

# THE LOCAL Ly $\alpha$ FOREST: ABSORBERS IN GALAXY VOIDS

KEVIN M. MCLIN,<sup>1,2,3</sup> JOHN T. STOCKE,<sup>1,2,3</sup> R. J. WEYMANN,<sup>4</sup> STEVEN V. PENTON,<sup>1,2</sup> AND J. MICHAEL SHULL<sup>1,5</sup>

Received 2002 May 10; accepted 2002 June 18; published 2002 July 2

## ABSTRACT

We have conducted pointed redshift surveys for galaxies in the direction of bright active galactic nuclei whose *Hubble Space Telescope* far-UV spectra contain nearby ( $cz \lesssim 30,000 \text{ km s}^{-1}$ ), low column density [ $12.5 \leq \log N_{\text{H I}}(\text{cm}^{-2}) \leq 14.5$ ] Ly $\alpha$  forest absorption systems. Here we present results for four lines of sight that contain nearby ( $cz \lesssim 3000 \text{ km s}^{-1}$ ) Ly $\alpha$  absorbers in galaxy voids. Although our data go quite deep [ $-13 \leq M_B(\text{limit}) \leq -14$ ] out to impact parameters of  $\rho \lesssim 100\text{--}250 h_{70}^{-1} \text{ kpc}$ , these absorbers remain isolated and thus appear to be truly intergalactic, rather than part of galaxies or their halos. Since we and others have discovered no galaxies in voids, the only baryons detected in the voids are in the Ly $\alpha$  “clouds.” Using a photoionization model for these clouds, the total baryonic content of the voids is  $4.5\% \pm 1.5\%$  of the mean baryon density.

*Subject headings:* galaxies: halos — intergalactic medium — large-scale structure of universe — quasars: absorption lines

## 1. INTRODUCTION

Since the discovery three decades ago of foreground absorption systems in quasi-stellar object (QSO) spectra, their origin and nature have been the subject of ongoing interest, particularly the Ly $\alpha$ -only absorption systems. Bahcall & Spitzer (1969) suggested that the Ly $\alpha$  lines arose in the diffuse gas of extended galaxy halos, while Arons (1972) proposed that they might be primordial material falling into galaxy halos. More recently, computer simulations of structure formation (Bond, Szalay, & Silk 1988; Hernquist et al. 1996; Miralda-Escudé et al. 1996; Davé et al. 1999) have supported the hypothesis that these absorbers are not directly related to galaxies but rather are gas associated with a density-varying intergalactic medium (IGM).

Because the relationship between Ly $\alpha$  absorbers and galaxies can be studied in detail only at low  $z$ , the *Hubble Space Telescope* (HST) is required to discover absorbers for this purpose. The HST QSO Absorption Line Key Project used the Faint Object Spectrograph (FOS) to detect higher column density absorbers [ $\log N_{\text{H I}}(\text{cm}^{-2}) \geq 14$ ] at  $z = 0\text{--}1.6$  (Bahcall et al. 1993; Weymann et al. 1998), followed by more sensitive discovery programs with the Goddard High Resolution Spectrometer (GHRS) and Space Telescope Imaging Spectrograph (STIS; Morris et al. 1991; Impey, Petry, & Flint 1999; Tripp, Lu, & Savage 1998) extending to somewhat lower equivalent width limits ( $W \geq 50\text{--}100 \text{ mÅ}$  at  $z \lesssim 0.3$ ). Finally, in a large (31 sight line) systematic study, Penton, Shull, & Stocke (2000a, 2002), Penton, Stocke, & Shull (2000b), and S. V. Penton, J. M. Shull, & J. T. Stocke (2002, in preparation) have used GHRS and STIS at medium resolution ( $\sim 20 \text{ km s}^{-1}$ ) to study the lowest col-

umn density absorbers [ $12.3 \leq \log N_{\text{H I}}(\text{cm}^{-2}) \leq 14.5$ ] at  $cz \leq 30,000 \text{ km s}^{-1}$ . These very low  $z$  studies are particularly useful for understanding the galaxy-absorber relationship, because at such low redshifts even faint dwarf galaxies can be detected in the vicinity of the absorption systems.

