The Local Lyα Forest: Association of Absorbers with Galaxies, Voids and Superclusters

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Abstract. We describe recent discoveries of low column density (N_{HI} ≤ 10^{14.5} cm^{-2}) H I Lyα absorbers made with the Hubble Space Telescope (HST) which have allowed us a first look at gas in local intergalactic space between us and the “Great Wall”. Despite the mere 2.4 m aperture of HST, these new observations allow us to detect absorbers with column densities, N_{HI} ≈ 10^{12.5} cm^{-2}, as low as those found using Keck/HIRES at high-z. Owing to the proximity of these absorbers to the Earth, the 197 absorbers in our combined GHRS + STIS sample provide our best view of the relationship between these absorbers and galaxies, voids, and supercluster filaments. Unlike previous results based on galaxy surveys near higher-N_{HI} absorbers, we find no evidence that these lower-N_{HI} absorbers are extended galaxy halos. Rather, the majority (78%) are associated with large-scale filamentary structures of galaxies, while 22% are found in galaxy “voids”. Since these Lyα absorbers are currently the only baryons detected in the voids, we use their properties to estimate that the voids contain 4.5 (±1.5)% of the Universal baryon density.

1. Introduction

Unlike virtually all other astronomical objects, Lyα absorbing “clouds” were first discovered at great distances (z ≥ 2) due to cosmological redshifts and the near-UV atmospheric cutoff. It has only been with the advent of the Hubble Space Telescope (HST) that nearby examples have been found and studied (Bahcall et al. 1991, 1993; Morris et al. 1991; and subsequent HST QSO Absorption Line Key Project papers by Jannuzi et al. 1998 and Weymann et al. 1998). While these absorbers are abundant enough to account for all baryons at z ≥ 2, their still substantial numbers at z ∼ 0 imply that ≥20% of all baryons remain in these clouds locally (e.g., Shull, Penton & Stocke 1999a; Penton et al. 2000b; Davé et al. 1998, 2000). Thus, any account of the present-day distribution of baryons must include an accurate census of these clouds and the mass associated with them, as inferred from their column densities and physical extent.

While the above baryon census is ample reason for studying the local Lyα forest in detail, it is also only at low-z that Lyα absorber locations can be compared accurately with galaxy locations, so that the relationship between these “clouds” and galaxies can be determined. The degree to which absorbers correlate with galaxies has been controversial: Lanzetta et al. (1995) and Chen...
et al. (1998) argue that the absorbers are the extended halos of individual bright galaxies (see also Lin et al. 2000 and Linder 2000), while others (Morris et al. 1993; Stocke et al. 1995; Impey, Petry & Flint 1999; Davé et al. 1999; Penton et al. 2001a) argue that the absorbers are related to galaxies only through their common association with large-scale gaseous filaments, arising from overdensities in the high-redshift Universe.

The intensity of this debate is evident in the differing views presented at the conference and in these proceedings. The results reported in this paper come chiefly from an on-going survey of the local Lyα “forest”, which utilizes spectra like that shown in Figure 1, and which is being conducted by our group at Colorado (J.M. Shull, S. Penton, M. Giroux & K. McLin), in collaboration with J. van Gorkom (Columbia), C. Carilli and J. Hibbard (NRAO), and R.J. Weymann and M. Rauch (OCIW). Current results on the physical conditions and metallicities of the absorbers in our sample can be found in the article by J.M. Shull in this volume. Since the time of the meeting, we have incorporated 16 additional sightlines into this analysis and have discovered a few more close (≤ 200\( h_{70}^{-1}\) kpc) absorber-galaxy pairs in our on-going ground-based redshift survey program (McL in et al. 2001). Neither of these new results significantly affects the conclusions we drew at the time of the meeting.

2. The Absorber Sample

Surprisingly and luckily for local IGM research, the modest HST aperture is competitive with the 10 m aperture of the Keck Telescope (+HIRES spectrograph) in detecting Lyα absorbers because much brighter targets can be observed. Figure 1 shows an HST+STIS (Space Telescope Imaging Spectrograph) far-UV spectrum of the bright BL Lac Object PKS 2005-489, which detects Lyα absorbers as low in column density, N_{HI} ≥ 10^{12.5} cm\(^{-2}\), as the best Keck HIRES data (e.g., Hu et al. 1995), but within 20,000 km s\(^{-1}\) of the Earth. This allows us an unprecendented opportunity to search for faint galaxies that could be associated with these absorbers.

