0.1 aperture with the G140L and G140M gratings, as listed in Table 2. This table also gives details of the observations (the \(HST\) data set file names and date of the observations) and the total integration times of the spectra. Since the QSOs have a range of fluxes, the integrations were set to result in a 3 \(\sigma\) limiting equivalent width of at least 0.3 \(\AA\), or, in the case of the STIS data, to fill completely the one orbit necessary (this 3 \(\sigma\) limit is achievable in less than one orbit in almost all cases).

The preliminary GHRS data reduction was carried out with the standard CALHRS software using the final GHRS reference files, and further reduction and analysis were performed with the IRAF STSDAS package. To fully sample the point-spread function, quarter-diode substepping was employed, producing four spectra per exposure. In this mode, 6% of the time is spent measuring the background with the science diodes. The wavelength shifts between these different groups and then between the different exposures were determined to align all the spectra before combining them and merging the wavelength and flux information. With the G140L grating, the dispersion is 0.57 \(\AA\) per diode, corresponding to a velocity resolution of about 140 km s\(^{-1}\) at 1200 \(\AA\). The default wavelength scale is expected to have a maximum rms of 55 mA for G140L. However, zero-point shifts can be significant: even though we used the small aperture, which limits the effect of the uncertainty in the position of the target within the aperture, thermal effects in the GHRS, as well as geometrical effects, are a large source of wavelength error (see the GHRS Instrument Handbook). The wavelength accuracy achievable is about 30 km s\(^{-1}\), even when a wavelength calibration exposure is obtained just before the science exposure. For this reason, these zero points were corrected by assuming that low-ionization Galactic interstellar lines lie at the same velocity as the observed dominant component of the Galactic \(H_\text{I}\) along these sight lines. The strongest Galactic lines were used, such as Si II \(\lambda 1206.5,\) Si II \(\lambda 1260.4,\) and C ii \(\lambda 1334.5.\) The Galactic \(H_\text{I}\) LSR velocity measurements were taken from the Leiden Dwingeloo survey (Hartmann & Burton 1997).

For the STIS observations, the G140M centered at 1222 \(\AA\) provides a resolution of 20 km s\(^{-1}\) (with a pixel size of 0.05 \(\AA\)) and wavelength coverage from 1195 to 1249 \(\AA\). In addition, short G140L observations were obtained for the three QSOs at higher redshifts (PG 1049–005, PKS 1103–006, and PG 1259+593). This was to make sure that any absorption feature detected at \(1218–1222\) \(\AA\) (where our \(L_{\text{Ly}\alpha}\) lines are expected) is not in fact a \(L_{\text{Ly}\beta}\) line associated with some \(L_{\text{Ly}\alpha}\) line at higher redshift along the sight line. The G140L therefore provided us with a spectrum over a larger wavelength range (roughly 1130–1720 \(\AA\)) to check on this possibility. The standard CALSTIS procedures were followed to flat-field the individual spectra, extract them, and then wavelength-calibrate and flux-calibrate them. The MAMA spectroscopic accuracy is expected to be about 0.2 pixels when using the narrow slit (<3 km s\(^{-1}\) with G140M) but is ill defined in practice. Hence, the zero points were corrected in the same way as for the GHRS data, by shifting Galactic lines in the spectra to the main Galactic \(H_\text{I}\) LSR velocity. In this case, the Galactic lines used were Si III \(\lambda 1206.5\) and N i \(\lambda\lambda 1199.55,\) 1200.22, and 1200.71 when suitable. For the Galactic \(H_\text{I}\) velocities, several sight lines had higher resolution than Galactic spectra from Effelsberg (Wakker et al. 2001; 9’1 beam), and for the rest, the measurements were extracted from the Leiden Dwingeloo survey (Hartmann & Burton 1997; 36’ beam) or from NRAO 43 m data (Lockman & Savage 1995; 21’ beam). Care was taken with galactic features at non-LSR velocities because of high-velocity clouds (HVCs) present in some of our sight lines. For example, the Mrk 876 sight line crosses the region of Complex C, a prominent HVC covering 10% of the northern sky, and consequently, the Galactic and Complex C Si III lines are blended in the spectrum (Gibson et al. 2001). Our final shifts applied to the spectra differed from the original calibration by 0.8 km s\(^{-1}\) up to 11.6 km s\(^{-1}\) at most. Finally, after continuum fitting and normalization with a low-order polynomial, wavelengths and equivalent widths were measured, and Voigt profiles were fitted to the observed absorption lines. In the case of PG 1309+355, slightly better residuals were obtained when fitting three subcomponents to the line and similarly for PG 0804+761 when fitting two subcomponents. For sight lines with nondetections, equivalent-width limits were calculated following the equations of Ebbets (1995).

\(L_{\text{Ly}\alpha}\) absorption lines were successfully detected for five of our galaxy-QSO targets (illustrated in Fig. 1). Figure 2 shows the (unbinned) spectra with the detections, as well as the four spectra with nondetections. The profile fits are depicted in Figure 3. Table 1 lists the detections and their corresponding velocities and equivalent widths. In many cases, other \(L_{\text{Ly}\alpha}\) lines were also detected along the same sight lines at other various redshifts and do not necessarily seem to be associated with any nearby galaxy. These will be discussed more fully in a forthcoming paper. In all cases, the velocities of our detections agreed within the errors with those in the literature when available, for example, from higher resolution \(FUSE\) data detecting the \(L_{\text{Ly}\beta}\) counterparts of some of our lines. For PG 0804+761, our line of interest at \(V_{\text{Ly}\alpha} = 1570\) km s\(^{-1}\) has not been previously reported, but a higher redshift line in the spectrum that we detect at \(V_{\text{LSR}} = 5561 \pm 8\) km s\(^{-1}\) has been reported by Shull et al. (2000) at \(V_{\text{LSR}} = 5565\) km s\(^{-1}\) and by Richter et al. (2001) at \(V_{\text{LSR}} = 5553\) km s\(^{-1}\) from a \(FUSE\) \(L_{\text{Ly}\beta}\) line. For Mrk 876, Shull et al. (2000) report \(V_{\text{LSR}} = 958\) km s\(^{-1}\) (no errors quoted), for which we have \(V_{\text{LSR}} = 950 \pm 5\) km s\(^{-1}\).