Attempts to find galaxies associated with the higher column density Ly $\alpha$  absorbers using the FOS Key Project data (Lanzetta et al. 1995, hereafter L95) found that  $\sim 30\%$  of the FOS absorbers were associated with bright galaxies. Chen et al. (1998, hereafter C98) extrapolated the L95 results to fainter luminosities to conclude that all  $W > 300 \text{ mÅ}$  absorbers are associated with galaxies closer than impact parameters of  $\rho = 225 h_{70}^{-1} \text{ kpc}$ . This extrapolation remains untested because the bulk of the FOS absorption systems are too far away for fainter galaxies ( $L < L^*$ ) to be detected.

Using more sensitive HST/GHRS spectra, Morris et al. (1993) conducted a detailed galaxy survey of the 3C 273 sight line, finding mixed evidence for galaxies near both high and low column density absorbers. Subsequent studies by Tripp et al. (1998) and Impey et al. (1999) also found mixed results, even for a subset of 11 absorbers within the Virgo Cluster, where the luminosity function of galaxies is complete to  $M_B = -16$  (Impey et al. 1999).

In preliminary studies to the current work, Stocke et al. (1995) and Shull, Stocke, & Penton (1996) found low column density Ly $\alpha$  absorbers in galaxy voids. Stocke et al. (1995) conducted optical and H I 21 cm searches for galaxies near one “void absorber,” the  $cz = 7740 \text{ km s}^{-1}$  absorber in the Mrk 501 sight line, finding no optical galaxies at  $\rho < 106 h_{70}^{-1} \text{ kpc}$  to  $M_B \geq -16.2$  and no H I-emitting galaxies with  $M_{\text{H I}} \geq 6 \times 10^8 h_{70}^{-2} M_\odot$  within  $\rho < 500 h_{70}^{-1} \text{ kpc}$ .

Using a subsample of our GHRS sight lines, there are 45 low column density Ly $\alpha$  absorbers in regions where the Center for Astrophysics Redshift Survey is complete to at least  $L^*$ . Penton et al. (2002) find that  $29\% \pm 8\%$  of Ly $\alpha$  absorbers lie in galaxy voids and that, while there is some evidence that the remaining  $\sim 71\%$  of the absorbers are associated with the same large-scale structure filaments as the galaxies, there was no definitive association between any Ly $\alpha$  absorber and any individual galaxy. Penton et al. (2002) find no correlation between impact parameter and equivalent width for  $W \lesssim 200 \text{ mÅ}$ , or for impact parameters greater than  $200 h_{70}^{-1} \text{ kpc}$ , contrary to the predictions of L95 and

<sup>1</sup> Center for Astrophysics and Space Astronomy and Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Boulder, CO 80309; mclin@casa.colorado.edu, stocke@casa.colorado.edu, spenton@casa.colorado.edu, mshull@casa.colorado.edu.

<sup>2</sup> Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

<sup>3</sup> Visiting Astronomer, Las Campanas Observatory.

<sup>4</sup> Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101; rjw@ociw.edu.

<sup>5</sup> Also at Joint Institute for Laboratory Astrophysics, University of Colorado at Boulder, Boulder, CO 80309; and National Institute of Standards and Technology.

C98. However, Penton et al. (2002) do not address the relationship between absorbers and fainter galaxies.

In order to determine what relationship exists between the low-column Ly $\alpha$  absorbers and the faintest dwarf galaxies, we have undertaken a project based on the absorber sample of Penton et al. (2000a) and S. V. Penton, J. M. Shull, & J. T. Stocke (2002, in preparation). This sample is ideal because it contains many systems closer than  $cz = 10,000 \text{ km s}^{-1}$ . At such distances, we are able to probe well down into the galaxy luminosity function with multiobject spectroscopy on modest aperture telescopes, in some cases reaching the faintest dwarf galaxies ( $M_B \sim -12$ ). To achieve this aim, we have undertaken pencil beam galaxy redshift surveys in the direction of 15 of the 31 QSO sight lines studied with GHRS and STIS by Penton et al. (2000a) and S. V. Penton, J. M. Shull, & J. T. Stocke (2002, in preparation).

