Group 4: Outskirts of distant galaxies and systems

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

Formation and Evolution of Galaxy Outskirts
Proceedings IAU Symposium No. 321, 2016
A. Gil de Paz, J.H. Knapen & J.C. Lee, eds.
© International Astronomical Union 2017
doi:10.1017/S1743921316011595

The Neutral Hydrogen Cosmological Mass Density at z = 5

Neil H. M. Crighton[1], Michael T. Murphy[1], J. Xavier Prochaska[2], Gábor Worseck[3], Marc Rafelski[4], George D. Becker[5], Sara L. Ellison[6], Michele Fumagalli[7,8], Sebastian Lopez[9], Avery Meiksin[10] and John M. O'Meara[11]

[1]Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia. neilcrighton@gmail.com
[2]Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[3]Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[4]Infrared Processing and Analysis Center, Caltech, Pasadena, CA 91125, USA
[5]Space Telescope Science Institute, 3700 San Martin Dr, Baltimore, MD 21218, USA
[6]Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada
[7]Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
[8]Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[9]Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
[10]Scottish Universities Physics Alliance, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[11]Department of Chemistry and Physics, Saint Michael's College, One Winooski Park, Colchester, VT 05439, USA

Abstract. We present the largest homogeneous survey of redshift > 4.4 damped Lyα systems (DLAs) using the spectra of 163 quasars that comprise the Giant Gemini GMOS (GGG) survey. With this survey we make the most precise high-redshift measurement of the cosmological mass density of neutral hydrogen, $\Omega_{\rm HI}$. After correcting for systematic effects using a combination of mock and higher-resolution spectra, we find $\Omega_{\rm HI} = 0.98^{+0.20}_{-0.18} \times 10^{-3}$ at $\langle z \rangle = 4.9$, assuming a 20% contribution from lower column density systems below the DLA threshold. By comparing to literature measurements at lower redshifts, we show that $\Omega_{\rm HI}$ can be described by the functional form $\Omega_{\rm HI}(z) \propto (1+z)^{0.4}$. This gradual decrease from $z = 5$ to 0 suggests that in the galaxies which dominate the cosmic star formation rate, H I is a transitory gas phase fuelling star formation which must be continually replenished by more highly-ionized gas from the intergalactic medium, and from recycled galactic winds.

Keywords.

1. Introduction

The neutral hydrogen mass density of the universe, $\Omega_{\rm HI}$, is an important cosmological observable. It determines the precision with which cosmological parameters can be constrained by observations of the H I intensity power spectrum (e.g. Barkana & Loeb 2007; Chang *et al.* 2008; Wyithe & Loeb 2008; Padmanabhan *et al.* 2015), and we expect its evolution to be linked to the cosmic star formation history. The main contributor to $\Omega_{\rm HI}$ is high column density, predominantly neutral gas clouds (e.g. O'Meara *et al.* 2007; Zafar *et al.* 2013), self-shielded from ionizing radiation and therefore likely fuel for future star formation (e.g. Wolfe *et al.* 2005). Thus tracing the evolution of $\Omega_{\rm HI}$ from the end of reionization, through the epoch of the cosmic star formation peak at $z \sim 2$ to the present day is of central importance to our understanding of galaxy formation. It also provides

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

an excellent integral constraint which can be used to test theoretical models of galaxy formation.

At redshift < 0.3, H I 21 cm emission can be used to measure $\Omega_{\rm HI}$ either directly or by stacking analyses (e.g. Zwaan *et al.* 2005; Martin *et al.* 2010). At higher redshifts, where emission is too weak to be detected with current facilities, $\Omega_{\rm HI}$ can instead be inferred from the incidence rate of damped Lyα systems (DLAs, defined as absorption systems with $N_{\rm HI} \geqslant 20.3$ cm^{-2}), which trace the bulk of neutral gas in the universe (Prochaska *et al.* 2005). These systems are detected in absorption in the spectra of background quasars, and their characteristic damping wings allow column densities to be measured even at low spectral resolution.

Recent DLA surveys at $2 < z < 4$ using more than 10,000 quasars assembled from the Sloan Digital Sky Survey (SDSS) (Prochaska & Herbert-Fort 2004; Prochaska *et al.* 2005; Prochaska & Wolfe 2009; Noterdaeme *et al.* 2009, 2012) have shown that there is very little evolution in the H I mass density from $z = 3$ to the present day. This is starkly at odds with the strong evolution in the star formation rate over the same period (e.g. Madau & Dickinson 2014). Modern simulations and some observational studies interpret H I as a transitory phase fuelling star formation (e.g. Prochaska *et al.* 2005; Davé *et al.* 2013), which is continually replenished by more highly ionized gas from either the intergalactic medium (IGM) or recycled galactic outflows.

