The Local Ly\textalpha{} Forest: H I in Nearby Intergalactic Space

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Abstract. Detecting H I using redshifted Ly\textalpha{} absorption lines is $\sim 10^6$ times more sensitive than using the 21 cm emission line. We review recent discoveries of H I Ly\textalpha{} absorbers made with the Hubble Space Telescope (HST) which have allowed us a first glimpse at gas in local intergalactic space between us and the “Great Wall”. Despite its mere 2.4 m aperture, HST can detect absorbers with column densities as low as those found using Keck at high-$z$ ($N_{\text{HI}} \approx 10^{12.5}$ cm$^{-2}$). New results that will be discussed include: the evolution of absorbers with redshift, the location of absorbers relative to galaxies (including the two-point correlation function for absorbers), the metallicity of absorbers far from galaxies, and the discovery of hot $\sim 10^{5-6}$ K (shock-heated?) absorbers. The unique ability of VLA H I observations in discovering the nearest galaxies to these absorbers is stressed.

1. Introduction

Unlike virtually all other astronomical objects, Ly\textalpha{} absorbing “clouds” were first discovered at great distances ($z \geq 2$) due to cosmological redshifts and the near-UV atmospheric “cutoff”. It has only been with the advent of the Hubble Space Telescope (HST), with access to the ultraviolet, that nearby examples have been found and studied. One of the major unexpected discoveries made during the first year of HST was that the numerous Ly\textalpha{} absorption lines found at high-$z$ persist, albeit with fewer numbers, into the present epoch (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). Extrapolations of the steep redshift dependence of the number evolution of the lines seen at early times had predicted that very few low-$z$ Ly\textalpha{} lines would be found. While these absorbers likely account for the majority of all baryons at $z \geq 2$, their still substantial numbers at $z \sim 0$ imply that $\geq 20\%$ of all baryons remain in these clouds locally (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. Further, the evolving thermodynamic properties of the intergalactic medium (IGM) are probed using these clouds, as measurements of their doppler widths ($b$) reveal information about their temperatures. Observations of the changing $b$ distribu-
tion and metal content of Lyα absorbers with time reveal the history of energy and metal injection into the IGM from $z \approx 6$ to the present.

Although it is already clear that much or even most of the baryons could be in the local IGM, this number is quite uncertain, depending as it does on two poorly known quantities: (1) **cloud extent**: Physical extent measurements come only from common absorbers found in close pairs of QSO sightlines and suggest extents of 100-300 $h^{-1}$ kpc, but are difficult to interpret; see Impey (1999). Very large and elongated “clouds” are suggested by cosmological simulations (Cen et al. 1994; Davé et al. 1999), but sightline pairs alone cannot measure “cloud” shapes; (2) **ionized fraction**: Photoionized models of Lyα absorbers use the local AGN luminosity function (e.g., Shull et al. 1999) or limits on IGM H I cloud Hα emission (e.g., Donahue et al. 1995) to estimate the intensity and spectrum of the local IGM ionizing flux. As has been stressed by several authors (Cen & Ostriker 1999; Davé et al. 2000), as many as 30-40% of all baryons could be in a hot, shock-ionized phase, outside galaxy clusters and groups. If so, the ionized fraction of many Lyα absorbers has been underestimated by using photoionization models, and the majority of local baryons are in the IGM, not in galaxies. However, one must take care not to “double count” individual absorbers that are detected both in Lyα and O VI, but only to make sure that an appropriate ionized fraction is used in the accounting.

While the above 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 very extended halos of galaxies (see also Lin et al. 2000; Linder 2000), while Morris et al. 1993; Stocke et al. 1995; Impey, Petry & Flint 1999; Davé et al. 1999 and Penton et al. 2000b argue that the absorbers are related to galaxies only through their common association with large-scale gaseous filaments.

