INTERGALACTIC HYDROGEN CLOUDS AT LOW REDSHIFT: CONNECTIONS TO VOIDS AND DWARF GALAXIES[1]

J. MICHAEL SHULL,[2] JOHN T. STOCKE, AND STEVE PENTON

Center for Astrophysics and Space Astronomy, Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado, CB-389, Boulder, Colorado 80309

ABSTRACT

We provide new post-COSTAR data on one sightline (Mrk 421) and updated data from another (I Zw 1) from our *Hubble Space Telescope* (*HST*) survey of intergalactic Lyα clouds located along sightlines to four bright quasars passing through well-mapped galaxy voids (16 000 km s^{-1} pathlength) and superclusters (18 000 km s^{-1}). We report two more definite detections of low-redshift Lyα clouds in voids: one at 3047 km s^{-1} (heliocentric) toward Mrk 421 and a second just beyond the Local Supercluster at 2861 km s^{-1} toward I Zw 1, confirming our earlier discovery of Lyα absorption clouds in voids [Stocke et al., ApJ, 451, 24 (1995)]. We have now identified ten definite and one probable low-redshift neutral hydrogen absorption clouds toward four targets, a frequency of approximately one absorber every 3400 km s^{-1} above $10^{12.7}$ cm^{-2} column density. Of these ten absorption systems, three lie within voids; the probable absorber also lies in a void. Thus, the tendency of Lyα absorbers to "avoid the voids" is not as clear as we found previously. If the Lyα clouds are approximated as homogeneous spheres of 100 kpc radius, their masses are $\sim 10^9 \mathscr{M}_\odot$ (about 0.01 times that of bright L^* galaxies) and they are 40 times more numerous, comparable to the density of dwarf galaxies and of low-mass halos in numerical CDM simulations. The Lyα clouds contribute a fraction $\Omega_{cl} \approx 0.003 h_{75}^{-1}$ to the closure density of the universe, comparable to that of luminous matter. These clouds probably require a substantial amount of nonbaryonic dark matter for gravitational binding. They may represent extended haloes of low-mass protogalaxies which have not experienced significant star formation or low-mass dwarf galaxies whose star formation ceased long ago, but blew out significant gaseous material. © 1996 American Astronomical Society.

1. INTRODUCTION

Over the past two decades, redshift surveys of the nearby universe (Geller & Huchra 1989; Fairall et al. 1990) have mapped out a highly inhomogeneous galaxy distribution, with large "voids" bounded by sheetlike superclusters. A goal of studies of the content of these voids (Sanduleak & Pesch 1987; Szomuru et al. 1994; Weinberg et al. 1991; Strauss & Huchra 1988) is to understand how galaxy formation and subsequent interactions fit into a cosmological framework. With the *Hubble Space Telescope* (*HST*), we have undertaken a spectral search for low-redshift neutral hydrogen (Lyα) absorption clouds along sightlines to bright quasars behind well-mapped voids and superclusters. In our earlier work from Cycle 2 (Stocke et al. 1995, hereafter referred to as Paper I), on the first three sightlines, we detected eight definite Lyα absorption lines, ranging in equivalent width from 26 to 240 mÅ. Seven of these absorbers were located in supercluster galaxy structures. One absorber, in the sightline toward Mrk 501, was located in a void, more than 5.9 Mpc from the nearest bright galaxy.

This discovery demonstrated that the voids are not entirely empty of gaseous matter, but the statistics were low. In fact, a number of H I galaxies, *IRAS* galaxies, and emission-line galaxies have been found within the boundaries of the Bootes void (Tifft et al. 1986; Weistrop & Downes 1988; Dey et al. 1990; Szomoru et al. 1993), the Pegasus void (Fairall et al. 1990), and the Pisces–Perseus void (Henning 1992). However, the filamentary structure of galaxies inside the Bootes and Pegasus voids is similar to that found in the voids between the Local Supercluster and the "Great Wall" in the CfA survey (Huchra et al. 1993; see also our Fig. 3). Because the total extent of the voids is somewhat uncertain at the distance of Bootes, we chose our targets toward more local voids, with better-mapped galaxy distributions. For example, one Lyα cloud in the direction of Mrk 501 reported in Paper I is found within a filamentary structure of galaxies separating two large voids whose total size is comparable to the Bootes void.

In this paper, we report the results of additional *HST* Cycle 4 observations of I Zw 1 and Mrk 421. Toward I Zw 1, we are now able to upgrade a "probable" void absorber to "definite" status, and we have detected another Lyα absorber in a void toward the fourth target, Mrk 421. We update the distribution of Lyα clouds toward all four sightlines, analyze the physical parameters of these Lyα clouds, and make an estimate of their contribution to the baryonic mass density of the Universe. We conclude with a discussion of a possible

---

connection of Lyα clouds with dwarf galaxies and the implications of our detections for cosmology and galaxy formation.