For the equivalent widths, a large part of the uncertainties come from the continuum fitting, especially since some of the lines are on the edge of the Galaxy’s \(L_{\text{Ly}\alpha}\) damped wing. Hence, the errors presented in Table 1 are the sums in quadrature of the uncertainties (1 \(\sigma\)) from photon noise and the estimated errors.
| QSO          | Galaxy   | Type      | $M_B$ | Distance | $\hat{D}$ | $\hat{D}$ | $\rho / D_{25}$ | $V_{gal}$ | $V_{Ly\alpha}$ | $W$ | $b$ | $\log N_H^i$ |
|--------------|----------|-----------|------|----------|---------|---------|----------------|-----------|----------------|-----|-----|---------------|
| PG 0923+201 | NGC 2903 | SB(s)d    | -20.3 | 7.6      | 130.1   | 287     | 10.3           | 566       | -              | <0.14 | -   | -             |
| PG 1309+355 | NGC 5033 Group | SA(s)c | -20.1 | 11.7     | 81.5    | 276     | 7.6            | 875       | 876.9 ± 18     | 1.10 ± 0.17 | 87, 147, 153 | 13.6, 14.0, 14.0 |
| PG 0804+761 | UGC 4238 | SBd       | -18.7 | 20.6     | 22.7    | 136     | 9.5            | 1544      | 1569.9 ± 8     | 0.26 ± 0.03 | 131, 141 | 13.2, 13.2    |
| Mtk 110     | NGC 2841 | SA(r)b    | -21.2 | 14.1     | 84.0    | 344     | 10.4$^d$       | 638       | ...            | <0.09 | ...  | ...           |
| PG 1049−005 | UGC 5985 | S0/a      | -21.0 | 73.8     | 18.1    | 387     | 9.5            | 5538      | ...            | 0.08  | ...  | ...           |
| PKS 1103−006 | NGC 3521 | SB(r)sbc  | -20.9 | 10.7     | 51.9    | 162     | 4.7            | 805       | ...            | <0.22 | ...  | ...           |
| Ton 1542    | UGC 7697 | Scd       | -18.9 | 33.8     | 11.4    | 112     | 5.4            | 2536      | 2556.9 ± 12    | 0.29 ± 0.07 | 104  | 13.73         |
| PG 1259+593 | UGC 8146 | Scd       | -16.7 | 8.9      | 21.3    | 55      | 6.1            | 669       | 679 ± 12       | 0.33 ± 0.08 | 109  | 13.78         |
| Mtk 876     | NGC 6140 | SB(s)cd   | -18.8 | 12.1     | 47.8    | 169     | 7.6            | 910       | 935 ± 5        | 0.39 ± 0.07 | 131  | 13.87         |

$^a$ Blue absolute magnitude of the galaxy, corrected for Galactic and internal absorption, from the RC3.

$^b$ Calculated using $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, except for NGC 2841, which has a Cepheid distance.

$^c$ Impact parameter between the QSO sight line and the center of the galaxy.

$^d$ Ratio of the impact parameter to the optical diameter of the galaxy, measured at a surface brightness level of 25 mag arcsec$^{-2}$.

$^e$ Heliocentric velocity of the galaxy.

$^f$ Heliocentric velocity of the Ly$\alpha$ absorption. In the case of PG 1309+355, for which the line is better fitted by three components, the corresponding velocities are $v_1 = 714.7$, $v_2 = 840.4$, and $v_3 = 1016.0$ km s$^{-1}$.

$^g$ Similarly, for PG 0804+761, the two components have $v_1 = 1506.0$ and $v_2 = 1614.5$ km s$^{-1}$.

$^h$ Total equivalent width or 3 $\sigma$ detection limit in case of nondetection.

$^i$ Doppler b-parameter of the line or different components of the line.

$^j$ H I column densities.

$^k$ There is another galaxy close to this sight line, UGC 5047, at cz = 507 km s$^{-1}$. However, it is a small dwarf, and although it is only 108 $h_{75}^1$ kpc away, its $\rho / D_{25}$ is over 35.
from different reasonable placements of the continuum fit. The continuum signal-to-noise ratio (S/N) per resolution element in our spectra in the region of the expected or detected absorption ranges from 2.2 to 12, since our target QSOs have a wide range of fluxes (the lowest S/N, 2.2, is for PKS 1103–009, which had a detected flux only 2/3 the value estimated from IUE data).

3.2. H i Observations and Rotation Curves

To compare the five detections of Lyα absorption in spectra of background QSOs with the associated galaxies’ kinematics, we needed their velocity fields and rotation curves. For NGC 5033 and UGC 8146, these were available in the literature (Begeman 1987; Rhee & van Albada 1996). For the other three galaxies, we carried out Very Large Array (VLA) H i observations, for which the observational parameters are summarized in Table 3. The correlator was set to a 3.125 MHz bandwidth with 128 channels, for a channel separation of 5.2 km s⁻¹. The calibration and reductions were performed with the NRAO package AIPS, following standard procedures. The absolute flux calibration was determined by observing the standard source 1331+305. After applying calibration and bandpass corrections to the u-v databases, the continuum emission was subtracted in the visibility domain using channels free of line emission. Several sets of maps were produced for each galaxy, one with uniform weighting, which preserves the best resolution, and a few with natural weighting smoothed to various larger beams. These sets of maps were CLEANed well into the noise by monitoring the total cleaned flux as a function of the total number of CLEAN components recovered and were finally restored with a circular symmetric Gaussian beam. These maps were then corrected for the beam response of the antennae to rectify for attenuation away from the center of the primary beam. No H i emission other than that of the intended source was detected from other galaxies within the primary beam through the bandwidth observed.

Moment maps were obtained from each data cube, using Hanning smoothing in velocity and Gaussian smoothing spatially, to produce integrated total H i column density maps, intensity-weighted velocity maps, and velocity dispersion maps. H i rotation curves were obtained by fitting a tilted-ring model to the velocity fields (Begeman 1987; Côté et al. 2000) and are given in Table 4. In each case, the rotation curves are slowly rising and just barely reach the flat part at the last measured points. The errors in velocity were calculated from half the difference between the velocities on each side (receding and approaching) or from the formal errors given by the least-squares fits, whichever were the highest. The rotation curves were derived with the systemic velocities and orientation parameters (position angle and inclination) set to the values shown in Table 3. The derived systemic velocities agree extremely well with the de Vaucouleurs (1991, hereafter RC3) values, within 1 km s⁻¹. The orientation parameters as well agree within a few degrees with those derived optically (from the RC3), which show that these galaxies do not have strong warps in their outer H i gaseous envelopes. The H i distributions and H i velocity fields are shown in Figure 4, and the gas surface density profiles in Figure 5, for which the H i surface density values were scaled by 4/3 to account for the presence of helium. Although the three surface density profiles differ greatly, they are all within the range that is commonly detected in late-type spiral galaxies.