In this Letter, we present results from a subset of our data, namely, those sight lines in which absorption systems were found inside very nearby ( $cz \leq 3000 \text{ km s}^{-1}$ ) galaxy voids, defined by having no bright galaxy ( $M_B \leq -17.5$ ) closer than  $2 h_{70}^{-1} \text{ Mpc}$ . The study of void absorbers is important because those that lie within bright galaxy filaments are very likely to have a bright galaxy nearby; fainter galaxies will lie slightly closer, given their higher space density (Impey et al. 1999; Penton et al. 2002). In these cases, it is not clear whether the clouds are associated with individual galaxies or with the large-scale structure in which both the absorbers and galaxies are embedded. Absorbers in galaxy voids are immune to this effect: there are no bright galaxies nearby, and fainter galaxies are not expected to be close merely by chance. Thus, these void absorbers are uniquely suited to help determine whether all absorbers are galaxy halos or if some are truly intergalactic material, as is strongly suggested by simulations (e.g., Davé et al. 1999).

We present our work as follows: In § 2, we discuss our observational techniques and data reduction. In § 3, we introduce the void absorber sight lines and discuss our results as they pertain to the voids. In § 4, we summarize the conclusions from this work. We assume  $H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$  throughout.

## 2. OBSERVATIONS AND REDUCTIONS

These observations were obtained over the past 3 years at the DuPont 2.5 m telescope of Las Campanas Observatory (LCO) in Chile and at the 3.5 m WIYN<sup>6</sup> telescope at Kitt Peak National Observatory (KPNO) in Arizona. The LCO observations were taken with the wide-field CCD multiobject spectrometer designed and built by one of us (R. J. W.). The instrument employs metal slit masks to obtain redshifts of up to 60 galaxies at a time over a field of view of approximately  $12' \times 20'$ . The DuPont spectra range from just shortward of 4000 to 8000 Å, with a resolution of  $\lambda/\Delta\lambda \approx 2000$ . We typically used only the part of the spectrum shortward of 5500 Å in order to avoid confusion caused by sky subtraction. The WIYN observations were taken with the HYDRA fiber-fed multiobject spectrometer using the blue fiber cables, the G3 filter, and the KPC-007 600 line  $\text{mm}^{-1}$  grating. The wavelength coverage for these spectra was from 3800 to 5800 Å, with  $\lambda/\Delta\lambda \approx 4000$  at 4000 Å. Typically, 60–70 spectra were obtained in each fiber setup over a  $40'$  circular field

of view. For both LCO and WIYN, we used a set of spectral templates, kindly provided by E. Ellingson, to measure galaxy redshifts using cross-correlation techniques. Velocities returned by this procedure have typical accuracies of  $\pm 150 \text{ km s}^{-1}$  for the faintest galaxies with usable redshifts.

Astrometric images were taken either at the 0.9 m telescope of KPNO using the T2kA or MOSAIC detectors or at the Las Campanas 40 inch telescope. Gunn  $r$  or Johnson  $R$  images were obtained and galaxy magnitudes converted to Johnson  $B$  using the colors appropriate for an Scd galaxy, as reported in Fukugita, Shimasaku, & Ichikawa (1995). This is a conservative choice of color conversion since most galaxies have redder colors and thus fainter  $B$  magnitudes for their red magnitudes. Integration times ensured a depth well below our desired limiting magnitude of  $m_r = 19$  ( $m_B \sim 19.7$ ). Object detection and galaxy/star separation were accomplished using the Picture Processing Package (PPP), provided for our use by H. Yee (Yee 1991), or SExtractor (Bertin & Arnouts 1996). Our surface brightness sensitivity varied somewhat from image to image, but typically we were able to automatically detect galaxies with  $\mu_r \leq 23 \text{ mag arcsec}^{-2}$  ( $\mu_B \leq 23.7 \text{ mag arcsec}^{-2}$ ). While these surface brightness limits do not extend to the very lowest values observed for galaxies in modern surveys, they do extend well into the low surface brightness (LSB) galaxy regime (McGaugh, Bothun, & Shombert 1995). A visual inspection of the images found a few objects of lower surface brightness that had been missed by the finding algorithm and that were added to our spectroscopy lists. PPP and SExtractor showed adequate agreement in object classifications and magnitudes. Yee (1991) describes experiments that show that the PPP magnitudes are equivalent to total magnitudes for objects well above the magnitude limit.