2. OBSERVATIONS

The spectra of our first three targets (Mrk 501, Mrk 335, I Zw 1) were taken with the Goddard High-Resolution Spectrograph (GHRS) aboard the *HST*, using the G160M grating with pre-COSTAR optics. These data and their interpretation are discussed in detail in Paper I). Since that paper, we have reobserved I Zw 1 (6.53 hr on 1995 February 6) and obtained a new spectrum (4.35 hr on 1995 February 1) of our fourth target, Mrk 421. I Zw 1 (0050+1225) is a bright quasar ($V = 14.0$, $cz = 18\,300$ km s^{-1}) located at $l = 123.75°$ and $b = -50.2°$, while Mrk 421 is a bright BL Lac object ($V = 12.9$, $cz = 8880$ km s^{-1}) located at $l = 179.8°$ and $b = +65.0°$. Both observations used the G160M grating and the COSTAR enhancement of the GHRS optics to obtain 40 km s^{-1} resolution in the interval 1222–1259 Å. These wavelengths correspond to redshifted velocities $cz \approx 1500$–$10\,500$ km s^{-1} extending roughly from the local supercluster to the "Great Wall" (Geller & Huchra 1989). In this paper we assume a Hubble constant $H_0 = (75$ km s^{-1} Mpc$^{-1})h_{75}$. The four QSO targets (Mrk 501, Mrk 335, I Zw 1, and Mrk 421) were chosen because of their brightness ($V \leq 14$) and their location behind well-studied galaxy distributions with foreground voids considerably emptier than the Bootes Void (Sanduleak & Pesch 1987; Szomoru *et al.* 1994; Weinberg *et al.* 1991; Strauss & Huchra 1988).

Our data reduction was identical to that in Paper I. All spectra were taken through the 2″ large science aperture using the standard quarter-diode substepping pattern to yield pixels of 0.018 Å in the FP-split mode. We reduced our spectra with the STSDAS spectral reduction package within IRAF, and the wavelength scale was determined by assuming that the Galactic S II absorption features at 1250.584 and 1253.811 Å lie at zero velocity in the local standard of rest (LSR). The statistical significance of the absorption features was determined from measured noise in the continuum and from uncertainties in continuum placement. The status of "definite" absorber was given to features greater than 4σ significance; "probable" detections were those of 3–4σ significance.

In Fig. 1 we show the coadded spectrum of I Zw 1 (6.53 hr of new data added to 7.21 hr of previous data taken on 1993 September 8). We have definite detections of five spectral features: three Lyα lines and two Galactic S II absorbers. By combining the two spectra, we confirm our previous definite detections of Lyα absorbers at heliocentric velocities 1617±5 and 5130±12 km s^{-1}, and we upgrade the "probable" detection of the 2861±9 km s^{-1} absorber to definite status. The new spectrum of Mrk 421 is shown in Fig. 2. We detect a single Lyα absorber at high significance at velocity 3046±2 km s^{-1} and two Galactic S II lines. Table 1 lists the wavelengths, heliocentric velocities, equivalent widths, and significances of the features.

The two new absorbers toward I Zw 1 and Mrk 421 both lie within voids, confirming our previous discovery of Lyα
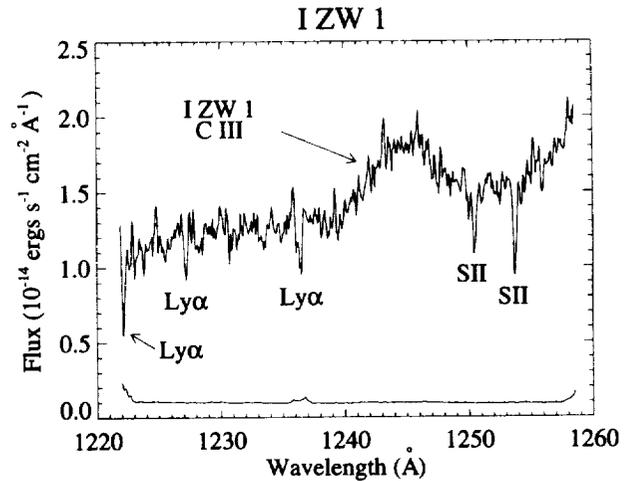

FIG. 1. *HST*/GHRS spectrum of I Zw 1 taken with G160M grating; figure shows combined data from pre-COSTAR (7.21 hr) and post-COSTAR (6.53 hr) exposures. Three definite Lyα absorbers are detected at wavelengths 1222.2, 1227.3, and 1236.5 Å. The second absorber at heliocentric velocity 2861±9 km s^{-1} and equivalent width 84±40 mÅ lies within the void of foreground galaxies. Lines at 1250.59 and 1253.81 Å are Galactic interstellar S II, and the broad emission line is C III λ1175 from the QSO.