## 2. Results

Surprisingly, and luckily for local IGM research, the modest HST aperture is competitive with the 10m 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 with column density, $N_{\text{HI}} \geq 10^{12.5}$ cm$^{-2}$, as low as the best Keck HIRES data (e.g., Cowie et al. 1995). For reference to other H I work in this conference, these absorbers have $\sim 10^6$ times lower column densities than the weakest detections using the 21 cm emission line. The results reported here 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, in collaboration with J. van Gorkom (Columbia), C. Carilli and J. Hibbard (NRAO), and R. Weymann and M. Rauch (OCIW). These UV spectra also allow important studies (i.e., metallicities) of high velocity clouds (HVCs)
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Figure 1. An HST/STIS medium resolution (19 km s\(^{-1}\)) spectrum (Penton et al. 2001, in preparation) of the bright BL Lac Object PKS 2005-489 illustrates the best data obtained for this project. The deep, broad absorption at left center is the damped Lyα absorption due to the Milky Way. Other Galactic metal lines (S II, Si II, N I, N V, and Si III) are marked with a “G”. The weakest Lyα absorbers have column densities comparable to the weakest absorbers found in the best Keck spectra of high-z QSOs, \(N_{HI} = 10^{12.5}\) cm\(^{-2}\).

not possible by other methods and which bear critically on the nature of these HVCs (see Gibson et al. contribution to this volume).

All specific results reported here use only the Goddard High Resolution Spectrograph (GHRS) portion of our dataset, which includes 15 targets (Penton et al. 2000a,b, 2001). Fifteen additional targets have now been observed using STIS, which will extend the current results significantly. From our GHRS survey the following results have been obtained:

1. Although only 116,000 km s\(^{-1}\) in pathlength has been observed in our GHRS survey, we have detected 81 (\(\geq 4\sigma\)) absorbers at \(cz \leq 20,000\) km s\(^{-1}\), yielding a \(dN/dz \sim 200\) per unit redshift at \(N_{HI} \geq 10^{13}\) cm\(^{-2}\) or one “cloud” every 20 \(h_{75}^{-1}\) Mpc! The 20% baryon fraction quoted above uses this line density, a 100 \(h_{75}^{-1}\) 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. 1999). Figure 2 compares line densities as a function of redshift for two column density regimes: (1) \(N_{HI} \geq 10^{14}\) cm\(^{-2}\) from the Bechtold (1994) high-z compilation and the HST Key Project low-z results of Weymann et al. (1998); and (2) \(10^{13.1} \leq N_{HI} \leq 10^{14}\) cm\(^{-2}\) from Kim et al. (1997) at high-z and our GHRS survey at \(z \leq 0.067\). The overall trend in these two different column density regimes appears similar, and has been interpreted using
Figure 2. The Lyα absorber number density \(dN/dz\) as a function of redshift. The overall trends for two different column density regimes \((10^{13.1} \leq N_{\text{HI}} \leq 10^{14} \text{ cm}^{-2} \) at top and \(N_{\text{HI}} \geq 10^{14} \text{ cm}^{-2} \) at bottom) are described in detail in the text.

2. The absorber \(b\)-value distribution at \(z \sim 0\) is similar to that found at high-\(z\), with a median \(b\)-value of 35 km s\(^{-1}\). No obvious correlation between \(b\) and \(N_{\text{HI}}\) is found. However, when compared to \(b\)-values obtained from a curve-of-growth (COG) analysis using higher-order Lyman lines (Shull et al. 2000) from spectra obtained with the Far UV Spectroscopic Explorer.
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(FUSE), Lyα line widths are a factor factor of two higher than the b-values inferred from the COG. The FUSE data suggest that local Lyα absorbers contain sizable nonthermal motions arising from cosmological expansion and infall. Measuring the actual b-values of these clouds is necessary to determine the IGM “effective equation of state” (Hui & Gnedin 1997; Ricotti, Gnedin & Shull 2000) and thus when heat has been input into the IGM. Higher resolution HST spectra and more FUSE spectroscopy of low-column-density absorbers are now being obtained to measure the b-values and clustering (see next item) of these clouds more precisely.

3. The two-point correlation function (TPCF), which measures the clustering of Lyα absorbers, is similar to that found at high-z in that there is a 4σ excess power over random at \( cz \leq 200 \text{ km s}^{-1} \). 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, although some investigators (Impey & Bothun 1997; Linder 2000) suggest that this may indicate that low-surface-brightness (LSB) galaxy halos may be responsible.

4. Using available bright galaxy redshift surveys, we have searched for the nearest known galaxies to these absorbers and have found no close matches among a subset of 45 absorbers in sky regions surveyed down to at least \( L^\ast \). Typical nearest-neighbor distances are several hundred kpc to a few Mpc (median 1 Mpc) for \( H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Seven of these absorbers lie in well-defined galaxy voids, with no known galaxies within 2-5 \( h^{-1} \text{ Mpc} \). Deep optical and 21 cm observations still in progress have failed to locate any galaxies close to these “void” absorbers (McLin et al., this volume).