Owing to our desire to obtain spectra of as many galaxies as possible within our survey regions, we were quite conservative with the use of the object classifiers. We thus obtained spectra of many objects classified as possible galaxies that are, in fact, stars. Since objects were selected for observation based primarily on location, so as to maximize the number of objects per mask or fiber setup, we expect that the fraction of stars among our unobserved objects at each magnitude limit is similar to the fraction among our observed objects. Therefore, the galaxy completeness fraction in each field (see Table 1) takes into account the fraction of stars misclassified as possible galaxies in that field.

## 3. RESULTS

We have observed four sight lines from Penton et al. (2000a) and S. V. Penton, J. M. Shull, & J. T. Stocke (2002, in preparation) that contain seven Ly $\alpha$  absorbers in voids (no galaxies at  $M_B \leq -17.5$  within  $2 h_{70}^{-1} \text{ Mpc}$ ), based on bright galaxy data from the CfA catalog (Huchra et al. 1983). Table 1 gives a summary of our void absorber data, including, by column, (1) target name, (2) active galactic nucleus (AGN) heliocentric recession velocity, (3) absorber heliocentric recession velocity, (4) rest equivalent width ( $W$ ) of the Ly $\alpha$  absorption in units of milliangstroms, (5) apparent  $B$ -magnitude limit of our spectroscopy, (6) radius of the field of view covered at the distance of the void absorber, (7) percentage of galaxies for which we have a redshift to  $m_B(\text{limit})$  listed in column (5) within the field of view listed in column (6), and (8) the absolute  $B$ -magnitude limit of our spectroscopy at the distance of the absorber. The void absorber in the VII Zw 118 sight line is actually a blend of two absorbers with comparable equivalent widths. The combined

<sup>6</sup> The WIYN Observatory is a joint facility of the University of Wisconsin at Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory.

TABLE 1  
GALAXY VOID ABSORBERS

| AGN<br>(1)                 | $CZ_{\text{AGN}}$<br>(km s <sup>-1</sup> )<br>(2) | $CZ_{\text{abs}}$<br>(km s <sup>-1</sup> )<br>(3) | $\mathcal{W}$<br>(mÅ)<br>(4) | $m_B(\text{limit})$<br>(5) | Radius<br>(kpc)<br>(6) | Complete<br>(%)<br>(7) | $M_B(\text{limit})$<br>(8) |
|----------------------------|---------------------------------------------------|---------------------------------------------------|------------------------------|----------------------------|------------------------|------------------------|----------------------------|
| Mrk 421 .....              | 9000                                              | 3035                                              | 87 ± 15                      | 18.7                       | 252                    | 95                     | -14.5                      |
| Mrk 509 .....              | 10,312                                            | 2548                                              | 211 ± 32                     | 20.0                       | 105                    | 96                     | -12.8                      |
| VII Zw 118 .....           | 23,881                                            | 2426                                              | 189 ± 151                    | 18.6                       | 201                    | 91                     | -14.0                      |
| VII Zw 118 .....           | 23,881                                            | 2469                                              | 144 ± 116                    | 18.6                       | 205                    | 91                     | -14.0                      |
| HE 1029-140 .....          | 25,782                                            | 1979                                              | 103 ± 45                     | 18.8                       | 41                     | 70                     | -13.3                      |
| Mrk 501 <sup>a</sup> ..... | 10,092                                            | 5990                                              | 55 ± 46                      | 19.0                       | 82                     | 100                    | -15.7                      |
|                            | 10,092                                            | 7740                                              | 53 ± 36                      | 19.0                       | 106                    | 100                    | -16.2                      |

<sup>a</sup> Data from Stocke et al. 1995.

equivalent width (333 mÅ, as it would appear in an *HST/FOS* spectrum) of this system places it well within the equivalent width limits suggested by L95 to be galaxy halos. The Mrk 421 and VII Zw 118 fields were observed at WIYN, the other two at LCO. At the bottom of Table 1 we have added data on the two void absorbers reported in Stocke et al. (1995) and Penton et al. (2002). While farther away than the other four objects in Table 1, these two absorbers give results entirely consistent with the results presented herein.