clouds in voids. The galaxy distributions are shown in Fig. 3, based on the CfA merged galaxy redshift catalog (Huchra *et al.* 1993). Because the Mrk 501 sightline lies near the eastern edge of the CfA survey, we obtained 20 additional redshifts at R.A. greater than 17 hr from the ongoing survey to verify that the voids in front of Mrk 501 extend well beyond 17 hr (Huchra, private communication). The galaxy distributions toward Mrk 501 and Mrk 421 are shown at somewhat higher declinations ($\delta = 39° \pm 4°$) than those usually displayed by the CfA group (de Lapparent *et al.* 1986; Peebles 1993). These sightlines traverse comparable portions of "supercluster" and "void," determined according to the
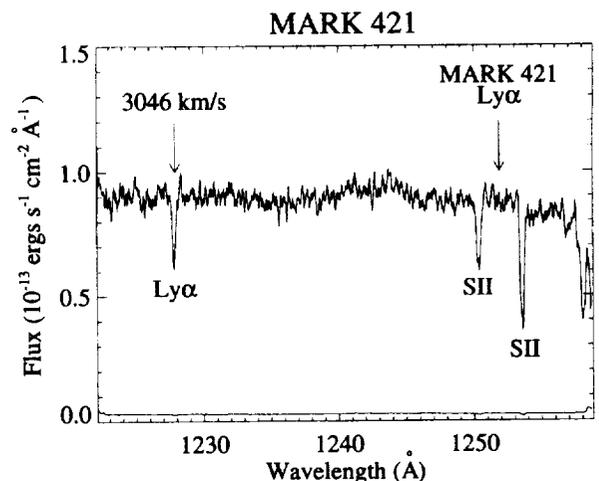

FIG. 2. *HST*/GHRS spectrum of Mrk 421 taken with G160M grating and post-COSTAR optics. A Lyα absorber at 3046±2 km s^{-1} and equivalent width 92±10 mÅ lies within the void of foreground galaxies. Lines at 1250.59 and 1253.81 Å are Galactic interstellar S II. A second arrow marks the expected (1252 Å) position of redshifted Lyα from the BL Lac object ($z_{em} = 0.0298$). The line at 1258.5 Å is unidentified; its wavelength is 1 Å shortward of S II 1259.52 Å, but the wavelength scale at the long end is uncertain.

TABLE 1. Detected absorption lines[a] towards I Zw 1 and Mrk 421.

Target	System Designation	Wavelength (Å)	Velocity (km s^{-1})	W_λ (mÅ)	Significance (σ)	Identification
I Zw 1	A	1222.23	1617 ± 5	120 ± 37	7.1	Lyα
I Zw 1	B	1227.27	2861 ± 9	84 ± 40	4.7	Lyα
I Zw 1	C	1236.47	5130 ± 12	84 ± 47	4.9	Lyα
I Zw 1		1250.56	.....	109 ± 44	8.9	S II Galactic
I Zw 1		1253.84	.....	132 ± 37	10.5	S II Galactic
Mrk 421	A	1228.02	3046 ± 2	92 ± 10	24	Lyα
Mrk 421		1250.55	.....	122 ± 11	35	S II Galactic
Mrk 421		1253.79	.....	195 ± 10	61	S II Galactic

[a] Features detected above 4σ significance. Velocities are heliocentric, assuming that the S II lines are at the Galactic LSR.

TABLE 2. Nearest galaxy neighbors to Lyα clouds.

Target	System Designation	Absorber Velocity[a] (km s^{-1})	Nearest Galaxy	Galaxy Velocity[a] (km s^{-1})	$\delta\Theta$ (degrees)	Distance[b] (h_{75}^{-1} Mpc)
Mrk 335	A	1970	NGC 7817	2520	0.80	0.67
Mrk 335	B	2290	NGC 7817	2520	0.80	0.45
Mrk 335	C	4270	00008+2150	4670	2.00	2.2
Mrk 335	D	6280	00036+1928	6150	0.46	0.85
Mrk 501	A	4660	16510+3927	4830	0.45	0.51
Mrk 501	B:	6000	IC 1221	5690	7.6	10.5
Mrk 501	C	7530	1709+3941	7810	3.3	5.9
I Zw 1	A	1617	NGC 63	1300	8.8	3.3
I Zw 1	B	2861	A0054+1005	2890	2.5	1.7
I Zw 1	C	5130	00522+1325	5560	1.0	1.3
Mrk 421	A	3046	11267+3508	2540	5.6	4.3

[a] Heliocentric velocities

[b] Three-dimensional distance from Lyα absorber to galaxy, using a retarded Hubble flow model (Paper I)

"wavelet analysis" method (Slezak *et al.* 1993). We believe that our identifications of void and supercluster regions are accurate to ± 500 km s^{-1}.

We now compare our new results and those of Paper I and update the statistics based on the new data. Over the four

(a) α wedge for $\delta = 39.00 \pm 4.0°$

(b) α wedge for $\delta = 16.25 \pm 4.0°$

FIG. 3. "Pie diagram" distributions in galactocentric recession velocity and right ascension of the Lyα absorbers toward our four target AGN. The AGN are shown as the farthest symbols along the sightlines, and the Lyα absorbers are shown as circles (the three definite and one probable absorber in voids have an inscribed "X"). (a) Three absorbers toward Mrk 501 (at 4880, 6220, and 7740 km s^{-1} heliocentric velocity) and one toward Mrk 421 (at 3046 km s^{-1}); (b) three absorbers toward I Zw 1 (at 1617, 2861, and 5130 km s^{-1}) and four toward Mrk 335 (at 2185, 2520, 4490, and 6490 km s^{-1}).

sightlines, the pathlength ($c\Delta z$) through voids totals 16 000 km s^{-1}, while that through superclusters totals 18 000 km s^{-1}. We have now detected a total of ten definite Lyα absorption lines at a significance above 4σ (Table 2). The Lyα equivalent widths detected with the GHRS range from 26 to 240 mÅ, corresponding to column densities N(H I) between $10^{12.7}$ and 10^{14} cm^{-2} for Doppler parameter $b \approx 30$ km s^{-1}. The frequency of absorbers is approximately one every 3400 km s^{-1} of pathlength, above $10^{12.7}$ cm^{-2} column density, comparable to that estimated from GHRS observations of other AGN (Weymann 1993; Savage *et al.* 1995). These numbers are approximate, however, since proper treatments of the GHRS sensitivity function and the H I column density distribution have not yet been performed.

