Measuring $\Omega_b$ from the Helium Lyman-$\alpha$ Forest

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Abstract. A new method to extract $\Omega_b$ from high redshift intergalactic absorption is described, based on the distribution of HeII Ly$\alpha$ optical depths in the voids in the ionization zone of quasars. A preliminary estimate from recent HST-STIS spectra of PKS 1935-692 at $z = 3$ gives $\Omega_b h^2 = 0.0125^{+0.0016}_{-0.0014}$ (1-$\sigma$ statistical errors, for a $\Lambda$CDM cosmology) consistent with other estimates.

1. Introduction

In the last few years it has become possible to observe details of absorption by singly ionized helium. The observations combine new information about the history of quasars, intergalactic gas, and structure formation.

Early observations of the HeII Ly$\alpha$ absorption spectral region included the quasars Q0302-003 ($z=3.285$, Jackobsen et al. 1994, HS 1700+64 ($z=2.72$, Davidsen et al. 1996) and PKS 1935-692 ($z=3.18$ Tytler & Jackobsen 1996). Higher resolution (GHRS) observations of Q0302-003 Hogan, Anderson & Rugers 1997 and HE 2347-4342 ($z=2.885$, Reimers et al. 1997) revealed structure in the absorption which could be reliably correlated with HI absorption. Heap et al. have followed up with STIS on Q0302-003 (1999a) and HE 2347-4342 (1999b). The second observation should be particularly illuminating since HE 2347-4342 is relatively bright allowing a high resolution grating to be used. The Anderson et al. (1998) observations of PKS 1935-692 with STIS yield good zero level estimates important for estimating the optical depth $\tau$. Preliminary reductions of longer STIS integrations of PKS 1935-692 with the 0.1 $\AA$ slit by Anderson et al. (1999) confirm the 1998 results. Taken together, these data now appear to be showing the cosmic ionization of helium by quasars around redshift 3. Although it is possible that the medium is already ionized to HeIII by other sources at a lower level (Miralda-Escudé et al. 1999).

All of the objects show absorption with mean $\tau \geq 1$ at redshifts lower than the quasar. For the higher redshift QSO’s Q0302-033 and PKS 1935-692 (shown in Fig. 1) there is a clear shelf of $\tau \geq 1.3$ in a wavelength region of order 20 $\AA$ in observed wavelength blueward of the quasar emission line redshift, dropping to a level consistent with zero flux or $\tau \geq 3$ beyond that. The sharp edge led Anderson et al. to conclude that gas initially containing helium as mostly HeII was being double-ionized in a region around the quasars. The lack of a strong emission line for HeII Ly$\alpha$ suggests that ionizing flux is escaping so that the 228 $\AA$ flux may be similar to a simple power-law extension of the observed 304 $\AA$
rest frame flux. Hogan et al. (1997) used the same reasoning to estimate the
time required for quasars to create the double ionized helium region to be 20
Myr for a 20 Å shelf (dependent on the Hubble parameter, spectral hardness,
cosmology, baryon density and the shelf size).

The features present in HeII Lyα spectra are reflected in the HI Lyα forest
for these quasars. Attempts to model the HeII absorption with line systems
detected in HI suggest that very low column HI absorbers, difficult to differen-
tiate from noise in HI spectra, provide a substantial contribution to the HeII
absorption. Typically, in the shelf region, the ratio of HeII to HI ions is of order
20 or more, rising to at least 100 farther away (The cross-section for HeII Lyα
absorption is 1/4 that of HI). Both PKS 1935-692 and HE 2347-4342 display
conspicuous voids in the HeII absorption near the apparent edge of the HeIII
bubble with corresponding voids in the HI spectra.