All results reported here are based on data toward 15 targets studied with the Goddard High Resolution Spectrograph (GHRS) (Penton et al. 2000a,b, 2001a) and 16 targets observed using STIS (Penton et al. 2001b). In the entire survey, we have detected 197 Lyα absorbers at ≥ 4σ significance over a total unobscured pathlength Δz = 1.1. This yields dN/dz ~200 per unit redshift at N_{HI} ≥ 10^{13} cm\(^{-2}\) or one “cloud” every 20\( h_{75}^{-1}\) Mpc. The 20% baryon fraction quoted above uses this line density, a 100\( h_{70}^{-1}\) kpc spherical cloud extent and the standard 10^{-23} ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\) sr\(^{-1}\) local ionizing flux value (Shull et al. 1999b). To ensure that absorber-galaxy statistics are not biased due to incomplete galaxy survey information, we will quote results only for a subset of 86 absorbers that lie in regions of space surveyed for galaxies down to at least L* based upon the CfA redshift survey catalog (Huchra et al. 1992), February 8, 2000 version and/or our own galaxy redshift survey work (McL in et al. 2001). Preliminary results for a smaller group of 56 absorbers in regions surveyed down to 0.1L* also are presented. Most of the results presented herein are described in detail for the GHRS sample in Penton et al. (2001a).
Figure 1. An HST/STIS medium resolution (19 km s$^{-1}$) spectrum (Penton et al. 2001b) of the bright BL Lac Object PKS 2005-489 illustrates the best data obtained for this project. The deep, broad absorption at 1216 Å is the damped Lyα absorption due to the Milky Way. Other Galactic metal lines (S II, Si II, Mg II, N I and Si III) are marked with a “G”. The weakest Lyα absorbers have column densities, $N_{\text{HI}} = 10^{12.5}$ cm$^{-2}$, comparable to the weakest absorbers found in the best Keck/HIRES spectra of high-$z$ QSOs. The heliocentric velocity scale at top is for the Lyα absorbers only.
3. Absorber Galaxy Relationships

The two-point correlation function (TPCF), which measures the clustering of local Lyα absorbers, is similar to that found at high-z in that there is a 4σ excess power over random at $cz \leq 200$ km s$^{-1}$, but with no excess power at any larger $\Delta(cz)$. Impey, Petry & Flint (1999) found a similar result using lower resolution spectra. The absence of significant clustering of these absorbers is strong evidence that Lyα clouds do not arise in galaxy halos. But some investigators (see e.g., Fernandez-Soto et al. 1996) suggest that unresolved blends in Lyα absorption lines could cause us to underestimate the clustering of Lyα absorbers. However, the local galaxy halo TPCF has a large amount of excess power out to $\sim 1000$ km s$^{-1}$ as well as a signature of galaxy voids, neither of which are present in the Lyα TPCF (Penton et al. 2001a). Also, observations with STIS using the echelle gratings as well as Lyβ observations with FUSE (Shull et al. 2000) strongly suggest that there are at most 3 blended lines in each of our detected Lyα absorbers. Additionally, our absorber sample is at such low-z, that we can view the relationship between absorbers and galaxies directly, so that the TPCF is not as essential to understanding galaxy-absorber relationships as it is at high-z.

Using available bright galaxy redshift survey results and our own redshift survey work, we have searched for the nearest known galaxies to these absorbers and have found only a few close matches among the subset of 86 absorbers in sky regions surveyed down to at least $L^*$, although the detected close galaxies are almost always well below $L^*$ in brightness. For example, 6 of the 8 galaxies within $175h_{70}^{-1}$ kpc of an absorber are more than 2 magnitudes fainter than $L^*$ and almost all of these are in the Virgo Cluster (6 of these same 8), where the galaxy density is known to be much higher than elsewhere (Impey, Petry & Flint 1999). For 11 Virgo cluster absorptions, Impey et al. had found that the nearest-neighbor distances were so large that it was not possible to identify the absorber as a single galaxy halo. We find the same result: the median nearest galaxy neighbor distance from a Lyα absorber in the $L^*$ survey region sample is $800h^{-1}$ kpc, while the median nearest galaxy neighbor to another $L^*$ galaxy is $200h^{-1}$ kpc away in the same region (see Figure 2). Thus, even for galaxies as bright as $L^*$ it is problematical to identify a low column density absorber with a single galaxy. This and other features of the nearest neighbor distributions are shown in Figure 2, where the Lyα absorber sample has been split into two equal parts by number at 86 mÅ. While the stronger absorbers follow the galaxy nearest-neighbor distances more closely than the weaker absorbers (the two Lyα subsamples differ at the 4.5σ level), the stronger absorbers cluster much more weakly with galaxies than galaxies cluster with each other (5σ difference) but the weaker absorbers are not randomly distributed relative to galaxies either (7σ difference). Thus, even with a much larger and more uniformly surveyed sample, our current conclusions do not differ from our earlier work (Stocke et al. 1995).