Three clouds lie within voids (one each toward Mrk 501, I Zw 1, and Mrk 421) and seven are associated with supercluster walls, including three in the Local Supercluster. Expressed as heliocentric velocities, the three definite void absorbers lie at 3046 km s^{-1} toward Mrk 421, at 7740 km s^{-1} toward Mrk 501, and at 2861 km s^{-1} toward I Zw 1. The nearest known galaxies lie 4.3, 5.9, and $1.7h_{75}^{-1}$ Mpc away from these clouds, respectively (Table 2). In the case of absorber B toward I Zw 1, the nearest galaxy (A0054+1005 at $cz = 2890$ km s^{-1} and $1.7h_{75}^{-1}$ Mpc distance) is likely to be part of the Local Supercluster. We had classified the region surrounding the 2861 km s^{-1} absorber as a void prior to the *HST*/GHRS observations, and we believe that this absorber lies just beyond the Local Supercluster in that direction. The distances to other bright galaxy neighbors are considerably larger. At somewhat lower significance (3–4σ) we find one more probable Lyα absorber at 6000 km s^{-1} which also lies in a void toward Mrk 501.

Therefore, with combined pathlength 47% through voids and 53% through superclusters, we find that three of ten definite Lyα absorbers lie within voids. These statistics are small, and the addition of the fourth QSO sightline has shifted the fraction of Lyα absorbers within voids slightly higher than that (one out of eight) quoted in Paper I. According to binomial statistics for a uniform distribution of absorbers, the observed (three out of ten) situation could occur with
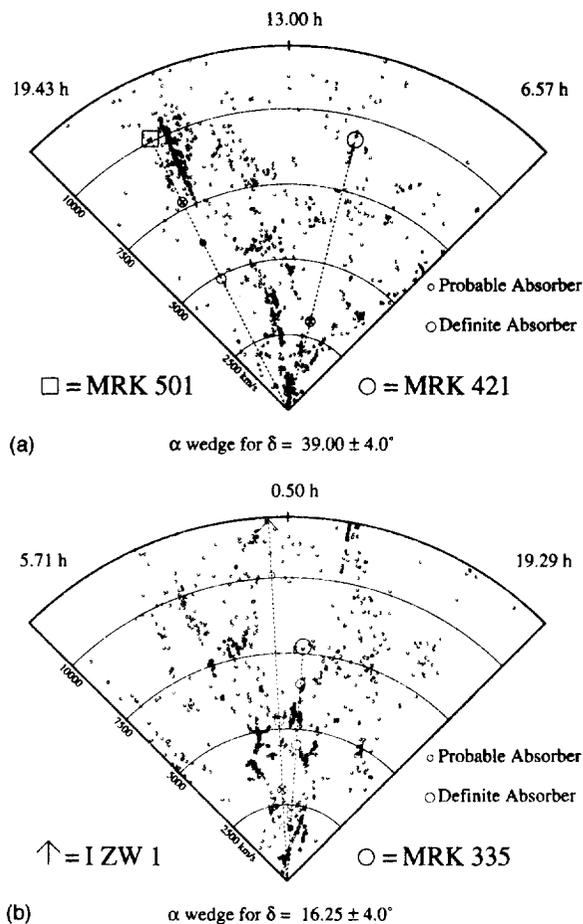
15% chance probability (19% when one includes the one additional "possible" absorber which also lies in a void). Therefore, the tendency of Lyα clouds to lie in superclusters cannot be stated as definitively as in Paper I. The range of distances to nearest-neighbor bright galaxies for the three void absorbers ($1.7-5.9h_{75}^{-1}$ Mpc) is comparable to that for the seven nonvoid absorbers ($0.45-5.9h_{75}^{-1}$ Mpc). However, the nearest neighbor to the possible void absorber toward Mrk 501 lies $10.5h_{75}^{-1}$ Mpc away, and the distribution of distances to the nearest galaxies to the void and nonvoid absorbers shows some differences inside and outside 1 Mpc (Paper I). For example, four of the seven nonvoid absorbers have neighbor galaxies within 1 Mpc. Evidently the discovery of more absorbers toward AGN behind well-mapped galaxy distributions is needed to settle the issue of how well Lyα absorbers trace the large-scale structure of galaxies.

These nearest bright galaxies are too far from the Lyα clouds to be physically associated in most models. Pencil-beam optical and 21 cm surveys of the area of sky surrounding Mrk 501 find no galaxy at comparable redshift to the 7530 km s^{-1} void absorption system within $100h_{75}^{-1}$ kpc with absolute magnitude $B\leqslant-16$ and no object with H I mass $\geqslant(7\times10^{8} . \mathscr{M}_{\odot})h_{75}^{-2}$ within $500h_{75}^{-1}$ kpc (Paper I). Thus, neither a faint optical galaxy nor a gas-rich galaxy is present close to this Lyα cloud. However, as we shall suggest in the next section, it is probable that the low-redshift Lyα absorbers may be associated with dwarf galaxies.

