The ACS/WFC3 Survey for Lyman Limit Systems

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THANK YOU!
THANK YOU!
THANK YOU!
THANK YOU!
THANK YOU!

Thursday 4 November 2010
Motivation for an LLS Survey
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- Follow the history of HI ionizing photons with cosmic time
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- Follow the history of HI ionizing photons with cosmic time
- Study the contributions of quasars and galaxies to the UVB
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- Study the contributions of quasars and galaxies to the UVB
- Our answers depend on the opacity of the IGM to ionizing radiation from Lyman limit systems
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- Motivation #2: Where are the metals hiding?!?!
Motivation

- Follow the history of HI ionizing photons with cosmic time
- Study the contributions of quasars and galaxies to the UVB
- Our answers depend on the opacity of the IGM to ionizing radiation from Lyman limit systems
- Motivation #2: Where are the metals hiding?!?!
- Motivation #3: We still don’t know what they are!
How to play the game
How to play the game

- Quasar surveys easily pick out Lyman limit systems with $\tau_{LL} > 2$
A DEFINITIVE SURVEY FOR LYMAN LIMIT SYSTEMS AT Z \sim 3.5 WITH THE SLOAN DIGITAL SKY SURVEY

J. Xavier Prochaska\textsuperscript{1}, John M. O'Meara\textsuperscript{2}, Gabor Worseck\textsuperscript{1}

ABSTRACT

We perform a semi-automated survey for \( n_{\lambda 12} \geq 2 \) Lyman Limit systems (LLSs) in quasar spectra from the Sloan Digital Sky Survey. Data Release 7. From a starting sample of 2473 quasars with \( \lambda_{\text{mag}} = 3.6 - 4.4 \), we analyze 469 spectra meeting strict selection criteria for a total redshift path \( \Delta z = 93.8 \) and identify 192 intervening systems at \( z_{\text{LLS}} \geq 3.3 \). The incidence of \( n_{\lambda 12} \geq 2 \) LLSs per unit redshift, \( \ell_{\gamma} \), is well described by a single-power law at these redshifts: \( \ell_{\gamma}(z) = \mathcal{C}_{\gamma} \left(1 + z\right)^{\mathcal{A}} \), with \( \mathcal{A} = 3.7, \mathcal{C}_{\gamma} = 1.9 \pm 0.2, \) and \( \ell_{\gamma}(z) = 5.2 \pm 1.5(68\% \text{ c.l.}) \). These values are systematically lower than previous estimates (especially at \( z < 4 \)) but are consistent with recent measurements of the mean free path to ionizing radiation. Extrapolaions of this power-law to \( z = 0 \) are inconsistent with previous estimations of \( \ell(z) \) at \( z < 1 \) and suggest a break at \( z \approx 2 \), similar to that observed for the Ly\( \alpha \) forest. Our results also indicate that the systems giving rise to LLS absorption decrease by \( \approx 50\% \) in comoving number density and/or physical size from \( z = 4 \) to 3.3, perhaps due to an enhanced extragalactic ultraviolet background. The observations place an integral constraint on the \( H I \) frequency distribution \( f(N_{HI}, \, X) \) and indicate that the power-law slope \( \beta \equiv d \ln f(N_{HI}, \, X)/d \ln N_{HI} \) is likely shallower than \( \beta = -1 \) at \( N_{HI} \approx 10^{18} \text{ cm}^{-2} \). Including other constraints on \( f(N_{HI}, \, X) \) from the literature, we infer that \( \beta \) is steeper than \( \beta = -1.7 \) at \( N_{HI} \approx 10^{19} \text{ cm}^{-2} \), implying at least two inflections in \( f(N_{HI}, \, X) \). We also perform a survey for proximate LLSs (PLLSSs) and find that \( \ell_{\gamma}(\text{PLLSSs}) \) is systematically lower (\( \approx 25\% \)) than intervening systems. Finally, we estimate that systematic effects impose an uncertainty of \( 10 - 20\% \) in the \( \ell(z) \) measurements; these effects may limit the precision of all future surveys.

Subject headings: absorption lines – intergalactic medium – Lyman limit systems – SDSS

1. INTRODUCTION

Studies of hydrogen absorption in the lines of sight towards distant quasars have served to both define, and in recent years bring precision to, our cosmological models. The low density, highly ionized Ly\( \alpha \) forest lines (a.k.a. the intergalactic medium, IGM), with \( H I \) column densities \( N_{HI} < 10^{17.5} \text{ cm}^{-2} \), have through their aggregate statistical properties (e.g. their flux power spectrum, mean flux, and column density distributions) constrained cosmological parameters such as the primordial power spectrum and the matter mass density to astrophysical parameters like the amplitude of the ionizing background (e.g. Rauch 1998; Croft et al. 2002; McDonald et al. 2005; Tytler et al. 2004; Faucher-Giguere et al. 2008b). The high density, predominantly neutral damped Ly\( \alpha \) systems (DLAs), with \( N_{HI} > 10^{20.5} \text{ cm}^{-2} \), trace the gas which forms stars, and likely represent the progenitors of modern-day galaxies (e.g. Wolfe et al. 1995, 2005; Prochaska \& Wolfe 2009).