4. RESULTS

4.1. Lyα Detections

Figure 2 shows the five Lyα absorption detections among our nine target QSOs, and Table 1 gives their details. The target galaxy-QSOs that give rise to successful Lyα detections have impact parameters from 55 to 169 h₇⁵⁻¹ kpc, and the detections correspond to H i column densities ranging from log N_{HI} = 13.0 to 13.9 cm⁻². PG 1309+355 (NGC 5033), with an impact parameter of 276 h₇⁵⁻¹ kpc, also gives rise to a detection; however, in this case, it was later found that NGC 5033 is part of a small, loose group of galaxies and is surrounded by a swarm of dwarf galaxies, some of which are closer to the QSO sight line than is NGC 5033 (e.g., UGC 8261, UGC 8323, and UGC 8314). Hence, it is not possible to attribute the absorption detection to NGC 5033 alone. We return to this case later on.

In each case, the Lyα line velocity matches extremely well the systemic center-of-mass velocities of the galaxies. In particular, for PG 1259+593 and Mrk 876, their Lyα absorption lines correspond to velocities of 679 and 935 km s⁻¹, respectively, which are the lowest redshift Lyα lines ever detected in association with nearby galaxies. Presumably, closer galaxies, e.g., M31, could produce Lyα lines of even lower redshift, but they would be impractical to detect because of the damped wing of the Milky Way absorbing all the continuum flux. In fact, in Figure 2, in all our spectra the slope of the Galaxy’s damped wing is clearly seen; i.e., the Lyα detections are within the range covered by the Galaxy’s damped wing, which extends to at least ~1220 Å, sometimes 1222 Å.

As for the Lyα nondetections, they occur for galaxy-QSO separations ranging from 162 to 387 h₇⁵⁻¹ kpc. Their 3 σ limiting
equivalent width is in each case above the level needed to detect an absorption line even weaker than the ones detected in the other five spectra. In terms of H i column density limits, it corresponds to a 3 σ detection limit around $\log N_{\text{HI}} = 13.1 \text{ cm}^{-2}$ on average. This at first sight thus appears to confirm the findings of several studies of moderately low redshift galaxy surveys associated with absorbers, which seem to indicate that most galaxies are surrounded by tenuous gas out to ~240 $h_{75}^{-1}$ kpc. Chen et al. (1998, 2001), in a continuation of the work of Lanzetta et al. (1995), find for 34 galaxy-absorber pairs at $z = 0.07–0.89$ with impact parameters $\rho$ from roughly 16 to 233 $h_{75}^{-1}$ kpc a nearly unity covering factor for tenuous gas halos around typical $L_*$ galaxies out to that radius. Furthermore, Chen et al. (1998) found that the absorbing gas equivalent width depends on the galaxy-QSO impact parameter, as well as the galaxy $B$-band luminosity, which if true would greatly strengthen the case for a direct association between the absorber and its nearest galaxy. Meanwhile, for lines with equivalent widths greater than 0.3 Å, Bowen et al. (1996) found that the covering factor is 44% between 67 and 400 $h_{75}^{-1}$ kpc for 38 galaxies at $z = 0–0.08$, lying less than 400 $h_{75}^{-1}$ kpc from a sight line of a bright QSO observable with the Faint Object Spectrograph. Recently, Bowen et al. (2002) detected Ly$\alpha$ lines in the outer regions of all eight nearby galaxies probed, with
impact parameters up to $265 \ h_{75}^{-1} \ \text{kpc}$, down to $W > 0.1 \ \text{Å}$. Our results accord with these studies. All our detections occur at an impact parameter less than $180 \ h_{75}^{-1} \ \text{kpc}$ from the nearest galaxy, and only one of our nondetections occurs for $\rho < 180 \ h_{75}^{-1} \ \text{kpc}$ (PKS 1103–006 [NGC 3521] at $\rho = 162 \ h_{75}^{-1} \ \text{kpc}$). Note, however, that there is considerable uncertainty in the values of $\rho$ because of the distance dependence (see above). All these results seem very suggestive of a link between the detected absorbers and their neighboring galaxies. But one needs to look into the detailed kinematical match between the Ly$\alpha$ absorption line and the kinematics of the inner galaxy to probe more directly any direct link between an extended gaseous disk or halo of the galaxy and the absorber’s velocity.

4.2. Matching the Galaxies’ Kinematics with the Absorbers

We try to compare here the velocity of the QSO Ly$\alpha$ system with that of the associated galaxy. For four of five detections, the associated galaxy is confirmed to be isolated; hence, the absorber can be unambiguously matched to this galaxy, assuming it is indeed due to a galaxy. For three of these galaxies, UGC 4238, UGC 7697, and NGC 6140, we obtained the H$\alpha$ rotation curves (§ 3). The fourth one, UGC 8146, has been observed by the Westerbork Synthesis Radio Telescope, and its rotation curve was extracted from Rhee & van Albada (1996).