3. CHARACTERISTICS OF THE CLOUDS

We now derive the physical characteristics of the H I clouds. If the clouds are exposed to metagalactic photoionizing radiation of specific intensity $J_{912}=(10^{-23}$ ergs cm^{-2} s^{-1} sr^{-1} Hz$^{-1})J_{-23}$ at 912 Å and (energy) spectral index $\alpha_s\approx1.5$, the hydrogen ionization correction can be large, but derivable from the assumptions of photoionization equilibrium and cloud geometry. The void Lyα lines toward Mrk 501, I Zw 1, and Mrk 421 have equivalent widths of 48, 65, and 92 mÅ, respectively, corresponding to column densities $N(\text{H I})\approx1-3\times10^{13}$ cm^{-2} for Doppler-broadening parameter $b\approx30$ km s^{-1}. Other low-redshift Lyα clouds have H I columns up to 10^{14} cm^{-2}. Since the total mass of photoionized homogeneous Lyα clouds is probably dominated by the upper end of the distribution, we will hereafter scale to a characteristic column density $N(\text{H I})=(10^{14}$ cm$^{-2})N_{14}$.

To make further progress, we need an estimate for the cloud sizes. However, unlike the situation with high-redshift Lyα clouds, we lack definitive information on the size of the low-z absorbers. From the absorber coincidences and anticoincidences toward the double-quasar Q1343+266A,B at $z=2.03$ (Bechtold *et al.* 1994; Dinshaw *et al.* 1994) the radii of Lyα absorbers at $z=1.79-2.03$ have been estimated to lie in the range $50\leqslant R\leqslant370h_{75}^{-1}$ kpc, with a median value of $120h_{75}^{-1}$ kpc. At low redshift, no such measurements have been performed. Sizes much smaller than 100 kpc would require unacceptably large space densities (Weymann 1993; Maloney 1993). The only physical information on low-z cloud size comes from studies (Lanzetta *et al.* 1995) of 46 galaxies in the fields of *HST*/FOS Lyα absorbers. Each of

five galaxies within $90h_{75}^{-1}$ kpc corresponds to a Lyα absorber, whereas the frequency is only five of ten galaxies between 90 and $200h_{75}^{-1}$ kpc and one of nine galaxies beyond $200h_{75}^{-1}$ kpc. Lanzetta *et al.* (1995) also found an anticorrelation between Lyα equivalent width and (Lyα-galaxy) impact parameter. However, as we showed in Paper I, the trend for lower-column absorbers to have larger impact parameters does not appear to extend beyond 100–200 kpc for the lower-column H I clouds detected by *HST*/GHRS. Taking all this evidence into account, we adopt a characteristic radius $R=(100 \text{ kpc})R_{100}$ and carry along the scaling parameter R_{100} to demonstrate the sensitivity of some quantities to this uncertain size.

The precise distribution of density in these Lyα clouds is uncertain, and mass estimates based on photoionization corrections are imprecise. To obtain a first-order estimate, we assume that the clouds are homogeneous spheres of radius $R=(100 \text{ kpc})R_{100}$ and temperature $T=(10^{4.3} \text{ K})T_{4.3}$. In photoionization equilibrium, the neutral hydrogen density, $n_{\text{H I}}$, is

$$n_{\text{H I}}=\frac{n_e n_{\text{H II}}\alpha_{\text{H}}^{(1)}}{\Gamma_{\text{H}}}=(10.8)n_{\text{H}}^2T_{4.3}^{-0.726}J_{-23}^{-1}\left(\frac{\alpha_s+3}{4.5}\right), \qquad (1)$$

where we adopt an electron density $n_e=1.157n_{\text{H}}$ (for helium abundance $Y=0.239$) and assume a radiative recombination rate coefficient $\alpha_{\text{H}}^{(1)}=(2.48\times10^{-13} \text{ cm}^3 \text{ s}^{-1})T_{4.3}^{-0.726}$ and hydrogen photoionization rate $\Gamma_{\text{H}}=(2.66\times10^{-14} \text{ s}^{-1})[4.5/(\alpha_s+3)]J_{-23}$. If the mean column density is taken to be $N(\text{H I})\approx n_{\text{H I}}R$, then the total hydrogen density n_{H}, neutral fraction $x_{\text{H I}}=n_{\text{H I}}/n_{\text{H}}$, and cloud mass $\mathscr{M}_{\text{cl}}$ are,

$$n_{\text{H}}=(5.5\times10^{-6} \text{ cm}^{-3})J_{-23}^{1/2}T_{4.3}^{0.363}N_{14}^{1/2}R_{100}^{-1/2}\left(\frac{\alpha_s+3}{4.5}\right)^{-1/2}, \qquad (2)$$

$$x_{\text{H I}}=(5.9\times10^{-5})J_{-23}^{-1/2}T_{4.3}^{-0.363}N_{14}^{1/2}R_{100}^{-1/2}\left(\frac{\alpha_s+3}{4.5}\right)^{1/2}, \qquad (3)$$

$$\mathscr{M}_{\text{cl}}=(7.4\times10^{8} . \mathscr{M}_{\odot})J_{-23}^{1/2}T_{4.3}^{0.363}N_{14}^{1/2}R_{100}^{5/2}\left(\frac{\alpha_s+3}{4.5}\right)^{-1/2} . \qquad (4)$$