The majority of Ly\( \alpha \) forest lines and the DLAs have, through analysis of their Ly\( \alpha \) lines, precisely measured \( N_{HI} \) values that permit detailed study of their physical properties (e.g. metallicity). For systems with intermediate \( N_{HI} \) values (\( \approx 10^{19} \text{ cm}^{-2} \)), however, Ly\( \alpha \) and most of the Lyman series lines lie on the flat portion of the curve-of-growth making the \( N_{HI} \) value difficult to constrain. On the other hand, these systems are optically thick to ionizing radiation and impose a readily identified signature in a quasar spectrum at the Lyman limit. These so-called Lyman limit systems (LLSs), currently the least-well studied of \( H I \) absorption systems at high redshift, are the focus of this manuscript.

Historically, the LLSs were among the first class of quasar absorption line (QAL) systems to be surveyed (Tytler 1982). This is because their spectral signature is obvious in low-resolution, low S/N spectra. The principal challenge is that the Lyman limit occurs redward of the atmospheric cutoff only for systems with redshifts \( z \approx 2.6 \). For lower redshifts, one requires spectrometers on space-borne ultraviolet satellites. By the mid 1990’s, samples of several tens of LLSs were generated spanning redshifts \( 0 < z < 4 \) (Sargent et al. 1989; Lanzetta 1991; Storrie-Lombardi et al. 1994; Steidel-Larrea et al. 1995). These results were derived from heterogeneous sets of quasars discovered from a combination of color-selection, radio detection, and all-sky spectroscopic surveys. The spectra, too, were acquired with a diverse set of instrumentation and therefore varying S/N and spectral resolution mitigating differing sensitivities to the precise optical depth at the Lyman limit. Although the results were not fully consistent with one another, the general picture that resulted was a rapidly evolving population of absorption systems reasonably described by a \((1 + z)^{0.5}\) power-law.

Cosmologically, the LLSs contribute much if not most of the universe’s opacity to ionizing radiation. And, until recently, the observed incidence of the LLSs provided the only direct means of estimating the mean free path \( \lambda_{\text{HII}} \).
How to play the game

* Quasar surveys easily pick out Lyman limit systems with $\tau_{LL} > 2$
How to play the game

* Quasar surveys easily pick out Lyman limit systems with $\tau_{LL}>2$

* Surveys for $\tau_{LL}>>2$ also work well
THE SDSS DAMPED Lyα SURVEY: DATA RELEASE 3
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ABSTRACT
We present the results from a damped Lyα survey of the Sloan Digital Sky Survey. Data Release 3. We have discovered over 500 new damped Lyα systems at z > 2.2 and the complete statistical sample for z > 1.6 has more than 600 damped Lyα galaxies. We measure the H I column density distribution f(N, X) and its zeroth and first moments (the incidence f_{DLA} and gas mass-density Ω_{HI}^{DLA} of damped Lyα systems, respectively) as a function of redshift. The key results include: (1) the full SDSS-DR3 f(N, X) distribution (z ≈ 3.06) is well fit by a Γ-function (or double power-law) with 'break' column density N^{\text{break}} = 10^{21.5\pm0.1} cm^{-2} and faint-end slope α ≈ 1.8 ± 0.1; (2) the shape of the f(N, X) distributions in a series of redshift bins does not show evolution; (3) the incidence and gas mass density of damped systems decrease by 35 ± 5% and 50 ± 10% during ∼ 1 Gyr between the redshift interval z = [3.3, 5] to z = [2.2, 2.5]; and (4) the incidence and gas mass density of damped Lyα systems in the lowest SDSS redshift bin (z = 2.2) are consistent with the current values. We investigate a number of systematic errors in damped Lyα analysis and identify only one important effect: we measure 40 ± 20% higher Ω_{HI}^{DLA} values toward a subset of brighter quasars than toward a faint subset. This effect is contrary to the bias associated with dust obscuration and suggests that gravitational lensing may be important. Comparing the results against several models of galaxy formation in ΛCDM, we find all of the models significantly underpredict f_{DLA} at z = 3 and only SPH models with significant feedback (Nagamine et al.) may reproduce Ω_{HI}^{DLA} at high redshift. Based on our results for the damped Lyα systems, we argue that the Lyman limit systems contribute ∼ 33% of the universe’s H I atoms at all redshifts z = 2 to 5. Furthermore, we infer that the f(N, X) distribution for N_{HI} < 10^{20} cm^{-2} has an inflection with slope d\log f/d\log N > 1. We advocate a new mass density definition — the mass density of predominantly neutral gas Ω_{HI}^{neutral} — to be contrasted with the mass density of gas associated with H I atoms. We contend the damped Lyα systems contribute > 80% of Ω_{HI}^{neutral} at all redshifts and therefore are the main reservoirs for star formation.