To compare the inner galaxy dynamics with the velocity measured by the Ly$\alpha$ line, we assume that the line does indeed arise in the extended gaseous disk of the galaxy and see how well it matches the velocities of the H$\alpha$ rotation curve in that case. The observed radial velocity of the line, $V_{\text{obs}}$, is related to the corresponding rotation velocity $V_{\text{rot}}$ in the disk of the galaxy by

$$V_{\text{obs}} = V_{\text{sys}} + V_{\text{rot}} \sin i \cos \theta,$$

Fig. 2a

Fig. 2.—(a) GHRS G160L spectrum of PG 1309+355. (b) STIS G140M spectra for the other QSOs (PG 0804+761, Ton 1542, PG 1259+593, and Mrk 876), with the detected Ly$\alpha$ absorption lines associated with our target galaxies. Lines labeled “G” are galactic; those labeled “a.s.” are from the associated absorption systems found around PG 1309+355. Other Ly$\alpha$ lines are found at other redshifts as well. (c) Spectra of the QSOs with no detection of a Ly$\alpha$ absorption line associated with the target galaxy: GHRS G160L for PG 0923+201 and STIS G140M for the others.
where $V_{\text{sys}}$ is the systemic velocity of the galaxy, $i$ is its inclination, and

$$\cos \theta = \frac{X}{R},$$

where in the plane of the sky the QSO has coordinates $X$ along the galaxy major axis and $Y$ along the minor axis, with

$$R = \sqrt{X^2 + Y^2 \sec^2 i}.$$ 

$R$ is the radius in the plane of the galaxy at which the measurement lies, in other words, the deprojected impact parameter of the QSO (a figure demonstrating these formulae is provided in Kerr & de Vaucouleurs [1955], in which, however, the inclination angle is defined as $i = 0$ for an edge-on galaxy, contrary to the modern convention). For the orientation parameters of our galaxies, we have used those derived from the fits to their H$\text{I}$ velocity fields.

Figure 6 shows the resulting rotation curves. The inner points show the velocities obtained from the H$\text{I}$ velocity fields, and the single outer point is from the Ly$\alpha$ detection. The plotted curves are simply the best-fit cold dark matter (CDM) models (Navarro et al. 1996) to the inner rotation curve and serve to guide the eye to what velocities might be expected in these outer parts (note that such CDM curves are actually bad fits to observed rotation curves in the inner parts; see, e.g., Côté et al. [2000], but here we just need them as rough approximations for the outer parts). The rotation curves in every case just reach the flat part at the very last measured point(s) (see Table 4). Each case is discussed separately below.

4.2.1. NGC 6140

NGC 6140 is the only galaxy for which the Ly$\alpha$ velocity could be reasonably reconciled with the value expected if indeed it arises from an extended gaseous corotating disk. Although the Ly$\alpha$ line velocity is much lower than the maximum rotation velocity $V_{\text{max}}$ of the inner rotation curve or than the
velocity expected from CDM models at that radius, there are some ways to make it consistent with a disk velocity at that radius. For example, a strong warp in the orientation parameters of the galaxy in the outer parts would change the deprojection factors, and hence, the calculated Lyα rotation velocity could rise to match the expected value. The present Lyα velocity was calculated using the H i orientation parameters. One would need a warp as large as about 40° in inclination or alternatively 22° in inclination and −31° in position angle to bring the velocity in line with the value expected for a disk. Most galaxies are observed to be warped in their outer parts, but such strong warps are rare for isolated galaxies. But although unusually large, one cannot a priori dismiss the possibility of such a warp in NGC 6140. Another possibility to consider is whether, for whatever reason, the disk, as well as the dark matter halo, of NGC 6140 is truncated just outside the radius of the last measured point in H i. In this case, the velocities in the outer parts should follow a Keplerian falloff, and the velocity expected at the radius of the Lyα velocity would fall to about 46.2 km s\(^{-1}\), close to the measured value \(V_{\text{Ly}\alpha} = 36.2 \pm 5\) km s\(^{-1}\). Finally, another possibility is that the measured velocity is not due to gas actually in the disk plane but to material at a certain \(z\)-height in a thick disk or halo. Assuming a thick rotating disk in which the circular velocities decrease rapidly as a function of scale height, \(v(z) = v_0 e^{-|z|/h}\), where \(v_0\) is the velocity in the disk midplane and \(h\) is a velocity scale height, then one can easily recover from the model a lower velocity like the one observed here by choosing an appropriate value of \(h\). Except in the case of an infinitely large \(h\) for which the thick disk is corotating cylindrically, the velocities at some \(z\)-distance are much lower than

Fig. 3.—Normalized spectra with profile fits on the detected absorption lines, showing the subcomponents for PG 1309+355 and PG 0804+761 (vertical ticks).
at the midplane. This is observed in NGC 891, for example, in which some H\textsc{i} halo gas extending up to 5 kpc from the plane is seen to rotate 25–100 km s\(^{-1}\) more slowly than the gas in the plane (Swaters et al. 1997). Hence, the observed \(\text{Ly}\alpha\) velocity of NGC 6140 would not be at all unphysical but would simply reflect the presence of a rotating thick disk (with detectable gas only at higher \(z\)-height and none in the plane of the disk). For the moment, with only one sight line velocity at large radius, it is not possible to discriminate between these various possibilities and confirm any of them.

### 4.2.2. UGC 4238 and UGC 8146

The situation for UGC 4238 and UGC 8146 is different. In these two cases, assuming planar kinematics, the measured \(\text{Ly}\alpha\) velocity corresponds to a circular velocity actually larger than the expected CDM velocity or even the \(V_{\text{max}}\) reached by the inner rotation curve. A very significant increase of rotation velocity with radius would be required to explain the observed velocity. However, one can again invoke warps to make the observed velocity consistent with the extrapolation of the inner disk rotation. In fact, in these two cases, because of the particular orientation parameters of the galaxies and their angle with respect to their associated quasars’ sight line, one would need only mild warps (on the order of 10° in a suitable direction) to make the match. Consequently, one can still not dismiss a priori the possibility that the absorptions indeed arise from co-rotating gaseous extensions of the inner disks, albeit with nonplanar motions.

### 4.2.3. UGC 7697

The QSO Ton 1542 is situated at the southwest of the galaxy; the observed velocity \(V_{\text{obs}} = 2557 \text{ km s}^{-1}\) is greater than the systemic velocity \(V_{\text{sys}} = 2536\), yet the galaxy’s approaching side is toward the west, meaning that the velocities should all be smaller than \(V_{\text{sys}}\). The observed velocity from the absorption line is counterrotating with respect to the disk velocities. Furthermore, the observed velocities and geometry for UGC 7697 are such that warps cannot provide consistency with an extended gas disk. Unusually large warps would be required to reverse the inclination of the disk on the sky so that counterrotation is observed, and such twisted rotating disks would not likely be stable (with the exception of nearly face-on galaxies in which the reversal of the inclination would be easier to achieve; see, e.g., Cohen [1979] or Appleton et al. [1986], in which such a possibility is discussed to explain the apparent velocity reversals in IC 10 and M51). Counterrotation at very large radii has been observed in H\textsc{i} in a few galaxies, but those galaxies are always interacting with a nearby dwarf (for example, NGC 4449; Hunter et al. 1998) or also harbor inner counterrotation and hence easily stand out morphologically (like NGC 4826, the Evil Eye galaxy; Braun et al. 1994). Neither of these cases apply to any of the galaxies in our sample. In the case of UGC 7697, no amount of disk thickening or warps could explain the discrepancy (unless abnormally large). There is simply no physical way to produce