From the observed absorber frequency of one cloud with $N(\text{H I})\geqslant10^{13}$ cm^{-2} every 3500 km s^{-1} (Weymann 1993), one infers a redshift frequency $dN/dz=\phi_0(\pi R^2)(c/H_0)\approx86$. The local space density of the low-redshift Lyα systems is therefore

$$\phi_0=(0.68 \text{ Mpc}^{-3})R_{100}^{-2}h_{75}, \qquad (5)$$

approximately 40 times that of bright galaxies, L^* $=(9.1\times10^9L_{\odot})h_{75}^{-2}$, with luminosity function $\phi(L)dL$ $\equiv\phi^*(L/L^*)^\alpha\exp(-L/L^*)(dL/L^*)$. The recent CfA survey (Marzke *et al.* 1994) gave values $\phi^*=(0.017\pm0.004$ Mpc$^{-3})h_{75}^3$ and $\alpha=-1.0\pm0.2$, while other determinations (Sandage *et al.* 1985; Impey *et al.* 1988) of $\phi(L)$ find a faint-end slope $\alpha\approx-1.3$ or even steeper in the Virgo Cluster. However, statistics on the faint-end luminosity function are poor, and values of the slope (α) and normalization (ϕ^*) trade off against one another. For example, Marzke *et al.* (1994) noted a factor of three excess at the faint end, relative

to their $(\alpha = -1.0)$ fit, and claimed that this may be due to Sm-Im dwarf galaxies with $\alpha = -1.87$.

We are now in a position to compare the space density of the Lyα clouds to that of galactic constituents of the Universe. The volume filling factor of the Lyα clouds is

$$f = \left(\frac{4RH_0}{3c}\right)\left(\frac{dN}{dz}\right) = (0.0029)R_{100}h_{75}. \qquad (6)$$

If L^* galaxies have a mass-to-light ratio (Persic & Salucci 1992) of $9h_{75} \mathcal{M}_\odot/L_\odot$ within the Holmberg radius, the Lyα cloud masses correspond to $0.01m^*$, where $m^* \approx (8.2 \times 10^{10} \mathcal{M}_\odot)h_{75}^{-1}$. For a faint-end slope $\alpha = -1.3$, we estimate that galaxies with $0.003L^* \le L \le 0.03L^*$ have a space density 0.16 Mpc^{-3} h_{75}^3, four times less than that estimated for $(R = 100$ kpc) Lyα absorbers. Given the uncertainties in the luminosity function and Lyα cloud size, these space densities are in fair agreement. They are also comparable to those of low-mass halos found in estimates using the Press–Schechter formalism and in recent numerical CDM simulations (Efstathiou 1995), which predict a comoving space density $N(>M_h) = 1.7h_{75}^3$ Mpc^{-3} of halos with mass greater than $M_h \approx 5 \times 10^9 h_{75}^{-1} \mathcal{M}_\odot$. That particular simulation found $N(>M_h) \propto M_h^{-1}$ at low masses, appropriate for hierarchical clustering models in which the power spectrum of mass fluctuations $P(k) \propto k^{-3}$. An unanswered question from these simulations is the fraction of low-mass halos that undergo star formation at some epoch.

Many surveys of the faint end of the luminosity function (Sandage *et al.* 1985; Impey *et al.* 1998; Marzke *et al.* 1994) suggest a large space density of dwarf galaxies, some of which are difficult to detect owing to their low surface brightness. The Lyα absorbers could be the halos of the faint blue dwarf galaxies (Tyson 1988; Cowie *et al.* 1988) that have faded by the present epoch (Babul & Rees 1992; Salpeter 1993) or low-mass gas clouds whose cores have not yet undergone significant star formation. Our previous failure to detect any dwarf galaxies down to $M_B = -16$ at the position of the void absorber toward Mrk 501 (Stocke *et al.* 1995) accentuates the need for deeper imaging of these fields in search of dwarf galaxies down to $M_B \approx -13$. In the only such search conducted thus far, Rauch *et al.* (1995) failed to find any galaxies with $M_B \le -13$ near the 3C 273 sight line, including low surface brightness objects with $\Sigma_B \le 26.5$ mag arcsec^{-2}. Optical and 21 cm searches for such dwarfs are possible only for very local Lyα clouds, since many of the Lyα clouds (Bahcall *et al.* 1991; Morris *et al.* 1991) discovered by *HST* are too distant to set sensitive limits on the presence of dwarf galaxies. H I (21 cm) searches at $cz \le 10\,000$ km s^{-1} are straightforward, but studies of more distant gas require increasingly large amounts of observing time.

Similarly, spectra of the low-z Lyα clouds in the ultraviolet resonance lines of C IV, C III, and C II could set useful limits on possible star formation. From Eq. (2), the column density of carbon in all ion stages should be $N(\mathrm{C}) \approx (8 \times 10^{12}$ cm$^{-2})R_{100}^{1/2}N_{14}^{1/2}J_{-23}^{1/2}$ at 0.01 solar metallicity. If 10% of the carbon is in C IV, absorption lines at 1549 Å should be present at a very weak level (1–10 mÅ equivalent width). Lines from C II (1335 Å) or C III (977 Å) might set even

better metallicity limits if carbon exists in lower ionization states owing to a less intense or softer radiation field.