Subject headings: galaxies: evolution — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The damped Lyα systems are the class of quasar absorption line systems with H I column density N_{HI} > 2 × 10^{20} cm^{-2} (see Wolfe, Gawiser, & Prochaska 2005, for a review). Unlike the Lyα forest, the damped Lyα systems are comprised of predominantly neutral gas and are proposed to be the progenitors of galaxies like the Milky Way (e.g. Kauffmann 1999). Wolfe et al. (1996) established the N_{HI} = 2 × 10^{20} cm^{-2} threshold primarily to correspond to the surface density limit of local 21 cm observations at that time. It is somewhat fortuitous that this threshold roughly corresponds to the transition from primarily ionized gas to predominantly neutral gas (e.g. Viegas 1996; Prochaska & Wolfe 1996; Prochaska 1999; Vahidis et al. 2001). For the past two decades, several groups have surveyed high z quasars for the damped Lyα systems (Wolfe et al. 1986, 1995; Storrie-Lombardi et al. 1996a; Storrie-Lombardi & Wolfe 2000; Pieroux et al. 2003). These surveys measured the H I frequency distribution function and its moments: the incidence of the damped Lyα systems f_{DLA} and the gas mass density of these galaxies Ω_{HI}^{DLA}. The latter quantity has cosmological significance. Its evolution constrains the build-up of structure within hierarchi-
How to play the game

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- Surveys for $\tau_{\text{LL}} \gg 2$ also work well
How to play the game

- Quasar surveys easily pick out Lyman limit systems with $\tau_{LL} > 2$

- Surveys for $\tau_{LL} >> 2$ also work well

- The Lyman Alpha forest is well sampled
Difficulties
Difficulties

- Going below $z \sim 2.7$ means going to space
Difficulties

• Going below $z \sim 2.7$ means going to space

• The integrated opacity includes (and is probably dominated by) $\tau_{\text{LL}} \sim 1$
The good news
The good news

* Going below $z \sim 2.7$ means going to space!
The good news

- Going below $z \sim 2.7$ means going to space!
- The universe expands!
The ACS/WFC3 Survey
The ACS/WFC3 Survey

- Build a homogenous sample of QSOs from SDSS
The ACS/WFC3 Survey

- Build a homogenous sample of QSOs from SDSS
- Bright, z~2, no BAL
The ACS/WFC3 Survey

- Build a homogenous sample of QSOs from SDSS
- Bright, z~2, no BAL
- Cycle 15 (ACS) & Cycle 17 (WFC3) SNAP programs
The ACS/WFC3 Survey

- Build a homogenous sample of QSOs from SDSS
- Bright, z~2, no BAL
- Cycle 15 (ACS) & Cycle 17 (WFC3) SNAP programs
- 73 quasars to date
The ACS/WFC3 Survey

• Build a homogenous sample of QSOs from SDSS
• Bright, z~2, no BAL
• Cycle 15 (ACS) & Cycle 17 (WFC3) SNAP programs
• 73 quasars to date
• Redshift path at z~2 with WFC3 as big as SDSS at z~4!
SDSS0850+5636
SDSS0850+5636
No LLS

Thanks ST-ECF folks!
SDSS1011+0312
Partial LLS
SDSS1235+6301

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SDSS1235+6301

Full LLS
IGM Opacity --> The Mean Free Path
IGM Opacity-->The Mean Free Path
Old School
Old School

• Begin with counting the LLS
Old School

- Begin with counting the LLS
- Determine the N(HI) frequency distribution
Old School

- Begin with counting the LLS
- Determine the N(HI) frequency distribution
- Integrate them up!
Old School

• Begin with counting the LLS

• Determine the N(HI) frequency distribution

• Integrate them up!

$$\tau_{\text{eff,LL}}(z_{912}, z_q) = \int_{z_{912}}^{z_q} \int_0^\infty f(N_{\text{HI}}, z') \{ 1 - \exp \left[ -N_{\text{HI}} \sigma_{\text{ph}}(z') \right] \} dN_{\text{HI}} dz'$$
LLS Incidence Frequency

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LLS Incidence Frequency

Watch This space!