Furthermore, for those few galaxies found close ($\pm 300$ km s$^{-1}$ in $\Delta(cz)$ and at impact parameters $\leq 300h^{-1}$ kpc on the sky) to a local Lyα absorber, the distribution of locations is random in that volume; i.e., even the galaxies rather near to Lyα absorbers do not concentrate close to the absorber, as would be expected if they were physically associated. This is true both for the $L^*$ sub-
Figure 2. Nearest-neighbor cumulative distribution functions (CDFs) for the 86 absorbers in our 4σL* sample (definite Lyα absorbers in regions surveyed for galaxy redshifts down to at least L*). The solid line shows nearest-neighbor distances for the full 4σL* sample; the dotted and dash-dotted lines are for the upper half and lower half subsamples respectively. The dashed line is the nearest-neighbor distribution for galaxies within the same survey volume, while the triple dot-dashed line is the nearest-neighbor distribution for random locations in the survey volume, corrected for the sensitivity function, S(λ), of our HST GHRS + STIS observations. Each of these CDFs differ significantly from each other (see text).
sample (Penton et al. 2001a) and for the 0.1$L^*$ sample (McLin et al. 2001) and suggests that even when there is a galaxy close to the absorber, the placement of the galaxy is random with respect to the absorber, as would be expected if there were no direct physical association between the two.

Sixteen percent (14 absorbers) of these absorbers lie in well-defined galaxy voids, with no known galaxies within 2-5$h^{-1}_{70}$ Mpc. Deep optical and HI 21 cm observations still in progress have failed to locate any galaxies close to four of these “void” absorbers (McLin et al. 2001; Hibbard et al. 2001) down to impressively low limits due to their proximity to the Earth ($cz=2000-3000$ km s$^{-1}$). For the four nearest “void absorbers”, those in the MRK 421, MRK 509, VII Zw 118 and HE1029-140 sightlines, the CfA redshift survey catalog finds no $L \geq 0.1L^*$ galaxies within 2-5$h^{-1}_{70}$ Mpc, while pencil-beam optical spectroscopy finds no very faint ($M_B \leq -13$ to $-13.5$) galaxies within 100-250$h^{-1}_{70}$ kpc of the absorber and HI observations with the VLA finds no H I emitting object with $M \geq 10^8M_\odot$ present in a much larger region around three of these four absorbers (HE1029-140 has not yet been observed in H I 21 cm emission). Thus, the absence of galaxies in voids and near “void absorbers” is confirmed and the only detectable baryons in voids are the Ly$\alpha$ absorbers. By correcting for the somewhat variable sensitivity of our Ly$\alpha$ survey with redshift, we find that 22% of all absorbers are in voids and thus (recalling that the full Ly$\alpha$ absorber density accounts for $\sim 20\%$ of all baryons locally), the baryon density in voids is only 4.5 ($\pm 1.5\%$) of the total mean baryon density of the Universe determined by [D/H] ratio; see Penton et al. (2000b, 2001a) for the detailed calculations of $\Omega_{baryon}$ in Ly$\alpha$ absorbers. If Ly$\alpha$ absorbers have no bias factor, then the supercluster-to-void density ratio is at least 20:1.

The plots of the cumulative distribution of absorber nearest-neighbor galaxy distances and of equivalent width (EW) versus impact parameter ($\rho$) for our full sample are similar to those published previously (Stocke et al. 1995) and to the results found by Tripp, Lu & Savage (1998) and Impey, Petry & Flint (1999). The correlation between EW and $\rho$ contains all the salient features (e.g., lack of correlation at low-$N_{HI}$; we find no correlation whatsoever for our enlarged sample) expected from the N-body+hydrodynamic simulations of Davé et al. (1999). Davé et al. interpret this plot as due to large-scale structure filaments; i.e., the correlation between EW and $\rho$ does not require either a physical or a causal association with individual galaxy halos as proposed by Lanzetta et al. (1995) and Chen et al. (1998). Our TPCF results and discovery of a substantial fraction of all absorbers in voids supports the Davé et al. (1999) interpretation. Thus, it seems that this plot cannot be used to support the hypothesis that all Ly$\alpha$ absorbers are very extended galaxy halos, although we emphasize that our absorber sample and that of Lanzetta et al. (1995) and Chen et al (1998) do not overlap significantly in equivalent width.

