Quasar Absorption Lines and the Intergalactic Medium

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Abstract. The importance of HST for the study of quasar absorption lines and of the nature of the intergalactic medium is illustrated by reviewing selected results from past HST observations. Topics reviewed include the study of Ly$-\alpha$ absorbers at low redshift and the search for a diffuse IGM at high redshifts.

1. Opening the Ultra-violet Window

Soon after quasars were recognized as extragalactic sources (Schmidt 1963; Greenstein and Matthews 1963; Schmidt 1965) it was pointed out that as their light travels to Earth any intervening matter will leave its imprint on the spectra. This is true whether the intervening medium is full of diffuse hydrogen causing a uniform decrease of the quasar continuum (Gunn & Peterson 1965; Scheuer 1965) or discrete clouds producing separate absorption lines (by hydrogen, possibly associated with galaxies, Bahcall & Salpeter 1965; by hydrogen and other species in galactic halos, Bahcall & Salpeter 1966, Bahcall & Spitzer 1969). However, even before the discovery of quasars, Lyman Spitzer (1956) had pointed out the importance of UV spectroscopy for understanding the physical conditions of the gaseous content of the Galaxy, and by implication the halos of other galaxies and the gaseous content of the universe in general. As he pointed out, the majority of the strong resonance absorption lines occur in the rest frame UV (see Figure 1).

At high redshifts intervening absorption systems can be studied from the ground (for an example of the current state of the art see Figure 2). However, the gaseous content of the nearby universe and the far-UV lines (e.g. He II) occurring at high redshift can only be observed in the UV. Although HST is not the first telescope with UV sensitive spectrographs, it is the first to provide both the spectral resolution and the sensitivity to allow the extensive observation of the quasar absorption lines.

Here is a list of three of the many important studies that the observation of quasar absorption lines at UV wavelengths makes possible: 1.) The evolution of the gaseous content of the universe can now be traced by observing the changing number density per unit redshift of Ly$-\alpha$ absorbers from the present (using HST, from $z_{\text{abs}} \approx 0.0$ to $z_{\text{abs}} \approx 1.6$) back to when the universe was 10% of its current age (using groundbased telescopes like Keck to observe the most distant quasars). Such data are important for the study of cosmology, star and galaxy formation, development of large scale structures, and the composition of the ISM. The dramatic changes that occur from high to low redshifts are illustrated by comparing Figures 2-4. Quantifying and understanding these changes in detail is the continued focus of the HST quasar absorption line key project and other research efforts as well.

2.) For low redshift absorbers it is now possible to study their relation to individual galaxies, groups, or clusters – i.e. test the 1969 proposition of Bahcall and Spitzer, “that most of the absorption lines observed in quasi-stellar sources with multiple absorption redshifts are caused by gas in extended halos of normal galaxies.”

3.) Although efforts to detect a diffuse intergalactic medium (IGM) through continuous absorption by neutral hydrogen have failed, we can now extend the search by looking for
2. The HST Quasar Absorption Line Key Project

2.1. Design and Goals of the Survey

The HST quasar absorption line survey was an HST key project for cycles 1-3, with carryover observations extending into cycle 4. Led by John Bahcall, the survey had the ambitious goal of obtaining a large and homogeneous catalogue of absorbers suitable for the study of the nature of gaseous systems and their evolution (Bahcall et al. 1993). While the well known telescope problems in effect prior to the servicing mission reduced the original scope of the survey, the key project still successfully observed 89 quasars with the higher resolution (R= 1300) gratings of the Faint Object Spectrograph. A small subset of the quasars were observed from 1150–3300 Å, but the majority were observed only between 2200–3300 Å or 1600–3300 Å, depending on the redshift of the quasar. Targets were selected to be bright and have low Galactic extinction (b > 20 degrees). The distribution of the targets is shown in Figure 5. Redshifts of the observed quasars range between 0.25 and 2.0. Details of the
Figure 2. The large number of absorbers blueward of Ly$-$α, “the forest”, is quite evident in this Keck I and HIRES observation of the $z = 3.63$ quasar Q1222+2309 obtained by Womble et al. (1996).

Figure 3. The number of absorbers blueward of Ly$-$α is noticeably less in this HST and FOS spectrum of PG 1634+706 (Bahcall et al. 1996). Each Ly$-$α line is indicated with a vertical tick mark above the location of the line.

data calibration and analysis can be found in Schneider et al. 1993, Jannuzi & Hartig 1994, and Bahcall et al. 1996. In all of our analysis (from line measurements to line identifications) we have tried to remove subjective decision making from the process and replace it with well tested algorithms implemented through computer software. This allows us to run the same software on simulated data in order to improve our understanding of the limitations of both our data and our analysis techniques.