We have detected no galaxy coincident in velocity ( $\pm 300$  km s<sup>-1</sup>) with an absorber out to substantial impact parameters (100–250  $h_{70}^{-1}$  kpc, except for HE 1029–140, where our galaxy survey work is  $\leq 10\%$  complete at large impact parameters). In fact, there are no galaxies detected within the voids containing them. This absence is quite striking: not only have we failed to find galaxies within several hundred kilometers per second of any absorber, we have found no faint galaxies closer than the nearest bright galaxies that define the voids. Thus, even if we use the Ly $\alpha$  absorbers as markers for the presence of material in voids, a sensitive search for galaxies near these absorbers fails to find even very faint galaxies. These observations underscore previous negative searches for galaxies in voids (Popescu, Hopp, & Elsässer 1997; Szomoru, van Gorkom, & Gregg 1996a, 1996b).

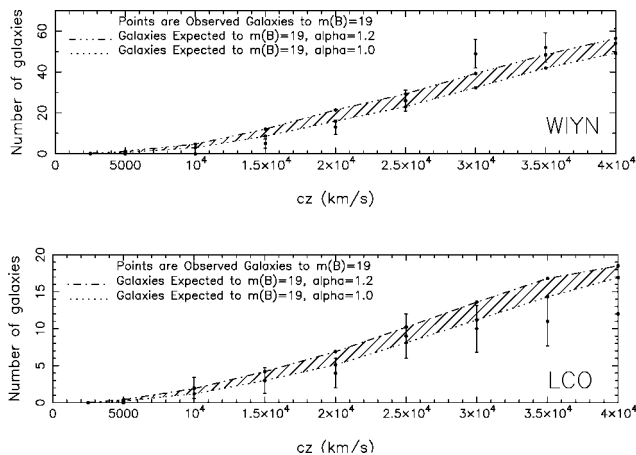


FIG. 1.—Cumulative number of galaxies expected compared to the number observed as a function of velocity ( $cz$ ) for our survey. We have used the functional form and normalizations from Schechter (1976) with different faint-end slope,  $\alpha$ , to compute the expected number of galaxies. The expected values are plotted as the dash-dotted line on the upper bound of the hatched region and the dotted lines on the lower bound, for  $\alpha = -1.2$  and  $-1.0$ , respectively. Both curves assume a limiting magnitude of  $m_B = 19$ . The top plot is for two WIYN fields, and the bottom for five fields taken at Las Campanas. The points and error bars mark the number of galaxies we have found in our sample, along with  $\sqrt{n}$  uncertainties.

We have tested the sensitivity of our observational procedure by comparing the number of galaxies detected to that expected in seven of our survey sight lines (five are from LCO and two are from WIYN), which are  $\geq 80\%$  complete to  $m_B \approx 19$  out to impact parameters  $\rho \geq 5'$ . We assume a standard Schechter (1976) luminosity function and normalizations for this comparison, with a faint-end slope of either  $\alpha = -1.0$  or  $-1.2$ . Out to  $cz = 40,000$  km s<sup>-1</sup>, the number of galaxies detected by our survey agrees well with the number predicted (see Fig. 1). Our success in measuring redshifts for faint galaxies gives us confidence that we are not missing objects simply because our program lacks the required sensitivity.