Here we present a measurement of $\Omega_{\rm HI}$ as traced by DLAs at $3.5 < z < 5.4$ using a homogeneous sample of 163 quasars with emission redshifts between 4.4 and 5.4. This represents an increase in redshift path of a factor of eight over the previous largest study at $z > 4.5$. Identifying DLAs becomes increasingly difficult at higher redshift, as H I absorption from the highly-ionized intergalactic medium (IGM) becomes more severe, and blending with strong systems below the DLA threshold can cause misidentification of DLAs. Therefore we carefully check for systematic misidentifications in our sample using both mock spectra and higher resolution spectra of DLA candidates. More than 70% of our DLA candidates (and $> 85\%$ at $z > 4.5$) have been observed at higher resolution (Rafelski *et al.* 2012, 2014), allowing us to confirm their $N_{\rm HI}$ despite the increased IGM blending at high redshift.

This conference proceedings is largely a summary of the result presented by Crighton *et al.* (2015). We have updated some of the discussion and figures to reflect recent results, but we refer the reader to that work if they would like a more detailed decription of our analysis.

2. Results

Our main data sample consists of GMOS spectra for the 163 quasars which comprise the Giant Gemini GMOS (GGG) survey (Worseck *et al.* 2014). The quasars were taken from the SDSS and all have emission redshifts $4.4 < z < 5.4$. At these emission redshifts, the quasar sightlines are likely unbiased regarding the number density of DLAs, unlike sightlines with $2.7 < z_{\rm em} < 3.6$ (Prochaska *et al.* 2009; Worseck & Prochaska 2011; Fumagalli *et al.* 2013). We also use a smaller sample of 59 quasars with higher resolution spectra. In contrast to the GGG sample, most of these quasars were targeted because of a known DLA candidate towards the quasar. One of these higher resolution spectra was taken with the Magellan Echellette Spectrograph on the Magellan Clay Telescope (Jorgenson *et al.* 2013) and the remainder were taken with Echellette Spectrograph and Imager on the Keck II Telescope (Rafelski *et al.* 2012, 2014). A total of 39 of these quasars are also in the GGG sample, and the remaining 20 have a similar emission redshift to the GGG quasars. We use these higher resolution spectra to assess the reliability of our

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

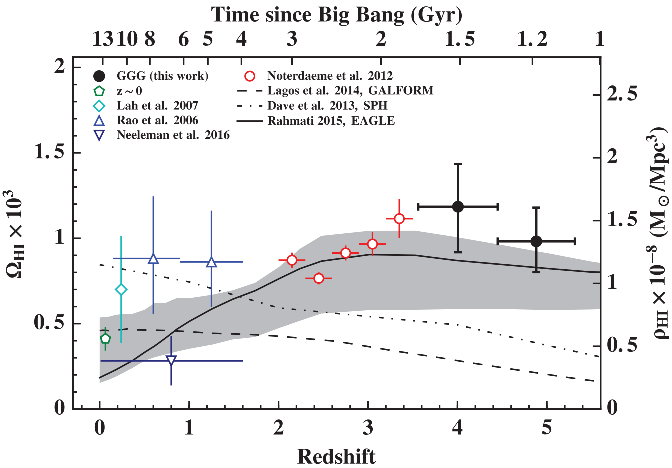

Figure 1. Measurements of $\Omega_{\rm HI}$ compared to recent theoretical predictions. For clarity, the mean of measurements at $z < 0.2$ (the errorbar shows the standard deviation) is shown. Lines show predictions from a recent semi-analytic model (Lagos *et al.* 2014), and numerical simulations (Davé *et al.* 2013 and EAGLE, Rahmati *et al.* 2015). All the models have been converted to our adopted cosmology. The recent EAGLE cosmological simulation matches the observations well, although uncertainties due to sub-grid physics and resolution effects (shown by the error range) are still substantial.

DLA identifications and to estimate the importance of systematic effects, but they are not included in the statistical sample used to measure $\Omega_{\rm HI}$. For a detailed description of the GGG spectra and the procedure used to reduce them, see Worseck *et al.* (2014).