HST+IUE

SDSS

\( l_{\text{C}}(z) \)

\( z \)
LLS Incidence Frequency
LLS Incidence Frequency
New School
New School
New School
New School
New School
New School
New School
New School
New School
New School
New School

\[ e^{-1} \]
New School

\[ e^{-1} \quad z \rightarrow r = \lambda_{\text{mfp}} \]
\[\tau_{\text{eff,LL}}(z_{912}, z_q) = \frac{c}{H_0 \Omega_m^{1/2}} (1 + z_{912})^3 \int_{z_{912}}^{z_q} \kappa_{912}(z') (1 + z')^{-11/2} dz'\]
SDSS Stacked Spectra

\[ \frac{f_\lambda}{f_{1450}} \]

\( \lambda_{\text{rest}} [1+z_q] \) (Angstoms)

Ly\( \beta \), Ly\( \delta \), Ly\( \gamma \)

\( \lambda_{912} \)
$z=3.61$, $\lambda_{mfp}^{912}=48.3$ $h^{-1}$Mpc
SDSS Stacked Spectra

$z=3.61, \lambda_{\text{mfp}}^{912}=48.3 \, h^{-1}\text{Mpc}$

$z=3.89, \lambda_{\text{mfp}}^{912}=41.0 \, h^{-1}\text{Mpc}$
SDSS Stacked Spectra

$z=3.61, \lambda_{mfp}^{912} = 48.3 \, \text{h}^{-1}\text{Mpc}$

$z=3.89, \lambda_{mfp}^{912} = 41.0 \, \text{h}^{-1}\text{Mpc}$

$z=4.23, \lambda_{mfp}^{912} = 24.8 \, \text{h}^{-1}\text{Mpc}$
SDSS MFP

\[ \lambda_{\text{mfp}} = 48.4 - 38 \times (z_q - 3.6) \]
WFC3 Stack

* Can we play the same game at lower z?
OMG w00t!

54 Quasar Stack
$<z_q> \sim 2.3$
OMG w00t!

54 Quasar Stack

$<z_q> \sim 2.3$

$\lambda_{MFP} = 170 \text{ Mpc}$
Mean Free Path

\[ \lambda_{\text{mfp}} = 48.4 - 38 \times (z_q - 3.6) \]
Mean Free Path
Mean Free Path

\[ \lambda_{\text{mfp}} = 37.0 \left[ \frac{1 + z_q}{1 + 3.9} \right]^{-\gamma} \]

\[ \gamma = 3.85 \]
Much left to do!
Much left to do!

- Refine the $l(z)$ analysis, incorporating ACS data...
Much left to do!

* Refine the $l(z)$ analysis, incorporating ACS data

* $f(N,z)$ for the partial LLS
Much left to do!

- Refine the $l(z)$ analysis, incorporating ACS data
- $f(N,z)$ for the partial LLS
- Do the stack right!
Questions
Questions

• How does the MFP evolve in z?
Questions

- How does the MFP evolve in $z$?
- How do $l(z)$ and $f(N,z)$ evolve in $z$?
LLS Incidence Frequency

\begin{figure}
\centering
\includegraphics[width=\textwidth]{LLS_Incidence_Frequency_graph.png}
\caption{Graph showing the LLS Incidence Frequency with data points for WFC3 and SDSS.}
\end{figure}

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LLS Incidence Frequency

\[ f_{\text{SFL}}(z) \]

GMOS

SDSS

WFC3

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LLS Incidence Frequency

\[ f(z) \]

- GMOS
- LRIS + MagE
- SDSS
- WFC3

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LLS Incidence Frequency

![Graph showing LLS incidence frequency with data points for GMOS, SDSS, WFC3, LRIS + MagE, and Cycle 18 SNAP.]
Mean Free Path

LRIS + MagE
Mean Free Path

LRIS + MagE

GMOS
Thanks!
$\lambda_{\text{mfp}}$ Implications: Reionization

$\lambda_{\text{mfp}}^{9/2} (h^{-1}_{72} \text{ Mpc})$

$1+<z_q>$

100

10

1

4

10
\[ \lambda_{mfp} \text{ Implications: Reionization} \]

- **Ansatz**
  - Demand \( \lambda_{mfp} \sim (1+z)^\gamma \)
    - Physically motivated
- **Extrapolate to \( z > 4 \)**
  - \( z_{\text{reion}} > 7.5 \)
  - \( z_{\text{reion}} < 20 \)
• **Ansatz**
  ‣ Demand $\lambda_{\text{mfp}} \sim (1+z)^\gamma$
    ✦ Physically motivated
• **Extrapolate to $z>4$**
  ‣ $z_{\text{reion}} > 7.5$
  ‣ $z_{\text{reion}} < 20$
• **Comparisons**
  ‣ Guesstimates from Ly$\alpha$
  ‣ Theory ‘predictions’

\[ \lambda_{912} \ (h^{-1}_{72} \ \text{Mpc}) \]