5. The cumulative distribution of distances to nearest-neighbor galaxies and the correlation of equivalent widths (EW) with impact parameters (ρ) found by Penton et al. (2001) are similar to those published previously (Stocke et al. 1995). In the latter case, they are similar to the results found by Tripp, Lu & Savage (1998) and Impey, Petry & Flint (1999). The EW-ρ correlation contains all the salient features (lack of correlation at low-N\( \text{HI} \)) 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; the EW-ρ correlation does not require either a physical or a causal association with individual galaxy halos as proposed by Lanzetta et al. (1995) and Lin et al. (2000). Our TPCF results and discovery of a substantial fraction (~16%) of all absorbers in voids supports the Davé et al. (1999) interpretation.

6. In one case, the sightline pair 3C273/Q1230+011 separated by 0.91° 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 (> 500 \( h^{-1} \text{ kpc} \)), elongated (>3:1) filament at \( cz=1000−2000 \text{ km s}^{-1} \). This preliminary result (Penton et al. 2001) suggests that 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 Survey) to map out the full extent of large-scale structure filaments in the local Universe.
Figure 3. An optical sky survey image with 21 cm contours overlaid (Shull et al. 1998) shows the location of all H I-emitting galaxies at \( cz \approx 17,000 \text{ km s}^{-1} \). The lowest H I contours are at \( 1.65 \times 10^{19} \text{ cm}^{-2} \) and total H I masses as low as \( 0.8 \times 10^9 \text{ M}_\odot \) are detected. The central “hub” is the location of PKS 2155-304, while the numbers on the “spokes” indicate the impact parameters for each H I galaxy assuming \( H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

7. For one case, a close grouping of Ly\( \alpha \) 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 that lie far from galaxies. Figure 3 shows the PKS 2155-304 field, overlaid with 21 cm emission contours (also at \( cz \approx 17,000 \text{ km s}^{-1} \)) from the VLA. Deep optical galaxy survey work (McLin et al. this volume) has failed to find fainter galaxies closer to the absorbers than the H I emitters, reinforcing the importance of the VLA in this program. No metal lines (C IV and Si III) have been detected as yet in the several strong Ly\( \alpha \) systems at this redshift, placing upper limits on the metallicity of these clouds of \(<1\% \) solar.

The metallicity result in #7 is still preliminary, awaiting better H I column densities and metal-line measurements from new HST (STIS) and FUSE spectra. Also on-going is an attempt to map the extent of metals in the IGM around galaxies using C IV observations for a subset of local, partially saturated absorbers found in our GHRS survey, in conjunction with the available pencil-beam galaxy survey data. Preliminary results suggest that metals have been spread up to \( \sim 150 h_{75}^{-1} \text{ kpc} \) from galaxies (Stocke et al. 2001, in preparation), in agreement with simulations by Gnedin (1998). However, since 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, in preparation), any metallicity result based on lower ionization species alone must be viewed with caution. The existence of this one Ly\( \alpha + \text{O VI} \)
absorber is additional evidence for these shock-heated “clouds” (see Tripp contribution to this volume). We note that virtually all O VI absorbers (the Davé et al. “hot-warm” phase) should be detectable in Lyα and present in our GHRS survey. Therefore, it is important not to “double count” absorbers when determining the total baryon content of the local Lyα “forest”.

Finally, the PKS 2155-304 field in Figure 3 underscores the important role to be played by the VLA in this work. Virtually all of the very close \( r \leq 200h_{75}^{-1} \) absorber-galaxy pairs to date are H I-discovered galaxies, including the closest impact parameter in our GHRS sample \( (100h_{75}^{-1} \text{ kpc in the MRK335 sightline; van Gorkom et al. 1996}) \) as well as the close proximity of the Haynes-Giovanelli H I cloud to the 3C273 and Q1230+011 sightlines (Penton et al. 2001). Only H I 21 cm observations are unbiased against the discovery of LSB galaxies, which have been suggested to be responsible for some local Lyα absorbers.