2.2. Past Results

The first nice surprise that HST presented to us was a larger number of low redshift Ly$-$α absorption systems in the spectrum of 3C 273 than might have been expected from a simple extrapolation of the evolution in the number density (per unit redshift) of such systems observed at high redshift (Bahcall et al. 1991; Morris et al. 1991). Early results have also been produced by HST on the nature and evolution of metal line systems (e.g. Reimers & Vogel 1993; Bergeron et al. 1994). Our understanding of the evolution of Lyman-limit systems from high redshifts down to $z = 0.4$ has been improved (Storrie-Lombardi et al. 1994; Stengler-Larrea et al. 1995) and a first attempt has been made to measure the proximity effect in the spectra of low redshift quasars (Kulkarni & Fall 1993).

The key project catalogue of Ly$-$α absorbers makes it easier to investigate the extent and nature of the relationship between Ly$-$α absorbers and individual galaxies, groups, or clusters. Many groups are actively working on this problem (e.g. incomplete or single field surveys: Bahcall et al. 1991, 1992; Morris et al. 1993; Spinrad et al. 1993; to more extensive surveys in progress that have presented partial results: Lanzetta et al. 1995; Stocke et al. 1995; Le Brun et al. 1995), but I have chosen to adapt a figure from Morris et al.’s (1993) study of the field of 3C 273 to illustrate both the progress that has been made and how much more needs to be done (Figure 6). Despite a complete redshift survey of even the
Figure 4. By the low redshifts probed by this HST observation of the quasar 3C 273 (Bahcall et al. 1991) the Ly–α forest seems to have been completely removed. However, the number of absorbers is still in excess of a simple extrapolation of the evolution observed at redshifts greater than 1.6 (Bahcall et al. 1991; Morris et al. 1991). Each Ly–α line is indicated with a vertical tick mark above the location of the line. The other absorption lines are caused by the ISM of our own Galaxy. Note the two Ly–α lines near zero redshift at the approximate velocity of the Virgo cluster.

Figure 5. The distribution in galactic coordinates of the 89 quasars observed as part of the HST quasar absorption line survey.

faintest galaxies in the field, the study of the 3C 273 field gives a mixed signal. While some absorbers appear to be associated with the same structures as the galaxies (as suggested by Lanzetta et al., actually part of the halos of the galaxies) other lines appear in voids (see also Stocke et al.) with no detected galaxy within 1 Mpc. The Morris et al. study is limited by the small number of Ly–α systems along the line of sight toward 3C 273, resulting in a limited comparison between the distribution of galaxies and absorbers. In fact no single line of sight provides enough Ly–α absorbers to allow the accurate determination of the fraction of all absorbers which are associated with galaxies or larger structures. For some of the other papers listed above the problem is similar or the galaxy redshift surveys that they use are incomplete. Some of the other surveys are also not able to address the relationship between the absorbers and groups or clusters of galaxies because the galaxy survey does not cover a large enough angular area to be able to identify a cluster or group. To determine accurately the fraction of Ly–α absorbers associated with galaxies and large scale structures requires both the completion of the key project catalogue of absorbers and an increase in the number of fields for which galaxy redshifts are available (e.g. Sarajedini et al. 1996).
Figure 6. Displayed in these pie-diagrams are the positions of the galaxies in the field of the quasar 3C 273 and the locations of Ly–α lines detected in the FOS and GHRS ultra-violet spectra of 3C 273. Angles have been exaggerated by a factor of 15 to improve the clarity of the figure, but results in a distorted plot with spherical structures appearing elongated transverse to the line of sight. Note that while some of the Ly–α absorbers appear associated with galaxies, several have no detected galaxy within 1 Mpc. Adapted from Morris et al. 1993, see their paper for complete discussion.

The key project spectra have also provided valuable information on our own Galaxy’s halo and ISM (Savage et al. 1993), the emission line properties and spectral energy distributions of quasars (Espey et al. 1994; Weymann et al. 1996; Laor et al. 1994, 1995; Sulentic this conference), and warm x-ray absorbers (in the quasar 3C 351, Mathur et al. 1994).