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**TABLE 3**

| Source       | Date          | Array | \(t_{\text{int}}\) (hr) | Central Velocity (km s\(^{-1}\)) | Beam\(^{\text{c}}\) (arcsec\(^{2}\)) | rms\(^{\text{b}}\) (mJy beam\(^{-1}\)) | \(V_{\text{sys}}\) (km s\(^{-1}\)) | (P.A.\(^{\text{e}}\)) (deg) | \((i)^{\text{f}}\) (deg) | \(M_{\text{H}_\text{i}}\) \((10^{6} \text{ M}_\odot)\) | \(D_{\text{H}_\text{i}}\) (arcmin) |
|--------------|---------------|-------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| UGC 4238.....| 1998 Nov 8    | VLA B/C | 1.5             | 1560           | 12 × 12        | 2.4            | 1544           | 255            | 62             | 2.27           | 5.0            |
| UGC 7697.....| 2000 Apr 17   | VLA C  | 4.6             | 2540           | 14 × 14        | 1.0            | 2535           | 99             | 80             | 1.69           | 2.5            |
| NGC 6140.....| 2000 Apr 21   | VLA C  | 4.3             | 910            | 14 × 14        | 1.2            | 911            | 276            | 49             | 3.51           | 9.3            |

\(^{a}\) Resulting beam size, full resolution (uniform weighting).

\(^{b}\) The rms noise in channel maps at full resolution after CLEANing.

\(^{c}\) Average position angle of the H\textsc{i} distribution.

\(^{d}\) Average inclination of the H\textsc{i} distribution.

\(^{e}\) Total mass of H\textsc{i}, at the adopted distances listed in Table 1.

\(^{f}\) H\textsc{i} diameter, at the 1 \(M_\odot\) pc\(^{-2}\) level.

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**TABLE 4**

**Rotation Curves**

| Radius (kpc) | Velocity (km s\(^{-1}\)) |
|--------------|-----------------|
| UGC 4238     |                 |
| 0.798        | 13.07 ± 1.79    |
| 1.995        | 37.7 ± 1.49     |
| 3.19         | 60.7 ± 0.76     |
| 4.389        | 67.5 ± 4.82     |
| 7.183        | 82.48 ± 4.36    |
| 9.98         | 91.46 ± 3.03    |
| 12.77        | 91.67 ± 2.8     |

| UGC 7697     |                 |
| 2.13         | 58.77 ± 0.52    |
| 4.42         | 73.99 ± 2.87    |
| 6.72         | 93.10 ± 0.82    |
| 9.01         | 105.52 ± 1.07   |
| 13.60        | 107.3 ± 2.25    |

| NGC 6140     |                 |
| 1.18         | 39.36 ± 4.5     |
| 2.35         | 66.93 ± 1.05    |
| 3.53         | 85.80 ± 4.87    |
| 4.81         | 100.03 ± 4.54   |
| 5.88         | 107.86 ± 0.29   |
| 7.06         | 110.48 ± 2.4    |
| 8.24         | 111.39 ± 2.68   |
| 9.41         | 112.69 ± 4.04   |
| 10.59        | 115.74 ± 6.34   |
| 11.77        | 119.60 ± 7.11   |
| 12.95        | 122.53 ± 6.11   |
| 14.12        | 126.91 ± 5.30   |
| 15.3         | 133.43 ± 3.33   |
| 16.48        | 138.31 ± 2.28   |
| 17.65        | 140.21 ± 2.05   |
| 18.83        | 138.75 ± 3.89   |
| 20.01        | 139.85 ± 9.63   |
such a velocity with an extended corotating disk. This is sobering because UGC 7697 is one of the galaxies for which the QSO is at the smallest impact parameter, and yet the absorption’s velocity does not match. It is also interesting to note from Figure 1 that for UGC 7697 the QSO lies close to the projected optical major axis in angle (compared with the other galaxies). If the gas has a higher column density in the disk than in the halo, we should expect a clear detection of the rotating H\textsubscript{i} disk of UGC 7697, if it does reach this radius at the N\textsubscript{HI} = 10^{13} \text{ cm}^{-2} level.

Note that some have invoked the existence of very low surface brightness galaxies or dwarf galaxies, undetected in the optical, that could lie closer to the QSO sight line than the apparently nearest galaxy and from which the Ly\alpha line could originate. In the case of UGC 7697, this is very unlikely since we also acquired deep H\textsubscript{i} pointings with the VLA on all our QSO fields and should have detected such galaxies, down to a few times 10^{6} \text{ M}_\odot (to be presented in a forthcoming paper).