There are two main contributions to the final error on $\Omega_{\rm HI}$. The dominant contribution is the statistical error due to the finite sampling of DLAs, and we estimate this error using 1000 bootstrap samples. The second is the systematic uncertainty in the correction factor, $k(N_{\rm HI})$, described in more detail by Crighton *et al.* (2015). We estimate the effect of this uncertainty using a Monte Carlo technique: $\Omega_{\rm HI}$ is calculated 1000 times, each time drawing $k(N_{\rm HI})$ from a normal distribution with a mean given by the $k(N_{\rm HI})$ histogram bin value and σ determined by the uncertainty on that bin, assuming no correlation between uncertainties in adjacent bins. Then the final error in $\Omega_{\rm HI}$ is given by adding these two uncertainties in quadrature. We confirmed that $N_{\rm HI}$ error of each DLA (0.2 dex), has a negligible contribution compared to these statistical and systematic uncertainties. We also check that using $N_{\rm HI}$ measurements from the high-resolution spectra, where available, does not significantly change $\Omega_{\rm HI}$.

Figure 1 shows our new results together with previous measurements of $\Omega_{\rm HI}$, converted to our adopted cosmology. We assume a 20% contribution to $\Omega_{\rm HI}$ from absorption systems below the DLA threshold, and where previous DLA surveys have quoted $\Omega_{\rm HI}^{\rm DLA}$, we convert to $\Omega_{\rm HI}$ using the relationship $\Omega_{\rm HI} = 1.2\Omega_{\rm HI}^{\rm DLA}/1.3$. Our measurement at $\langle z \rangle = 4$ is higher than, but consistent with earlier measurements by Songaila & Cowie (2010).

3. Discussion

Several groups have made measurements of $\Omega_{\rm HI}$ at $z > 4.5$ using DLA surveys (Péroux *et al.* 2003, Guimarães *et al.* 2009, Songaila & Cowie 2010). These are cumulative results – that is, each new measurement contains quasars from previous samples, and the $\Omega_{\rm HI}$ value is correlated with previous results. This is appealing as it maximizes the signal-to-noise of the $\Omega_{\rm HI}$ value, but combining heterogeneous quasar surveys in this way makes statistical

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

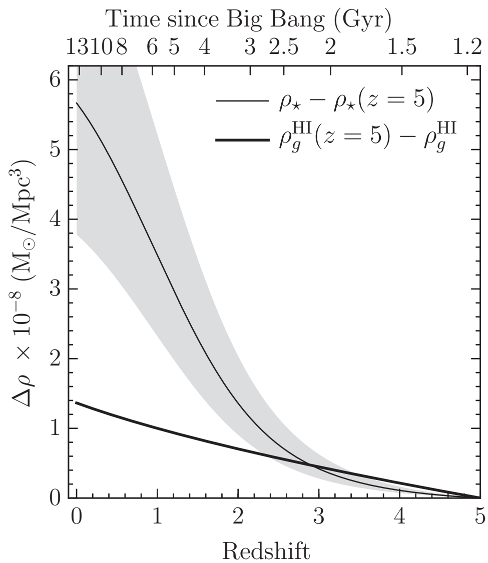

Figure 2. The increase in comoving stellar mass density from $z = 5$ to 0 (from Madau & Dickinson 2014, thin line and shading) and the corresponding decrease in H I gas mass density over the same period (thick line) using the fitting formula described in the text. The H I gas phase contributes less than $\sim 20\%$ of the mass necessary to form stars from $z = 3$ to 0, and so must be continually replenished by more highly ionized gas. Note that the shaded error range on the stellar mass density represents systematic uncertainties in different estimators, and is not a 1σ error.

errors challenging to quantify. At $z > 4.4$ different identification methods can produce a systematic uncertainty in $\Omega_{\rm HI}$ which, although smaller than the statistical uncertainties for our current DLA sample, may still be considerable. Since previous analyses did not use mock spectra to explore systematic effects, it is difficult to estimate the true uncertainty in $\Omega_{\rm HI}$ when combining heterogeneous quasar samples with different selection criteria. In contrast, our sample has homogeneous data quality, quasar selection method and DLA identification procedure, and we use mock spectra to test any systematic effects.