While we cannot rule out the possibility that very LSB galaxies ( $\mu_B \geq 24$  mag arcsec<sup>-2</sup>) might be responsible for the void absorbers (Linder 1998), our surface brightness limits are low enough to require that any undetected galaxies in these regions are extreme LSBs (McGaugh et al. 1995). Rauch, Weymann, & Morris (1996) did not find any LSB galaxy associated with two very nearby absorbers in the 3C 273 sight line, nor did Impey et al. (1999) find any LSB galaxies in the Virgo Cluster associated with absorbers. Recent observations by Bowen, Pettini, & Blades (2001) find Ly $\alpha$  absorption in the PKS 1004+130 sight line 200  $h_{70}^{-1}$  kpc from an LSB galaxy. These authors find a high surface brightness galaxy closer to the sight line and interpret the complex Ly $\alpha$  absorption as arising in an intragroup medium, not from a combination of galaxy halos. H I observations could detect gas-rich LSB galaxies that might be missed in optical studies (Szomoru et al. 1996a, 1996b; Spitzak & Schneider 1998; Zwaan et al. 1997; Rosenberg & Schneider 2000). Van Gorkom et al. (1993, 1996) used Westerbork and the Very Large Array (VLA) to search for H I toward nine Ly $\alpha$  absorbers in four sight lines, detecting galaxies close to four of them. However, in only one case, that of a dwarf ( $M_B = -16$ ) toward Mrk 335, is the projected distance from the sight line to the galaxy  $\leq 100$   $h_{70}^{-1}$  kpc. But this object has a high central surface brightness ( $m_B \approx 19.5$  mag s<sup>-2</sup>) and would not have been missed by this survey. For the other five absorbers, the nearest galaxy neighbors are several hundred kiloparsecs away. At these distances, other galaxies become comparably close, making association with a single galaxy halo problematic (Shull et al. 1996, 1998; Penton et al. 2002).

Van Gorkom et al. (1996) find that the rate of H I detections is not affected by the presence of Ly $\alpha$  absorbers, evidence that the matches they have found between absorbers and galaxies are likely to be chance associations rather than actual individual physical connections. New VLA H I observations have targeted three of the void absorbers in Table 1, with sufficient sensitivity to address the H I-rich LSB galaxy possibility definitively (J. E. H. Hibbard et al. 2002, in preparation). Thus, while we cannot exclude categorically the presence of extreme LSB gal-

axies near these void absorbers, there is no positive evidence for association between any Ly $\alpha$  forest absorber and an LSB galaxy to date.

#### 4. SUMMARY AND CONCLUSIONS

We have presented a subset of the results from our pencil beam redshift survey toward 15 AGNs containing nearby Ly $\alpha$  absorbers, namely, four sight lines that pass through very nearby ( $cz \leq 3000 \text{ km s}^{-1}$ ) galaxy voids. The absorbers in these voids are all sufficiently near that we could have detected faint dwarf galaxies to limits of  $M_B \lesssim -14.3$  or fainter within 100–250 kpc of the sight line. In one sight line, HE 1029–140, our survey is too incomplete to be definitive. The remaining fields are more than 90% complete for  $M_B \leq -12.8$  to  $-14.5$ , or to  $\mu_B \leq 23.5 \text{ mag arcsec}^{-2}$ . While our survey puts strong constraints on the optical luminosity of any normal surface brightness galaxy that could be associated with the void absorbers, the possibility remains that extreme LSB galaxies ( $\mu_B \geq 24 \text{ mag arcsec}^{-2}$ ) could be present. A 21 cm search has been made for H I near three void absorbers (J. E. H. Hibbard et al. 2002, in preparation) and will address the presence of hydrogen-rich LSBs near the void absorbers.

The results of this optical survey strongly suggest that the void absorbers are a primordial population of objects. This is in keeping with results from cosmic structure formation simulations (e.g., Davé et al. 1999) and is contrary to the hypothesis

of C98 that all Ly $\alpha$  absorbers are associated with galaxies. The primordial nature of these void absorbers can be definitively addressed by searching for metals in them.

The current observations allow a first determination of the total baryon content in voids. Since no galaxies have been found by us or others in voids, the only baryons detected inside the voids are the Ly $\alpha$  absorbing clouds. Based on a standard photoionization model, Penton et al. (2002) have determined that the local Ly $\alpha$  forest accounts for  $\sim 20\%$  of the total baryons predicted by big bang nucleosynthesis. By comparing their measured value of  $dN/dz$  outside of voids to that in the voids, and by assuming the same values for the local ionizing radiation flux and the sizes of Ly $\alpha$  clouds in both void and nonvoid absorbers, S. V. Penton, J. M. Shull, & J. T. Stocke (2002, in preparation) show that the void absorbers account for  $\sim 22\% \pm 8\%$  of local absorption per unit path length (i.e., the 29% quoted earlier, corrected for the relative amount of path length through voids in the survey). This implies that  $4.5\% \pm 1.5\%$  of the total baryons reside in the voids. This calculation assumes that all baryons in voids are detectable either as galaxies or Ly $\alpha$  absorbers; i.e., if a warm-hot IGM component is present without detectable Ly $\alpha$  absorption, we have not accounted for it.