Reionization and the origin of the HeII Lyα forest can addressed with de-
tailed theoretical treatments (eg. Zheng & Davidsen 1995, Zhang et al. 1998,
Fardal et al. 1998, Abel & Haehnelt 1999, Gnedin 1999). Wadsley, Hogan &
Anderson (1999) presented numerical models of the onset of full helium reionization
around a single quasar. The models integrated one-dimensional radiative trans-
fer along lines of sight taken from cosmological hydrodynamical simulations and
used flux levels comparable to PKS 1935-692. The results reinforced the basic
interpretation of PKS 1935-692 by Hogan et al. (1997) as the growth of an He III
bubble over time in a medium that was mostly HeII. In addition void recoveries
in the large ionized bubbles similar to that observed for PKS 1935-692 occurred
often among a random set of simulated lines of sight. The gas temperature in
such bubbles is strongly affected by the ionization of He II to He III, particularly
because the first photons to reach much of the gas will be quite hard since the
softer photons are absorbed close to the quasar until the gas is optically thin. In
particular the underdense medium reaches temperatures of order 15000K. We
make a simple analytical argument for this result in the next section.

Given our fairly good guess as to the physical conditions near PKS 1935-
692 we are in position to attempt to convert the observed optical depths into
a density in baryons. Comparing optical depths measured for the small sample
of voids in the shelf region of PKS 1935-692 to distributions of void widths
and densities from simulations we can build an estimate of Ωb, the total cosmic
density in baryons. The are still uncontrollable systematic uncertainties in this
estimate but these differ from other techniques and can be addressed with better
simulations and a larger sample of quasars. The main focus of this paper is the

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2. Estimating $\Omega_b$ Using Helium Quasar Observations

In He II Lyα absorption spectra only the voids are sufficiently low density to
allow measurements of the optical depth. The highly ionized void gas is opti-
cally thin to the ionizing radiation and cool enough to ignore collisional effects,
resulting in a fairly simple relation between optical depth and gas density,
\[
\tau_{\text{HeII}} = 1.0 \times 10^{10} n_{\text{HeII}} / (\frac{dv}{dl} / 100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \\
= 106 \frac{\alpha(T)}{\Gamma} (\frac{\rho}{\bar{\rho}})^2 \Omega_b h^2 \left( \frac{1 + z}{4} \right)^6 \left( \frac{dv}{dl} / 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \right)^{-1},
\]

(1)

where \( \tau_{\text{HeII}} \) is the optical depth for absorption of He II Ly\(\alpha \), \( n_{\text{HeII}} \) is the number density of He II ions, \( \frac{dv}{dl} \) converts from real space to wavelength (velocity) space and \( \rho \) is the gas density. The recombination rate \( \alpha(T) \) contains the only temperature dependence. The photo-ionizations per second \( \Gamma \) is determined from the rest frame HeII ionizing flux, \( F_{228\AA} \) can be extrapolated from the rest frame flux at 304\(\AA \) which is estimated (assuming a cosmological model) from the observed continuum flux at 304\(\AA \)\((1 + z_q)\), where \( z_q \) is the redshift of the quasar.

The fraction of HeII depends on temperature roughly as \( T^{-1/2} \) through the recombination coefficient. The radiative transfer models of Wadsley et al. (1999) gave temperatures around 15000K for the underdense gas near quasars. The optical depth to a He II ionizing photon travelling \( \delta z = 0.1 \) (The size of the PKS 1935-692 shelf region) at redshift \( z = 3 \) (SCDM, \( \Omega_b = 0.05, H_0 = 50\text{km s}^{-1} \text{ Mpc}^{-1} \)) is approximately \( \tau = 62(E_\gamma/54.4\text{ eV})^{-3} \). The optical depth falls to 1 for photons with energies, \( E_\gamma \sim 215\text{eV} \). Thus the HeII in the outer half of the shelf region will be ionized preferentially by photons in the energy range 100-200 eV. Injecting 100-54.4 eV per helium atom is equivalent to a temperature increase of 13000 K when the energy is distributed among all the particles. The cooling time for the underdense gas is very long, dominated by adiabatic expansion. Gas elsewhere will gain \( \sim 4000 \text{ K} \) due to HeIII reionization.