3. The Future

Over the next few years, we expect that our own work, as well as that of others, will increase the accuracy of every result in items #1-5 above, including a revised value for the local baryon content of the IGM which is probably accurate to 50%. The \( dN/dz \) relationship will be known in detail for both the high and low column density absorbers. Future work on items #6 and #7 will determine whether Lyα absorbers arise in large-scale structures or in very extended galaxy halos. If the former (which we strongly suspect based upon our own investigations) some local Lyα absorbers will be found which were never “polluted” with metals from the galaxies which co-habit the universal filamentary structure with them.

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Questions

Linder: We don’t have a good sense of where all the galaxies are located within the Davé et al. simulation (such as LSB galaxies). Furthermore, an anti-correlation between equivalent width and impact parameter will be seen whether absorbers arise in galaxies or not. Thus, the anti-correlation seen by Davé et al. does not provide compelling evidence that absorbers do not arise in galaxies.

Stocke: It is certainly true that the Davé et al. simulations locate galaxies by a quite simple criterion that may have “missed” LSB galaxies. However, it is striking that both the observations and the simulations show similar slopes in the EW vs. \( \rho \) relation as well as similar spreads in the data at both high and low column density. You may need to explain why 16% of Ly\( \alpha \) absorbers are found in galaxy voids. We have looked for faint galaxies near these “void” absorbers and not found any. Also, to date, I know of no close association between any low-z Ly\( \alpha \) forest cloud and any LSB galaxy, despite sensitive attempts to find them (e.g., Rauch, Morris & Weymann; Impey, Petry & Flint 1999; and our own H I work in collaboration with van Gorkom and Carilli). Because LSB galaxies are fairly abundant in H I, our H I surveys near Ly\( \alpha \) absorbers should have found some. So far we have not.

Meiksin: The flattening in \( dN/dz \) for the Ly\( \alpha \) forest toward low redshift can be accounted for predominantly as an ionization effect: the proximity effect tells us the ionizing background has decreased by an order of magnitude or more from
$z = 3$ to $z = 0$. This decrease is independent of the nature of the ionizing photon sources.

Stocke: I do not take the proximity effect results at $z \approx 0$ as definitive, but you are quite correct that the observational constraints (proximity effect at high $z$ and limits on H$\alpha$ emission from intergalactic H I clouds at $z < 1$) argues for a substantial decrease in ionizing flux, regardless of the sources.

Bland-Hawthorn: What about the possibility of condensation trails as the galaxies move through their environment? You could imagine metal enriched material a megaparsec away from the source.

Stocke: Yes, one could imagine such a thing. But the trick would be to prove that this is what is going on. Indeed, simulations (e.g., Gnedin 1998) show that mergers and winds can move supernovae-enriched gas $100 - 200 h^{-1} \text{kpc}$ away from their creation site and cluster gas extends several hundreds of kpc from the cluster center. Sensitive searches for metal enriched gas far away from galaxies are difficult and have just begun, so until we find such gas, I am not too concerned about explaining its precise origins.

Katz: In the simulation, the Ly$\alpha$ absorbers come not from galaxies but from structures containing galaxies. The simulations do include supernovae feedback, but it doesn’t produce winds.

Stocke: Thanks, Neal, for that clarification. I add only that other simulations (e.g., Gnedin 1998) do show that supernovae winds and galaxy merger events can move gas only about $100 - 200 h^{-1} \text{kpc}$ from galaxies, but nowhere near as far as the distances we observe Ly$\alpha$ clouds to be due to those galaxies (e.g., the “void” absorbers).

Disney: Is the change in the ionizing flux used to explain the change of $dN/dz$ with $z$ a simulation result, or an observation? How secure is it?

Stocke: Please see my reponse to Avery Meiksin’s question. The proximity effect is a measured quantity, which can be used to infer the mean ionizing background. The error bars are significant ($\sim 50\%$), despite large samples of QSO absorbers (Scott et al. 2000). Other estimates of the ionizing intensity, $J_0$ at low redshift are more indirect (Shull et al. 1999), and depend both on QSO luminosity functions and radiative-transfer simulations. I would claim that the nearly two orders of magnitude drop in the ionizing flux from $z \approx 2$ to $z = 0$ is quite secure observationally, although its mean value in the IGM, to say nothing of its dispersion, has not been measured at $z \approx 0$ directly.