4.2.4. From the Literature: NGC 988 and NGC 3942

Our conclusion that the Ly\alpha absorptions cannot arise in simple extended disks is confirmed by two other galaxies associated with Ly\alpha absorbers taken from the literature, for which similar results are found. Bowen et al. (2002) targeted a sample of eight nearby galaxies near the sight lines of QSOs and active galactic nuclei. Most of their galaxies are not isolated (contrasting with the careful selection criteria of our sample) but are
part of binary pairs or small groups (their sample was produced by cross-correlating the RC3 with the Veron-Cetty & Veron [1996] catalog and choosing galaxies with velocities greater than 1300 km s\(^{-1}\) and impact parameters for QSOs of less than 200 \(h_7\) kpc). However, two galaxies, NGC 988 and NGC 3942, are reasonably isolated, at least on the scale of a few hundred kpc. Their projected separations from their associated QSOs are 211 and 123 \(h_7\) kpc, respectively, and no other galaxies around a diameter of 400 kpc from these QSO sight lines are known. Unfortunately, no rotation curves, in either optical (in H\(\alpha\)) or H\(_I\), are available for these two galaxies. But for the sake of comparing the inner galaxy’s kinematics with the Ly\(\alpha\) absorption velocity, we can use the magnitudes of NGC 988 and NGC 3942 to derive approximate rotation curves, using the universal rotation curve of Persic & Salucci (1996; in which they obtained, on the basis of a sample of 1100 rotation curves, a relation between the shape and amplitude of a rotation curve, and the luminosity of the galaxy). We see below that these approximations are more than satisfactory for us to draw conclusions. The Ly\(\alpha\) line velocities observed in the spectra of Mrk 1048 and PG 1149–110 are taken from Bowen et al. (2002). One last important piece of information needed to compare the inner and outer velocities is the sense of rotation of the galaxy; i.e., we must determine whether the QSO lies behind the approaching or the receding side of the galaxy (otherwise, it is not known whether the velocity difference is due to corotation or counterrotation). This might be difficult to establish without a proper two-dimensional velocity field for these two galaxies. Fortunately, NGC 988 and NGC 3942 are reasonably nearby and extended in angular size, and hence, their H\(_I\) envelope should be at least a few arcminutes in diameter. In that case, it is possible to detect the change in shape of the H\(_I\) global profile at different positions around the galaxy in the HiPASS scans (HiPASS is the All-Southern-Sky H\(_I\) survey performed with the Parkes multibeam receiver and is available on-line; Barnes et al. 2001). By retrieving the H\(_I\) profiles on each side of the galaxy (the pointings in the on-line catalog are separated by roughly 8\(^\circ\) from each other), it is possible to follow the change from a double-peaked profile for NGC 988 (with a systemic velocity of 1504 km s\(^{-1}\)) to a profile with a single peak at roughly 1400 km s\(^{-1}\) at the east to one around 1600 km s\(^{-1}\) at the west and hence determine that for NGC 988 the approaching side is on the east and the receding one is on the west. Similarly, for NGC 3942, the approaching side is seen to be in the southeast and the receding one in the northwest. With this information, one can then plot the rotation curves of Figure 7. They confirm the findings on our galaxies above. Because for NGC 988 the velocity difference between the Ly\(\alpha\) absorption line and the systemic velocity of the galaxy is already quite large, this translates into a rotation velocity (with the appropriate deprojections) that is ridiculously too elevated (~1192 km s\(^{-1}\)), and no amount of warping, no matter how
severe, can bring this velocity down to a value close to $V_{\text{max}}$. For NGC 3942, the calculated rotation velocity is also inadequate, as we find here another case of counterrotation. Again NGC 3942 has a relatively small impact parameter to the Lyα line, compared with those in our sample, with the projected distance corresponding to $147 \, h_{75}^{-1} \text{kpc}$, and yet, already at that radius we no longer detect the extended corotating gaseous disk of the galaxy.

**4.3. The Nature of the Lyα Detections**

Could it be that somehow, although not in a corotating disk or halo, this detected gas is still associated with the galaxy? After all, the Milky Way is known to be surrounded by HVCs, which can have velocities above or below the Galaxy’s rotation velocity by several hundred km $s^{-1}$ (see, e.g., Wakker 1991). Following strong supernova events, some ejected gas might hide in a hot phase until eventually it cools down and could then be detected to low column densities in our sight lines at very large radii. Multiple supernova remnants can drive a super-bubble to evolve quickly into a blowout, leaving a hole in the galactic disk (e.g., Mac Low & McCray 1988). Some gas can even be accelerated beyond the escape velocity and blown away, completely unbound from the galactic potential (de Young & Heckman 1994). For small dwarf galaxies, for which gas can more easily escape the potential, it might be possible to generate large ($100 \, \text{kpc}$ size) gaseous halos with supernova-driven winds (Nath & Trentham 1997). For larger galaxies, it is expected that there is a local circulation of gas (to a few scale lengths above the...
disk) via a fountain-type flow (Shapiro & Field 1976). However, it might be unlikely to blow gas out of a more normal galaxy (closer to $L_*$) to distances of more than 100 kpc, corresponding to factors of up to 7.5 times the diameter of the galaxy, as is the case here for NGC 6140.

Another possibility is that we are intercepting satellite objects (very small galaxies or clouds of gas) orbiting around the primary galaxy. This would explain the counterrotating velocities, as satellite objects can have retrograde, as well as prograde, orbits. In fact, in the study of the supermassive disk galaxy NGC 5084, orbited by a record number of nine satellite dwarf galaxies (Carignan et al. 1997), the large majority of the satellite objects (seven out of nine) are on retrograde orbits. The problem with this explanation, however, is the overly large covering factor of the detected gas for impact parameters less than 160 kpc. In the Bowen et al. (2002) study, they detect all QSOs at impact parameters less than 265 $h_{75}^{-1}$ kpc (down to $W > 0.11$ Å), and in our case, all QSOs at less than 136 $h_{75}^{-1}$ kpc are detected. It would thus be very unlikely that by chance the sight lines always intercept one of the satellites, especially if we consider the range of orientation parameters of the targets. Moreover, these satellite objects would have to have very unusual properties compared with other dwarf galaxies, since we have deep VLA H i pointings for all our fields in which we would have detected any objects above about $10^6 M_\odot$ (to be presented elsewhere).

Another important clue in constraining the nature of the detected Ly$\alpha$ absorbers is the inspection of the lines’ equivalent widths. A strong argument in favor of the extended galactic disks’ origin of the Ly$\alpha$ lines has been the apparent anticorrelation between equivalent width and impact parameter for the lines, with the absorption stronger the closer it is to the galaxy (Lanzetta et al. 1995). The Chen et al. (1998) study also finds a dependence on the luminosity of the galaxy of the form

$$ \log \frac{N}{10^{20} \text{ cm}^{-2}} = -5.33 \log \frac{\rho}{10 \text{ kpc}} + 2.19 \log \frac{L_\beta}{L_\odot} + 1.09, $$

meaning that brighter galaxies have stronger absorptions at a given radius. Tripp et al. (1998) discussed a few possible selection biases that could explain this anticorrelation. Most interestingly, Bowen et al. (2002) plotted this relation for their eight nearby galaxy-QSO pairs and found that the Chen et al. luminosity dependence is not confirmed. In fact, they found a correlation in the opposite sense, significant at the 2.8 $\sigma$ level, implying that stronger absorbing lines are associated with fainter galaxies. They concluded that this relation is probably coincidental, simply a result of small number statistics. In our data, with four points, we find a dependence between that of Chen et al. (1998) and that of Bowen et al. (2002); in fact, it is consistent with no dependence on luminosity. Meanwhile, the hydrodynamical simulations of Davé et al. (1999) have successfully reproduced the anticorrelation of equivalent widths and impact parameters in the context of the cosmic web. They showed that the cosmic gas that loosely traces the large-scale structure has three phases: the strongest absorbers arising near galaxies because the gas is denser there; the majority of the absorbers arising at impact parameters between 40 and $360 h_{75}^{-1}$ kpc from shock-heated gas around galaxies; and at impact parameters farther than $360 h_{75}^{-1}$ kpc, the absorbers associated with a cooler diffuse gas component.