2.3. Some New and Future Results

A continuing focus of the key project is to determine the nature and evolution of the low redshift Ly–α absorbers. The number density of such systems as a function of redshift is summarized in Figure 7 (see Bahcall et al. 1996 for details). At low redshift (z < 1.3), the key project data analyzed to date (about 10% of the expected final catalogue) is consistent with no evolution for $\gamma = 0.58 \pm 0.50$ and $dN/dz \propto (1 + z)^\gamma$. This result is derived from a maximum likelihood estimation for the observed lines in those spectral regions where the 4.5 $\sigma$ detection limit is less than 0.24 Å. We further find that the slope of the observed low-redshift $dN/dz$ relation differs at the 2 – 4.5$\sigma$ level of significance from the slope deduced from various ground-based samples that refer to redshifts $z > 1.6$ (Lu et al. 1991; Press et al. 1993; Bechtold 1994).
Figure 7. The number density of Ly-$\alpha$ absorption systems is shown as a function of redshift. At redshifts below 1.6 the data come from Bahcall et al. 1996, including approximately 10% of the final HST key project catalogue of Ly-$\alpha$ absorbers. At higher redshifts two samples (Lu et al. 1991; Bechtold 1994) are plotted which give similar but not identical results. The separate fits to the HST and Lu et al. data are shown as the two solid lines, with slopes of $\gamma = 0.48 \pm 0.54$ and $2.68 \pm 0.27$ respectively. The dashed line shows the best fit to a single power law for both the HST and the Lu et al. data and has a slope of $1.58 \pm 0.13$. A KS test indicates that this fit is only acceptable at the 2.7% level. Fits using the Bechtold (1994) data give similar results although a single power law fit is not ruled out as strongly. The fits were done using a maximum likelihood technique on the unbinned data. The binned data have been placed on the figure for reference purposes only.
As the number of absorbers in the analyzed catalogue increases it becomes possible to study the clustering properties of Ly$-\alpha$ absorbers. While we have yet to detect any signal in the two-point correlation function, we have found evidence that about half of the extensive metal line systems seen at redshifts between 0.4 and 1.3 are accompanied by highly-clustered clumps of Ly$-\alpha$ lines which are physically associated with the metal-line systems (details in Bahcall et al. 1996).

Our understanding of both the redshift evolution of all absorption systems and of their clustering properties will improve as we complete the catalogue of absorption systems. The last observation of the key project was made in May of 1995. At the time of this meeting all of the quasar spectra have been reduced, lines measured, and the lines are being identified. The key project results I have reviewed have been based on only part of the total absorption line data set (see Figure 8). While we have analyzed one sixth of the objects, the remaining five sixths include most of the higher redshift objects and four fifths of the observed redshift path length. Expected improvements upon completion of the catalogue include: 1.) examining the evolution of Ly$-\alpha$ systems not only as a function of redshift, but also as a function of neutral column density and 2.) confirming or refuting the preliminary evidence for clustering of Ly$-\alpha$ absorbers around metal line systems.

3. Has the IGM Finally Been Detected?

We now leave the universe at low redshift behind and examine the Herculean efforts that have been made to detect the diffuse intergalactic medium with HST (a complete and detailed account of this exciting area can be found in the contribution to these proceedings by Dr. Jakobsen). Excluding the detection of absorption assigned to weak individual “clouds” (the low column density end of the Ly$-\alpha$ forest; the Bahcall-Salpeter effect), all efforts to detect absorption by diffuse neutral hydrogen (the Gunn-Peterson effect) at ANY redshift have failed. The ionizing background radiation reduces the fraction of H I and He I (Sargent et al. 1980) and removes them as probes of the diffuse IGM (note, He I has been observed in high column density systems, the first detection being made with HST by Reimers & Vogel 1993). The lower ionizing background at short wavelengths might leave a higher fraction of He II and provide a means of detecting the diffuse IGM, but the short wavelength of He II (304 Å) means that it can only be observed at high redshifts. This
means that “clear” quasars, as Jakobsen call them, must be found. Such quasars must
be bright, have redshifts greater than 3 (to have He II observable with HST), and be free
of significant absorption from intervening “clouds”, particularly the high column density
systems whose Lyman-Limit absorption would preclude the observation of He II. Jakobsen
et al. (1994) and Tytler et al. (personal communication) both conducted searches during
cycles 1-3 using HST and respectively the FOC and FOS to find candidate “clear” quasars.
In cycle 4 both groups succeeded in detecting He II absorption in the spectra of distant
quasars.