We can obtain an estimate of the fractional contribution, $\Omega_{cl} = \phi_0 M_{cl}/\rho_{cr}$, of low-redshift Ly$\alpha$ clouds to the critical (closure) density, $\rho_{cr} = (1.06 \times 10^{-29}$ g cm$^{-3})h_{75}^2$, of the Universe from Eqs. (4) and (5). The value,

$$\Omega_{cl} = (0.0033)J_{-23}^{1/2}T_{4.3}^{0.363}N_{14}^{1/2}R_{100}^{1/2}h_{75}^{-1}\left(\frac{\alpha_s + 3}{4.5}\right)^{-1/2}, \qquad (7)$$

is comparable to that $(\Omega_* \approx 0.004)$ of optically luminous matter (Peebles 1993) and is 15% of the total baryonic limit, $\Omega_b = (0.022 \pm 0.004)h_{75}^{-2}$, inferred (Walker *et al.* 1991) from the constraints of Big Bang nucleosynthesis. Thus, these clouds have overdensities $\sim 50J_{-23}^{1/2}N_{14}^{1/2}R_{100}^{-1/2}T_{4.3}^{0.363}$ with respect to the smooth baryonic background density, $\Omega_b\rho_{cr}$.

We note that our estimates for the low-redshift absorbers are uncertain, since they depend on poorly known geometric parameters of the clouds. For example, we do not know the distributions of cloud size and $N(\mathrm{H\,I})$, assumed here to be constant at 100 kpc and 10^{14} cm^{-2}, respectively. We note that, while cloud mass scales as $R^{5/2}$, the total mass density and value of Ω_{cl} are less sensitive $(R^{1/2})$ to assumptions of cloud size. In addition, the distribution of matter within the low-redshift absorbers might also be inhomogeneous, either with a radial distribution of density or clumps. Each of these distributions would accentuate, through recombinations, the regions with highest density. One could also relax the assumption of spherical clouds. By generalizing the spherical assumption to disk geometries, Madau & Shull (1996) showed that the value of Ω_{cl} is reduced by a factor $\langle a \cos\theta\rangle^{-1/2} \approx (2/a)^{1/2}$, where $a > 1$ is the disk aspect ratio and θ is their viewing angle. So, for example, a ratio $a = 10$ would reduce Ω_{cl} by a factor 2.2.

4. DISCUSSION

In the protogalaxy scenario, the low-z Lyα clouds represent parcels of gas and dark matter that have recently ($z < 0.5$) turned around from the general Hubble expansion and now have mean overdensities ~ 50–200 times that of the background IGM. To be consistent with the frequency of absorbers, these parcels must have a space density comparable to that of dwarf galaxies. The hydrogen clouds around these galaxies may only recently have become detectable in Lyα absorption because of the rapid drop in the ionizing radiation field at low redshift. Whether these gaseous envelopes could retain their integrity following encounters with passing massive galaxies would depend on the distances of these galaxies and on the gas dynamical outcome of the encounter. No encounters may have occurred with the void absorbers toward Mrk 501 and Mrk 421, since neighboring galaxies from the supercluster walls moving over 10 Gyr with ≤ 500 km s^{-1} peculiar velocity would not be able to traverse the void.

In the faded dwarf galaxy scenario (Babul & Rees 1992; Efstathiou 1995), the low-redshift clouds are the extended gaseous halos of the faint blue dwarf galaxies detected in deep imaging surveys. Although we have modeled these objects as homogeneous spheres, it is likely that the cloud cores

have collapsed and formed stars, whose winds and supernovae blow matter out into the extended (100 kpc) envelopes required by the frequency, dN/dz, of Lyα absorbers. The fact that some Lyα clouds reside in regions devoid of bright galaxies is consistent with the observed low amplitude of angular correlation found (Efstathiou *et al.* 1991) for the faint blue galaxies. The scenario predicts that very low luminosity galaxies, similar to the Local Group dwarfs, should be found in deep ($B_{\lim} \approx 23$) ground-based optical images near the low-redshift Lyα clouds. In a deep imaging search for faint galaxies toward 3C 273 near the local Lyα clouds in the Virgo Cluster, Morris *et al.* (1993) and Rauch *et al.* (1995) found no dwarf galaxies to impressively faint limits ($M_B \leq -13$ and limiting surface brightness levels of ~ 26.5 mag arcsec^{-2}). Similarly sensitive searches are required for our cloud sample. Thus, H I (21 cm) observations and deep optical imaging are in progress (Carilli *et al.* 1996) to search for accompanying faint galaxies.