In one case, the sightline pair 3C273/Q1230+011, separated by 0.91$^\circ$ on the sky, we have a preliminary indication that both the 7 absorbers and 9 known galaxies in this vicinity are aligned along a single ($> 500h^{-1}_{70}$ kpc), elongated ($>3:1$) filament at $cz=1000-2000$ km s$^{-1}$ (Penton et al. 2001a). Additionally, Penton et al. (2001a) find a strong indication that this particular set of absorbers is not unique in this respect; i.e., for our full absorber sample there is a strong (4-12$\sigma$) statistical alignment of absorbers along galaxy filamentary structures.
This alignment with filaments is in contrast to the absence of any alignment between absorber locations and galaxy major axes found by Lanzetta et al. (1995). Eventually, perhaps with the Cosmic Origins Spectrograph (COS) on HST, we will be able to use Lyα absorbers and galaxy survey data (e.g., Sloan Digital Sky Survey) to map out the full extent of large-scale structure filaments in the local Universe.

For one case, a close grouping of Lyα absorbers at \( cz \approx 17,000 \text{ km s}^{-1} \) in the direction of PKS 2155-304, we have good metallicity limits (Shull et al. 1998) for low column density absorbers far from galaxies. Deep optical galaxy survey work (McLin et al. 2001) has failed to find fainter galaxies closer to the absorbers than the H I emitters found previously, the closest of which is \( \sim 400h^{-1} \text{ kpc} \) away on the sky. No metal lines (C IV and Si III) have been detected as yet in the several strong Lyα systems at this redshift, placing upper limits on the metallicity of these clouds of \( \leq 1\% \) solar. This result is still preliminary, awaiting better H I column density information from new HST (STIS) and FUSE spectra. So, while extensive metallicity surveys of Lyα absorbers have not yet been conducted with HST, it is possible that some clouds (e.g., the “void absorbers”) are devoid of metals, setting significant “fossil” constraints on the spread of metals in the early Universe due to supernovae winds and galaxy interactions (see e.g. Hui & Gnedin, 1997). However, we have found at least one absorber that is undetected in C IV, C III and C II but has strong O VI absorption (Tripp et al., 2001), so that any metallicity result based only on lower ionization species alone must be taken with caution. The existence of this one Lyα + O VI absorber is additional evidence for shock-heated “clouds” (see Tripp contribution to this volume). However, we caution that virtually all O VI absorbers (i.e., Chen & Ostriker’s “hot-warm” phase) should be detectable in Lyα and so should be present in our GHRS+STIS survey; i.e., it is important not to “double count” absorbers when determining the total baryon content of the local Lyα “forest”!

4. Why All the “Fuss”?

For the uninitiated viewing the debate on the relationship between Lyα absorbers and galaxies at the Pasadena Conference, one must ask whether the issue is primarily semantics or science. On the one hand, at this conference Ken Lanzetta and Hsiao-Wen Chen argued that all higher column density absorbers are individual, spherical galaxy halos with a nearly unity covering factor to Lyα absorption out to impact parameters of \( \sim 160h^{-1} \text{ kpc} \). In this paper I have presented evidence that the majority of lower column density absorbers are associated, not with individual galaxies, but with large-scale filamentary structures in which both the galaxies and the absorbers are imbedded. This is the view espoused by the cosmic simulators, who find these very extensive gaseous structures throughout their simulations at both high- and low-z. At the extremes, it is clear that both views are correct: there are certainly some higher column density absorbers that must be extended galaxy halos because they are so close to their “parent” galaxy (\( \leq 50h^{-1} \text{ kpc} \); e.g. the Mg II absorbers) as to be bound to it, while there are low column density absorbers demonstrably not associated with galaxies at all because they are in voids. In between, the data could argue for either stance and the differences might be largely semantic,
excepting for the issue of metallicity. If by galaxy “halo” we mean gas that was once within the galaxy and then was expelled to large radii, the local Lyα absorbers should contain gas with metallicities of $\geq 0.1$ Solar. There is preliminary evidence that this is the case for absorbers within $\sim 100$ kpc of the nearest bright galaxy (Chen et al. 2001; Stocke et al. in preparation) but not for the bulk of the forest which lies at much larger distances from bright galaxies (see Figure 2). Metallicities for some of these more representative clouds are needed to be more definite about the origin of gas in the local Lyα absorbers, including the “void absorbers”. If the bulk of the forest is “primeval”, then the observations can be used to test the simulations; but if, these absorbers are mainly the product of latter-day galaxy winds, then detailed “microphysics” must be included in the simulations to match the observational record. Focus on the issue of metallicity may allow workers in this field to stick to scientific rather than semantical concerns.

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