Since the publication of Crighton *et al.* (2015), there have been several new measurements of $\Omega_{\rm HI}$ at lower redshifts. Sánchez-Ramírez *et al.* (2016) used a new sample of high-resolution spectra to identify DLAs over the redshift range $3-4.5$, and they present a new technique for combining the results from previous work and estimating the uncertainty in the final result. Their results include, and are consistent with, the data presented here (albeit with increased uncertainties in the redshift range 2-4). Neeleman *et al.* (2016) present a new measurement using DLAs at low redshift, shown on Figure 1. They find a somewhat lower $\Omega_{\rm HI}$ than the previous best estimate in this redshift range (Rao *et al.* 2006) and show that the metal-selection method used by Rao to identify DLAs may have biased that study towards a high $\Omega_{\rm HI}$ value. The new Neelemann result is consistent with the local 21cm measurements for $\Omega_{\rm HI}$. As these new measurements are consistent with the previous sample used by Crighton *et al.* (2015), including them does not affect our conclusions.

Our results at $\langle z \rangle = 4.9$ show that there is no strong evolution in $\Omega_{\rm HI}$ over the ~ 1 Gyr period from $z = 5$ to $z = 3$. We see a slight drop in $\Omega_{\rm HI}$ between our $z \sim 4$ and $z \sim 4.9$ $\Omega_{\rm HI}$ measurements, but this difference is not statistically significant. If the metal content of DLAs does change suddenly at $z = 4.7$, as suggested by Rafelski *et al.* (2014), there is

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

no evidence it is accompanied by a concomitant change in $\Omega_{\rm HI}$. However, the uncertainties remain large and future observations should continue to test this possibility.

A power law with the form $\Omega_{\rm HI} = A(1+z)^{\gamma}$ can describe all of the existing measurements. This simple function provides a reasonable fit (χ^2 per degree of freedom = 1.44) across the full redshift range, with best-fitting parameters $A = (4.00 \pm 0.24) \times 10^{-4}$ and $\gamma = 0.60 \pm 0.05$. There is no obvious physical motivation for this relation, nor any expectation that it should apply at redshifts > 5. Nevertheless, it may provide a useful fiducial model to compare to simulations and future observations.

We also compare our new high-redshift value to lower redshift $\Omega_{\rm HI}$ measurements. As previous authors have noted (e.g. Prochaska *et al.* 2005; Prochaska & Wolfe 2009; Noterdaeme *et al.* 2009), $\Omega_{\rm HI}$ evolves from $z = 3$ to $z = 0$ by factor of $\lesssim 2$, at odds with the very strong evolution in the star formation rate over the same period. Moreover, the drop in $\Omega_{\rm HI}$ is much smaller than the increase in stellar mass over this period. Figure 2 demonstrates this point by showing the increase in comoving mass density in stars from $z = 5$, $\rho_\star - \rho_\star(z = 5)$ and the contemporaneous decrease in H I comoving gas mass density, $\rho_g^{\rm HI}(z = 5) - \rho_g^{\rm HI}$ using the power law fit discussed earlier. The mass in stars is calculated using the expression from Madau & Dickinson (2014), and the range shows an uncertainty of 50%, indicative of the scatter in observations around this curve. While the evolution of $\Omega_{\rm HI}$ from $z = 5$ to $z = 3$ remains uncertain, the H I phase at $z = 5$ contains ample mass density to form all the stars observed at $z \sim 3$, and the evolution predicted by the simple power law function is consistent with this scenario. From $z \sim 3$ to $z \sim 0$, however, there is a factor of 5–6 shortfall in H I mass density compared to amount needed to produce stars over the same period. This underscores that at $z \lesssim 3$, the H I phase must be continually replenished by more highly ionized gas, presumably through a combination of cold-mode accretion (e.g. Dekel *et al.* 2009) and recycled winds (e.g. Oppenheimer *et al.* 2010). The more highly ionized Lyman limit systems and sub-DLAs should then be important tracers of the interface between this H I phase and more highly ionized gas (e.g. Fumagalli *et al.* 2011).

References

Amari, S., Hoppe, P., Zinner, E., & Lewis R. S. 1995, *Meteoritics*, 30, 490

Barkana, R. & Loeb, A. 2007, *Reports on Progress in Physics*, 70, 627

Bouwens, R. J. *et al.* 2012, *ApJ*, 752, L5

Chang, T. C., Pen, U. L., Peterson, J. B., & McDonald, P. 2008, *Physical Review Letters*, 100, 091303

Crighton, N. H. M., Murphy, M. T., Prochaska, J. X., Worseck, G., *et al.* 2015, *MNRAS*, 452, 217