Support at the University of Colorado for work on the local Ly $\alpha$  forest comes from grants GO-06593.01 and GO-08182.01 from the *Hubble Space Telescope* Science Institute.

#### REFERENCES

- Arons, J. 1972, *ApJ*, 172, 553  
Bahcall, J. N., et al. 1993, *ApJS*, 87, 1  
Bahcall, J. N., & Spitzer, L., Jr. 1969, *ApJ*, 156, L63  
Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393  
Bond, J. R., Szalay, A. S., & Silk, J. 1988, *ApJ*, 324, 627  
Bowen, D. V., Pettini, M., & Blades, J. C. 2001, preprint (astro-ph/0107294)  
Chen, H. W., Lanzetta, K. M., Webb, J. K., & Barcons, X. 1998, *ApJ*, 498, 77 (C98)  
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, *ApJ*, 511, 521  
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, *PASP*, 107, 945  
Hernquist, L., Katz, N., Weinberg, D. H., & Miralda-Escudé, J. 1996, *ApJ*, 457, L51  
Huchra, J., Davis, M., Latham, D., & Tonry, J. 1983, *ApJS*, 52, 89  
Impey, C. D., Petry, C. E., & Flint, K. P. 1999, *ApJ*, 524, 536  
Lanzetta, K. M., Bowen, D. V., Tytler, D., & Webb, J. K. 1995, *ApJ*, 442, 538 (L95)  
Linder, S. M. 1998, *ApJ*, 495, 637  
McGaugh, S. S., Bothun, G. D., & Shombert, J. M. 1995, *AJ*, 110, 573  
Miralda-Escudé, J., Cen, R., Ostriker, J. P., & Rauch, M. 1996, *ApJ*, 471, 582  
Morris, S. L., Weymann, R. J., Dressler, A., & McCarthy, P. J. 1993, *ApJ*, 419, 524  
Morris, S. L., Weymann, R. J., Savage, B. D., & Gilland, R. L. 1991, *ApJ*, 377, L21  
Penton, S. V., Shull, J. M., & Stocke, J. T. 2000a, *ApJ*, 544, 150  
———. 2002, *ApJ*, 565, 720  
Penton, S. V., Stocke, J. T., & Shull, J. M. 2000b, *ApJS*, 130, 121  
Popescu, C. C., Hopp, U., & Elsässer, H. 1997, *A&A*, 328, 756  
Rauch, M., Weymann, R. J., & Morris, S. L. 1996, *ApJ*, 458, 518  
Rosenberg, J. L., & Schneider, S. E. 2000, *ApJS*, 130, 177  
Schechter, P. 1976, *ApJ*, 203, 297  
Shull, J. M., Penton, S., Stocke, J. T., Giroux, M. L., van Gorkom, J. H., Lee, Y. H., & Carilli, C. 1998, *AJ*, 116, 2094  
Shull, J. M., Stocke, J. T., & Penton, S. 1996, *AJ*, 111, 72  
Spitzak, J. G., & Schneider, S. E. 1998, *ApJS*, 119, 159  
Stocke, J. T., Shull, J. M., Penton, S. V., Donahue, M., & Carilli, C. 1995, *ApJ*, 451, 24  
Szomoru, A., van Gorkom, J. H., & Gregg, M. D. 1996a, *AJ*, 111, 2141  
———. 1996b, *AJ*, 111, 2150  
Tripp, T. M., Lu, L., & Savage, B. D. 1998, *ApJ*, 508, 200  
van Gorkom, J. H., Bahcall, J. N., Jannuzi, B. T., & Schneider, D. P. 1993, *AJ*, 106, 2213  
van Gorkom, J. H., Carilli, C. L., Stocke, J. T., Perlman, E. S., & Shull, J. M. 1996, *AJ*, 112, 1397  
Weymann, R., et al. 1998, *ApJ*, 506, 1  
Yee, H. K. C. 1991, *PASP*, 103, 396  
Zwaan, M. A., Briggs, F. H., Sprayberry, D., & Sorar, E. 1997, *ApJ*, 490, 173