Finally, it is worth speculating on possible dark-matter content. Since the Jeans mass, $M_J = (2 \times 10^{11}$

$\mathcal{M}_\odot) R_{100}^{1/4} J_{-23}^{-1/4} N_{14}^{-1/4} T_{4.3}^{1.32}$, safely exceeds the baryonic mass, the clouds are not gravitationally unstable. However, in order to bind them gravitationally, we require that $(2kT/m_H) \approx (G \beta \mathcal{M}_{cl}/R)$, where the ratio of total matter to baryonic matter is

$$\beta \equiv \mathcal{M}_{tot}/\mathcal{M}_{cl} = (10) R_{100}^{-3/2} N_{14}^{-1/2} J_{-23}^{-1/2} T_{4.3}^{0.636} . \qquad (8)$$

Thus, as in other large self-gravitating systems, the low-redshift Lyα clouds could contain substantial amounts of dark matter, unless the clouds are quite large ($R \approx 400$ kpc) as suggested for some clouds at higher redshift (Dinshaw *et al.* 1995). Since all baryonic matter has been included in the ionization correction [Eq. (1)], this dark matter would need to be nonbaryonic.

REFERENCES

Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346

Bahcall, J. N., Jannuzi, B. T., Schneider, D. P., Hartig, G. F., Bohlin, R., & Junkkarinen, V. 1991, ApJ, 377, L5

Bechtold, J., Crotts, A. P., Duncan, R. C., & Fang, Y. 1994, ApJ, 437, L83

Carilli, C., van Gorkom, J., Stocke, J. T., Perlman, E. S., & Shull, J. M. 1996 (in preparation)

Cowie, L. L., Lilly, S. J., Gardner, J., & McLean, I. S. 1988, ApJ, 332, L29

de Lapparent, V., Geller, M. J., & Huchra, J. P. 1986, ApJ, 302, L1

Dey, A., Strauss, M. A., & Huchra, J. 1990, AJ, 99, 463

Dinshaw, N., Impey, C. D., Foltz, C. B., Weymann, R. J., & Chaffee, F. H. 1994, ApJ, 437, L87

Dinshaw, N., Impey, C. D., Foltz, C. B., Weymann, R. J., & Chaffee, F. H. 1995, in QSO Absorption Lines, Proceedings of ESO Workshop, edited by G. Meylan (Springer, Heidelberg), p. 329

Efstathiou, G., Bernstein, G., Katz, N., Tyson, J. A., & Guhathakurta, P. 1991, ApJ, 380, L47

Efstathiou, G. 1995, MNRAS, 272, L25

Fairall, A. P., Palumbo, G. G. C., Vettolani, E., Kauffmann, G., Jones, A., & Baiesi-Pillastrini, G. 1990, MNRAS, 247, 21P

Geller, M. J., & Huchra, J. P. 1989, Science, 246, 897

Henning, P. A. 1992, ApJS, 78, 365

Huchra, J. P., *et al.* 1993, CfA Redshift Catalog, 1993 Version, obtained through the Astronomical Data Center

Impey, C., Bothun, G., & Malin, D. 1988, ApJ, 330, 634

Lanzetta, K. M., Bowen, D. V., Tytler, D., & Webb, J. K. 1995, ApJ, 442, 538

Madau, P., & Shull, J. M. 1996, ApJ, 457 (in press) (Feb. 1, 1996)

Maloney, P. 1993, ApJ, 414, 41

Marzke, R. O., Huchra, J. P., & Geller, M. J. 1994, ApJ, 428, 43

Morris, S. L., Weymann, R. J., Dressler, A., McCarthy, P. J., Smith, B. A.,

Terrile, R. J., Giovanelli, R., & Irwin, M. 1993, ApJ, 419, 524

Morris, S. L., Weymann, R. J., Savage, B., & Gilliland, R. L. 1991, ApJ, 377, L21

Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton University Press, Princeton)

Persic, M., & Salucci, P. 1992, MNRAS, 258, 14P

Rauch, M., Weymann, R. J., & Morris, S. L. 1995, ApJ (in press)

Salpeter, E. E. 1993, AJ, 106, 1265

Sandage, A., Binggeli, B., & Tammann, G. A. 1985, AJ, 90, 1759

Sanduleak, N., & Pesch, P. 1987, ApJS, 63, 809

Savage, B. D., Sembach, K. R., & Lu, L. 1995, ApJ, 449, 145

Slezak, E., de Lapparent, V., & Bijaoui, A. 1993, ApJ, 409, 517

Stocke, J. T., Shull, J. M., Penton, S., Donahue, M., & Carilli, C. 1995, ApJ, 451, 24

Strauss, A. M., & Huchra, J. 1988, AJ, 95, 1602

Szomoru, A., Guhathakurta, P., van Gorkom, J. H., Knapen, J. H., Weinberg, D. H., & Fruchter, A. S. 1994, AJ, 108, 491

Szomoru, A., van Gorkom, J. H., Gregg, M., & de Jong, R. H. 1993, AJ, 105, 464

Tifft, W. G., Kirshner, R. P., Gregory, S. A., & Moody, J. W. 1986, ApJ, 310, 75

Tyson, J. A. 1988, AJ, 96, 1

Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H.-S. 1991, ApJ, 376, 51

Weinberg, D. H. Szomoru, A., Guhathakurta, P., & van Gorkom, J. H. 1991, ApJ, 372, L13

Weistrop, D., & Downes, R. A. 1988, ApJ, 331, 172

Weymann, R. J. 1993, in The Evolution and Environment of Galaxies, edited by J. M. Shull and H. A. Thronson (Kluwer, Dordrecht), p. 213