Davé, R., Katz, N., Oppenheimer, B. D., Kollmeier, J. A., & Weinberg, D. H. 2013, *MNRAS*, 434, 2645

Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T., Mumcuoglu, M., Neistein, E., Pichon, C., Teyssier, R., & Zinger, E 2009, *Nature*, 457, 451

Fumagalli, M., Prochaska, J. X., Kasen, D., Dekel, A., Ceverino, D., & Primack, J. R. 2011, *MNRAS*, 418, 1796

Fumagalli, M., O'Meara, J. M., Prochaska, J. X., & Worseck, G. 2013, *ApJ*, 775, 78

Guimarães, R., Petitjean, P., de Carvalho, R. R., Djorgovski, S. G., Noterdaeme, P., Castro, S., Poppe, P. C. D. R., & Aghaee, A. 2009, *A&A*, 508, 133

Jorgenson, R. A., Murphy, M. T., & Thompson, R. 2013, *MNRAS*, 435, 482

Lagos, C. D. P., Baugh, C. M., Zwaan, M. A., Lacey, C. G., Gonzalez-Perez, V., Power, C., Swinbank, A. M., & van Kampen, E. 2014, *MNRAS*, 440, 920

Madau, P. & Dickinson, M. 2014, *ARA&A*, 52, 415

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press

Martin, A. M., Papastergis, E., Giovanelli, R., Haynes, M. P., Springob, C. M., & Stierwalt, S. 2010, *ApJ*, 723, 1359

Neeleman, M., Prochaska, J. X., Ribaudo, J., Lehner, N., Howk, J. C., Rafelski, M., & Kanekar, N. 2016, *ApJ*, 818, 113

Noterdaeme, P., Petitjean, P., Ledoux, C., & Srianand, R. 2009, *A&A*, 505, 1087

Noterdaeme, P. *et al.* 2012, *A&A*, 547, L1

O'Meara, J. M., Prochaska, J. X., Burles, S., Prochter, G., Bernstein, R. A., & Burgess, K. M. 2007, *ApJ*, 656, 666

Oppenheimer, B. D., Davé R., Kereš D., Fardal, M., Katz, N., Kollmeier, J. A., & Weinberg, D. H. 2010, *MNRAS*, 406, 2325

Padmanabhan, H., Choudhury, T. R., & Refregier, A. 2015, *MNRAS*, 447, 3745

Péroux, C., McMahon, R. G., Storrie-Lombardi, L. J., & Irwin, M. J. 2003, *MNRAS*, 346, 1103

Pontzen, A. & Pettini, M. 2009, *MNRAS*, 393, 557

Prochaska, J. X. & Herbert-Fort, S. 2004, *PASP*, 116, 622

Prochaska, J. X. & Wolfe, A. M. 2009, *ApJ*, 696, 1543

Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, *ApJ*, 635, 123

Prochaska, J. X., Worseck, G., & O'Meara, J. M. 2009, *ApJ*, 705, L113

Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neeleman, M., & Mendez, A. J. 2012, *ApJ*, 755, 89

Rafelski, M., Neeleman, M., Fumagalli, M., Wolfe, A. M., & Prochaska, J. X. 2014, *ApJ*, 782, L29

Rahmati, A., Schaye, J., Bower, R. G., Crain, R. A., Furlong, M., Schaller, M., & Theuns, T. 2015, *MNRAS*, 452, 2034

Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, *ApJ*, 636, 610

Sánchez-Ramírez, R., Ellison, S. L., Prochaska, J. X., Berg, T. A. M., Lòpez, S., D'Odorico, V., Becker, G. D., Christensen, L., Cupani, G., Denney, K. D., Pâris, I., Worseck, G., & Gorosabel, J. 2016, *MNRAS*, 456, 4488

Songaila, A. & Cowie, L. L. 2010, *ApJ*, 721, 1448

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, *ARA&A*, 43, 861

Worseck, G. & Prochaska, J. X. 2011, *ApJ*, 728, 23

Worseck, G. *et al.* 2014, *MNRAS*, 445, 1745

Wyithe, J. S. B. & Loeb, A. 2008, *MNRAS*, 383, 606

Zafar, T., Péroux, C., Popping, A., Milliard, B., Deharveng, J. M., & Frank, S. 2013, *A&A*, 556, A141

Zwaan, M. A., Meyer, M. J., Staveley-Smith, L., & Webster, R. L. 2005, *MNRAS*, 359, L30

https://doi.org/10.1017/S1743921316011595 Published online by Cambridge University Press