While the details can be found in Dr. Jakobsen’s contribution, here are some bottom
lines. There are now three detections of absorption due to He II. Two quasars (Q0302−003
and PKS1935−692) exhibit black, continuous absorption blueward of the expected wave-
length of He II at the redshift of the observed quasars (z > 3 for the two observed with
HST, see figures in Jakobsen et al. 1994 and Jakobsen’s contribution; Jakobsen and Tytler
1996). The lower limits on the optical depth of He II absorption are 1.7 in both cases. A
third quasar, HS1700+6414, was successfully observed by HUT (Davidsen 1995) and shows
He II absorption beginning at z = 2.7, but the absorption is not as strong as at the higher
redshifts observed with HST. It appears that both the HST and HUT observations can be
interpreted as consistent with each other given the possible evolution between redshifts of
3.2 to 2.7 (Jakobsen, this meeting).

One problem with any search for a diffuse component in the IGM is that as we are able
to detect and resolve lower column density systems we remove absorption from the previ-
ously unresolved “diffuse” component and move it into the “cloud” component. Q0302−003
has been observed with Keck and the HIRES echelle spectrograph and a population of very
low column density Ly-α clouds has been detected by Songaila et al. (1995) and they report
that the detected population is extensive enough that it is possible to explain the observed
He II absorption without invoking a diffuse IGM. Neither the HUT nor the HST FOC and
FOS observations have the spectral resolution necessary to distinguish directly between the
He II “forest” and a more diffuse and uniform absorption. The issue is likely to remain un-
settled until the existing lines of sight (or additional new detections, hopefully with brighter
background quasars) are successfully observed at a high enough spectral resolution that the
He II associated with the hydrogen forest clouds can be resolved.

There is a second complication. Cosmological simulations of the universe at intermedi-
ate and high redshifts (e.g. Katz et al. 1996) indicate that we should now expect a complex
distribution for the gas in the IGM with filamentary structures covering a large range of
physical scales and conditions. There might not exist any component that matches our ex-
pectations of a smooth or uniform “diffuse IGM”. It might be that the distinction between
numerous, closely packed, very diffuse (low column density) “clouds” and a more uniform
diffuse medium is purely a question of semantics, but the resolution of this issue has im-
lications for a variety of issues, including understanding the physical conditions that exist
during the formation of galaxies (see Jakobsen, these proceedings for further discussion).

4. End Matters

The 1990’s is the epoch of two revolutions in the the study of quasar absorption lines. Prior
to HST and the Keck telescopes, quasar absorption lines have been discussed and studied in
distinct subgroups, roughly separated by column density. At the extremes were the Ly-α
forest lines that were observed to be unclustered and possibly composed of primordial
material (based in part on the lack of any detected metal line absorption) and the damped
systems with their high column densities and large gas masses identified as the progenitors
of spiral galaxies (e.g. Wolfe 1988). Such divisions, while still useful, are getting fuzzy
as new results rapidly blur distinctions. Just one example (of many) is the detection of
weak CIV absorption associated with some fraction of low column density Ly-α absorbers,
systems that would have previously been securely identified as part of the primordial “forest clouds” (e.g. Cowie et al. 1995; Womble et al. 1996). Such wonderful observations require modification of the pre-HST-Keck picture of absorption line systems. How should we modify the old “standard picture”? I am not sure. But I do think that a second revolution is going to provide critical guidance in the development of the new more complex and detailed models. The second revolution is the progress theorists have made in leaving behind spherical cloud, slab, or mini-halo models and replacing them with the help of super computers to generate full hydrodynamic and SPH simulations of the evolution of the universe. Three groups are now able to not only generate simulations of large scale structures, but also simulated quasar absorption line spectra along numerous lines of sight through their simulations that can be compared to real observations (see Zhang, Y. et al. 1995; Hernquist et al. 1996 and Katz et al. 1996; Cen et al. 1994, Miralda-Escudé et al. 1996). The challenge ahead is to extract the best set of observables from both the simulations and the various data sets so that cosmological models might be discriminated against. Furthermore, enough simulations (and observational data!) need to be generated that the uniqueness of “good fit” models can be tested.

In his introduction to the Hubble Deep Field project, Bob Williams ably described how HST has opened up the distant universe to our view. He speculated that one of the Hubble Space Telescope’s lasting and important legacies would be providing us our first “clear” images of the early history of the universe. In the future HST will also be remembered for making possible unique studies of the more evolved and nearby universe. WFPC-2 is providing exquisite images of galactic sources and nearby objects that reveal a wealth of previously unobservable detail (see for examples the contributions to these proceedings by Bally, Livio, Machetto, and O’Dell). But HST should also be remembered for the unique information provided by its spectrographs. By making it possible to study quasar absorption lines in the ultra-violet HST has already provided important data about the gaseous content of the universe at both low and high redshifts. This legacy will continue to grow as existing data is further analyzed and when STIS makes its appearance on HST.

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**References**

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