This result is corroborated by another interesting correlation, plotted by Bowen et al. (2002), between the equivalent widths and the local volume density of galaxies. For each sight line, they calculated the total equivalent width by summing all lines within $\pm 500$ km s$^{-1}$ and plotting them against the number of galaxies with $M_{\text{lim}} < -17.5$ in a cylinder of radius $2 h^{-1} \text{ Mpc}$ and length equal to the distance between $+500$ and $-500$ km s$^{-1}$ from the Ly$\alpha$ line. Their choice of $M_{\text{lim}}$ was dictated by the limiting apparent magnitude for completeness in the RC3 along their sight lines. They find that the higher the density of $M_\beta < -17.5$ galaxies in a given volume, the stronger the equivalent width of Ly$\alpha$ absorption over 1000 km s$^{-1}$. This suggests that the strength of the Ly$\alpha$ absorbers is not related to their nearest galaxy neighbor but rather to the overall volume density of galaxies within a few Mpc of the sight line.
of Ly$\alpha$ lines versus the estimated volume density of galaxies around our targets are similarly plotted. Following Bowen et al. (2002), we summed all components of Ly$\alpha$ absorption within +500 and −500 km s$^{-1}$ from the main Ly$\alpha$ line. Only in one case (PG 0804+761) was there another Ly$\alpha$ absorber to include within that range. Similarly, we considered only galaxies with $M_{\text{lim}} < -17.5$ within a 2 $h^{-1}$ Mpc radius and within +500 and −500 km s$^{-1}$ in the RC3.

Our data agree very well with the Bowen et al. (2002) result, within the errors (our errors in $n$ are simply $\sqrt{n}$). The sight line to Ton 1542 goes through the least dense area (with only two galaxies bright enough within the 2 $h^{-1}$ Mpc radius), and the Ly$\alpha$ line is indeed the weakest of all our targets. On the other hand, the sight line to PG 1309+355 and close to NGC 5033 is surrounded by galaxies (in fact, we had to eliminate NGC 5033 a posteriori from the rotation curve analysis precisely because of this; there are too many other galaxies close to the QSO, and hence, it was not possible to attribute the Ly$\alpha$ detection to any galaxy in particular). Furthermore, the Ly$\alpha$ line in the spectrum of PG 1309+355 is by far the strongest and most complex, blending several components into a line with total equivalent width $1.14 \pm 0.09$ Å. The other three sight lines, with small equivalent widths, fall between the former and the latter in terms of the volume density of galaxies. The three data points all lie at higher volume density than the Bowen et al. points of similar equivalent width, but if we consider the small number statistics here it is probably not a significant offset. These galaxies all lie at systemic velocities smaller than those studied by Bowen et al., so it is possible that the neighborhoods of these local galaxies have been better surveyed. On the other hand, these galaxies are so close (<1500 km s$^{-1}$) that estimating the galaxy volume density by adding all galaxies within +500 and −500 km s$^{-1}$ probably does not make much sense if we consider the large deviations from a smooth Hubble flow that are seen at these small distances from us.

While the choice of a 2 $h^{-1}$ Mpc radius for estimating the galaxy volume density in Bowen et al. (2002) was rather arbitrary, the limiting value $M_{\text{lim}} < -17.5$ was guided by the estimated completeness to $B_{\text{lim}} = 15.5$ of the RC3 for the farthest targets of their sample. In our case, because our galaxies are closer, we can inspect the volume density down to a fainter limit using the RC3. In fact, we know that our strongest line, for PG 1309+355, is surrounded by dwarf galaxies in close proximity but that the galaxies were not counted in the previous volume density estimate because they were of lower magnitude than $M_{\text{lim}} < -17.5$. For Figure 9, we have recomputed volume densities of galaxies down to $M_{\text{lim}} < -16.5$, which corresponds to $B_{\text{lim}} = 15.5$ for our sample objects in a smaller cylinder, with radius 0.5 $h^{-1}$ Mpc. Again, the relation holds very well, although we are dealing with even smaller number statistics.

It thus appears that there is a relationship between the Ly$\alpha$ column density along a sight line and the surrounding volume density of galaxies. This makes sense if the absorbers are simply part of the cosmic web. The galaxies have condensed in the densest parts of this network of filaments and sheets of gas, and hence, the Ly$\alpha$ detections are denser when crossing a web filament or sheet rich in galaxies. The Ly$\alpha$ absorbers are detected only within less than about 170 $h^{-1}$ kpc down to our limiting equivalent widths in the neighborhood of galaxies because that is where the gas has higher column density in the filament, in the dense region from which the galaxy has condensed. On a larger scale, the Ly$\alpha$ line is stronger when crossing the core of a filament or a busy intersection of filaments of the web, where one finds a higher density of galaxies, on a scale of radius 2 $h^{-1}$ Mpc. That the relationship still seems to hold on the smaller scale of radius 0.5 $h^{-1}$ Mpc when we consider the density of lower luminosity galaxies (Fig. 9) is perhaps not surprising, as small groups of galaxies (like the agglomeration around PG 1309+355) tend to be found on the periphery of larger clusters, while most of our other targets are probably in semivoid regions (since galaxies were purposely selected to be isolated for this project). It is not obvious what the relevant scale for calculating the surrounding galaxy density should be. In simulations of the cosmic web, the filaments have various thickness, although they are definitely on the order of megaparsecs, down to the detectable
column densities as given here (Miralda-Escudé et al. 1996; Davé et al. 1999). Observations of double QSO sight lines also find that, by looking at Lyα lines common to both spectra, the typical scale is around 0.5 Mpc (Dinshaw et al. 1997, 1998).