As voids evolve they approach an attractor solution resembling empty universes and their relative growth slows when they reach around 0.1 times the mean density, making that value fairly representative. We used \( N \)-body simulations of 3 cosmologies (Standard CDM, Open CDM and \( \Lambda \)CDM) to get probability distributions for the quantity we label normalized opacity \( O = (\rho/\bar{\rho})^2 / (\frac{dv}{dl} / H_{\text{HUBBLE}}) \) as a function of void width. \( O \) may be directly related to the void optical depths via (1). The set of voids allows a statistical maximum likelihood comparison of the simulated distribution of \( O \) to the distribution of void widths and optical depths observed. Figure 1 shows the probability distribution of \( O \) in voids (equivalent to void optical depth) and void widths for the \( \Lambda \)CDM cosmology. The optical depth from the simulation was normalized so that mean density gas expanding with the Hubble flow gives an optical depth of 1.0.

The effect of gas pressure on the dynamics of gas in the voids should be negligible and was ignored in our simulations. Thus the gas follows the dark matter exactly. The simulations were performed using Hydra (Couchman 1991) with 64 Mpc periodic simulation volumes \((\sim 6000 \text{ km s}^{-1} \text{ at } z = 3)\) containing \( 128^3 \) particles. A preliminary convergence study indicated that the statistics of \( O \) are relatively insensitive to resolution however our resolution is still lower than that of the best current Lyman-\(\alpha \) forest studies which also include gas. We were constrained by the need to include larger scales so that the large void portion of
Figure 1. Probability contours for void optical depths and velocity widths along random lines of sight in a ΛCDM simulation with the 5 void optical depths and widths from PKS 1935-692 overplotted as green crosses. The opticals depths (in helium II Lyman-α absorption) are normalized so that mean density gas expanding with the Hubble flow at $z = 3$ has an optical depth of one. The probabilities are cumulative in velocity and are approximately indicative of the number of voids to be expected per unit redshift interval. The simulations (described in the text) predict $\sim 3$ voids with sizes $\gtrsim 300$ km s$^{-1}$ in the interval $z = 3.09$ to $z = 3.15$ where 5 were detected.

Our sample was reasonable. Higher resolution gives slightly larger estimates for $\Omega_b$.

The ratio of $\tau_{\text{HeII}}$ to $O$ that has the maximum likelihood gives an estimate for the total baryon density as follows,

$$\Omega_b h^2 = 0.0178 \left( \frac{\tau_{\text{HeII}}}{O} / 3.5 \right) \left( \frac{F_{\nu, 228 \mu \text{m}}}{6 \times 10^{-23} \text{erg s}^{-1} \text{Hz}^{-1} \text{cm}^{-2}} \right)^{\frac{1}{2}} \left( \frac{H(z)}{400 \text{km s}^{-1} \text{Mpc}^{-1}} \right)^{\frac{1}{2}} \left( \frac{3 + \alpha}{4.8} \right)^{-\frac{1}{2}} \left( \frac{Y}{0.25} \right)^{\frac{1}{2}} \left( \frac{1 + z}{4.0} \right)^{-3} \left( \frac{T}{15000 \text{K}} \right)^{\frac{1}{4}}.$$  \hspace{1cm} (2)

In this equation all the quantities are given as ratios with typical values estimated from PKS 1935-692, with $\rho/\bar{\rho}$ being the local density divided by the cosmological mean density, $dv/\tilde{dV}_{\text{HUBBLE}}$ the local expansion rate along the line-of-sight compared to the mean, $H(z) = H_0 \left( \Omega_M (1 + z)^3 + \Omega_{\text{CURV}} (1 + z)^2 + \Omega_A \right)^{1/2}$ local...
3. Results for PKS 1935-692

The exact systemic redshift of PKS 1935-692 is uncertain due to an absence of narrow IR emission lines. We use $z = 3.19$.

We used the 5 large voids observed over the range $z = 3.09 - 3.15$ for PKS 1935-692. This range should be far enough from the quasar to avoid “associated” absorbers caught in the quasar outflow. The fits are shown in figure 2. He II and H I absorption are both plotted with the models for each overplotted as dashed lines. The He II spectrum was modeled with the known HI Lyα absorption lines and 5 parameter values for the optical depth in each void. The ratio of the HI to HeII optical depths was a sixth free parameter. The models were convolved with the same spectral point spread function as the observations and include same level of photon shot noise. The best model was determined using maximum likelihood and the fitting errors determined with Monte Carlo
realizations. The emptiest void has a reasonable probability according to the simulations, however since it has been suggested that it could be due to a local ionizing source we calculated the effect of removing it, which was a $\sim 40\%$ increase in the estimate for $\Omega_b$.