It is also interesting to look at the Doppler b-parameters from the Voigt profile fits and compare them with those obtained by Bowen et al. (2002; keep in mind that some b-values are uncertain because of the W-b degeneracy for saturated lines). In most of their sight lines, several resolved Lyα lines were added (within their +500 and −500 km s⁻¹ limit) to make the total equivalent widths plotted in Figure 8. In contrast, for most of our sample, the total equivalent widths come mostly from a single line. PG 0804+761 is an exception because two lines were added and also because the main line associated with the galaxy (i.e., the one that matches more closely in velocity) is better fitted by two profiles than by one. Similarly, for PG 1309+355, the profile, which has the highest equivalent width of all, is very broad and shows several features, and the fit is considerably improved by fitting three Voigt profiles rather than a single one. Interestingly, the trend in Figure 8 holds well whether one is considering the addition of several narrow lines (typically \( b < 50 \) km s⁻¹) in the case of the Bowen et al. (2002) sample or the denser, wider single b-lines from our sample. One cannot exclude that our single lines are actually unresolved groups of narrower lines. If not, depending on the environment, there might be a real physical difference in the density and temperature of the cosmic web gas, since our galaxies were mostly selected to be isolated, while those of Bowen et al. (2002) belong to pairs or small groups. The Bowen et al. (2002) lines are also at redshifts on average twice as distant as those of our sample. While some evolution with redshift is expected for the density of the cosmic web, since at lower redshift more of the gas has condensed along the filaments (Davé et al. 1999), the two samples discussed here probably do not cover a range wide enough in redshift to see this. Our b-values go up to about 150 km s⁻¹, unusually large for Lyα forest absorption lines, although a few of the Bowen et al. (2002) sample do reach similar values. If the lines are indeed composed of only a single component and we assume that the line width is purely due to the gas kinetic temperature [in which case \( b = (2kT/m_p)^{1/2} \)], where \( k \) is Boltzmann’s constant and \( m_p \) is the proton mass], then this would represent absorption from hot gas at a temperature of \( T = 60.6b^2 \); in our cases, \( T = 0.4–1.4 \times 10^6 \) K.

On the basis of these relationships, it thus appears that the cosmic web is the most likely explanation for the origin of our Lyα absorption-line detections. Thus, the positive Lyα detections, despite appearing in proximity to the target galaxies, are not directly related to these galactic disks but are only indirectly related because of the position of these galaxies in the large-scale structure of the cosmic web.

5. SUMMARY AND CONCLUSIONS

Sight lines of QSOs at impact parameters 55–387 \( h^{-1} \) kpc from nine nearby galaxies (at systemic velocities from 566 to 5538 km s⁻¹) were probed, using GHRS and STIS. In five cases, a Lyα absorption line was successfully detected at a velocity coincident with the galaxy’s. Some of these Lyα lines are the lowest redshift Lyα lines ever detected, and, in fact, most of them are on the wing of the Milky Way Lyα damped line (hence, introducing uncertainties in the derived equivalent widths). The positive detections occur for galaxy-QSO pairs with separations from 55 to 169 \( h^{-1} \) kpc, while nondetections are for pairs with separations from 162 to 387 \( h^{-1} \) kpc. Although at first sight it appears that the Lyα lines might genuinely arise in the extended disks of the target galaxies, this is not what transpires when we inspect the detailed kinematics of these galaxies. H i velocity fields were obtained at the VLA for our galaxies (in one case the velocity field was available from the literature), to derive their rotation curves. When we compare the inner rotation curves of the galaxies with the velocities at large radius provided by the Lyα lines, it appears that it is very difficult to explain these Lyα velocities as part of the extended gaseous rotating disks. In most cases, one would need to invoke large warps in the extreme outer gas disks to reconcile the observed velocities with the predicted ones. Worse, in some cases, the Lyα line velocity in fact indicates counterrotation with respect to the inner disk rotation.

In light of these results, it appears that, down to levels of about \( 10^{13} \) cm⁻², there is no detectable gas corotating in an extended gaseous disk at radii greater than \( 35 \alpha^{-1} \) kpc. The cosmic web is the most likely origin for the detected Lyα lines. The observed equivalent widths of the lines are consistent with this picture. Indeed, the equivalent widths are correlated with the local volume density of galaxies around the sight line. This makes sense if the Lyα lines arise from the cosmic web, which is denser in regions of higher volume density of galaxies (since the galaxies have formed by condensing in the denser parts of the network). This correlation would be difficult to explain if the Lyα lines arose from halos or extended disks of the nearest galaxy. One could argue that the equivalent widths should be larger for sight lines close to larger galaxies, which tend to be found in regions of higher galaxy volume density, which could then explain the trend observed. However, if this were the case, then one would observe presumably an even stronger correlation between the equivalent widths and the luminosity of the nearby galaxy, and, although this was reported by Chen et al. (1998), it is now clearly contested by the results of Bowen et al. (2002), as well as by our sample, for which no correlation is found between equivalent widths and luminosities.

Note that these results do not necessarily imply that the dark matter halos of these galaxies do not exist at the radii probed by our QSO sight lines. It simply means that there is no longer any detectable gas in rotation in an extended gas disk at these radii and that the Lyα lines detected are due to foreground or background cosmic web gas surrounding the galaxy. In fact, weak-lensing studies seem to indicate that, indeed, the dark matter halo extends very far out, typically farther than 300 \( h^{-1} \) kpc for a \( L_* \) galaxy (e.g., Smith et al. 2001). But there is no gas to trace its dynamics out there, at least down to our limiting column densities. H i as traced by background QSOs, therefore, is not a useful tracer of galactic potential in the far outer regions of an ~200 kpc halo. Only weak lensing and, perhaps, Hα in recombination from the extended ionized disk (Bland-Hawthorn et al. 1997) could be tracers of dynamics at such radii. These QSOs turn out, however, to be extremely useful for probing the phases of the cosmic web gas. Many more sight lines are required, however, before one can attempt to understand the cosmic gas distribution and density, as well as its evolution with redshift. The planned HST COS spectrograph would have allowed us to probe the sight lines of fainter QSOs, which would greatly increase the available sample, and we hope that the decision regarding HST can be reversed in the future. Eventually, the next generation of sensitive giant radio telescopes, such as the Canadian Large Adaptive Reflector (Côté et al. 2002) and the Square Kilometer Array, will be able to efficiently survey large areas of the sky down to column densities as deep as \( 10^{16} \) cm⁻² and hence, trace directly in emission the structure of such low column density gas in the cosmic web.
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