The ionizing flux was inferred from the observed PKS 1935-692 continuum level at 304 $\text{Å}$ rest frame and extrapolated to $z > 3$ and 228 $\text{Å}$. Assuming the quasar redshift is $z = 3.19$ this gives a flux of $6 \times 10^{-23} \text{erg s}^{-1} \text{Hz}^{-1} \text{cm}^{-2}$ (for standard CDM) at $z = 3.125$ which is in the middle of the voids. The sample of helium quasars is quite small and though PKS 1935-692 does not have any known variability all quasars are thought to be intrinsically variable due to the nature of the fueling and emission processes. Selection effects favour the idea that PKS 1935-692 is currently brighter than its average value over the last few thousand years (the ionization response timescale). If PKS 1935-692 has recently brightened then (2) implies that our $\Omega_b$ estimate is biased upward. If there is additional foreground continuum absorption then our estimates are biased low.

The results are tabulated below with 1-$\sigma$ fitting errors indicated (Monte Carlo). Aside from the uncertainties mentioned above, there is still uncertainty in the temperature through the $T^{1/4}$ dependence. If the gas was pre-ionized to HeIII the underdense gas could be colder by a factor of order 2 which would lower the $\Omega_b h^2$ estimates by 20%. A larger sample of quasars would make the greatest improvement in the robustness of this measurement.

| $\Omega_M$ | $\Omega_{\Lambda}$ | $H_0$ | $\sigma_8$ | $\Omega_b h^2$ |
|------------|--------------------|-------|------------|----------------|
| A CDM      | 0.335              | 0.665 | 70         | 0.0125 $^{+0.0016}_{-0.0014}$ |
| Open CDM   | 0.37               | 70    | 0.91       | 0.0186 $^{+0.0026}_{-0.0023}$ |
| Standard CDM | 1.0               | 50    | 0.67       | 0.0150 $^{+0.0021}_{-0.0019}$ |

Table 1. Preliminary results for $\Omega_b h^2$ for 3 Cosmologies. The errors shown are fitting errors: systematic uncertainty is significantly greater.

References

Abel, T. & Haehnelt, M. 1999, ApJ, 520, L13
Anderson, S.F., Hogan, C.J., Williams, B.F. & Carswell, R.F. 1998, accepted AJ
Couchman, H.M.P. 1991, ApJ, 368, 23
Croft, R. A. C., Weinberg, D. H., Katz, N. & Hernquist, L. 1997, ApJ 488, 532
Davidsen, A.F., Kriss, G.A. & Zheng, W. 1996, Nature, 380, 47
Fardal, M. A., Giroux, M. L., & Shull, J. M. 1998, AJ, 115, 2206
Gnedin, N. 1999, *Cosmological Reionization by Stellar Sources*, astro-ph/9909383
Heap, S.R, Williger, G.M., Smette, A., Hubeny, I., Sahu M., Jenkins, E.B., Tripp, T.M., Winkler, J.N. 1999a, ApJ, submitted, astro-ph/9812429
Heap et al. 1999b, in preparation
Hogan, C.J., Anderson, S.F. & Rugers, M.H. 1997, AJ, 113, 87
Jackobsen, P. et al. 1994, Nature, 370, 35
Miralda-Escudé, Haehnelt, M. & Rees, M.J. 1999, ApJ accepted, astro-ph/9812306
Reimers, D., Köhler, S., Wisotzki, L., Groote, D., Rodriguez-Pascual, P. Wamsteker, W. 1997, A&A, 327, 890
Tytler, D. & Jackobsen, P. 1996, (unpublished)
Wadsley, J.W, Hogan, C.J. & Anderson, S.F. 1999, 9th Annual October Astrophysics Conference (1998). College Park, Maryland. Eds S. Holt & E. Smith. Am. Inst. Phys. Press, 1999, 273, astro-ph/9812239
Zhang, Y., Meiksin, A., Anninos, P., & Norman, M. 1998, ApJ 495, 63
Zheng, W. & Davidsen, A. 1995, ApJ, 440, L53