A Lower Bound on the Cosmic Baryon Density (Weinberg et al; astro-ph/9701012)

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Outline

- Absorption in the Lyα forest
  Old and new data
- How much Hydrogen needed for observed absorption
  (Weinberg et al, astro-ph//9701012)

Quasar spectrum attenuated blue of Lyα

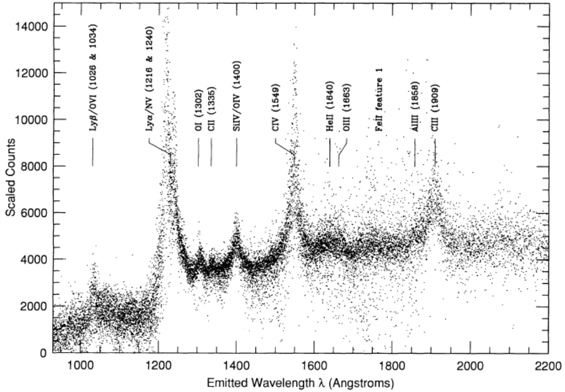
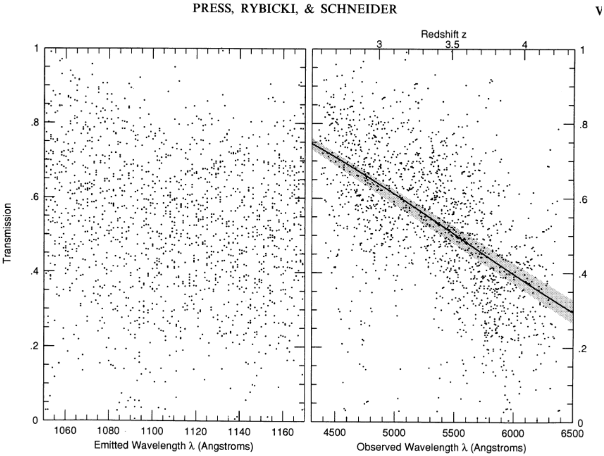


FIG. 1.—Observed spectra of 29 SSG quasars are here superposed after shifting each to its emission rest frame and scaling each to a common magnitude at 1450 Å. Despite indisputable differences in the individual quasars' continuum slopes and emission features, there is considerable similarity in the spectra. The principal interest of this paper is in the statistical analysis of the Lyman-α forest shortward of 1200 Å.

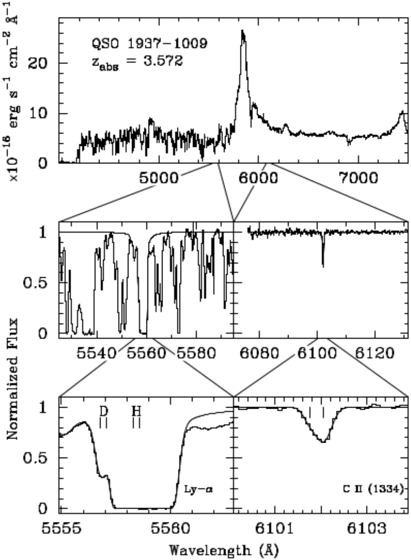
1993: composite of 29 quasars, $3.1 < z_q < 4.8$

Absorption vs z from extrapolation to $\lambda < \lambda_{\mathrm{Ly}\alpha}$

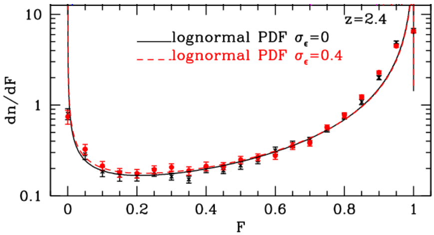


Optical depth: $\tau \sim 0.0037(1+z)^{3.46}$

High-resolution spectra: no need to extrapolate



$F = e^{-\tau}$.
$\overline{F}$ is the average of this distribution:



Peaks at $F = 0$ and $F = 1$

How much HI for a given optical depth?

A photon of wavelength λ traverses a medium containing neutral hydogen (number density n_{HI}) with a velocity gradient v'.
Resonance when $\lambda = \lambda_\alpha$ in restframe of hydrogen.
Absorption probability (optical depth) is

$$\tau = 0.416 \frac{\sigma_{Thom}}{\alpha^3} \frac{n_{HI}}{v'/c}$$

The velocity gradient has a cosmological compenent $H(z)$ and a fluctuating (peculiar velocity, v'_p) component.
The formula for τ assumes a well-defined velocity at each point (perfect fluid) with no thermal fluctuations

How many baryons for a given n_{HI}?

hydrogen atoms, electrons, and protons irradiated by non-thermal photons ($E > 13.6eV$) from quasars
If photoionization rate = recombination rate and $n_{HI} \ll n_H$:

$$n_\gamma n_{HI} \langle \sigma_{ioniz} c \rangle = n_p n_e \langle \sigma_{rec} v \rangle_T$$

$$\Rightarrow n_{HI} = n_b^2 \frac{\langle \sigma_{rec} v \rangle_T}{n_\gamma \langle \sigma_{ioniz} c \rangle} \qquad \langle \sigma_{rec} v \rangle_T \propto T^{-0.7}$$

$$\Rightarrow n_{HI} \propto \frac{(1+z)^6 \, \Omega_b^2 \, (1+\delta)^2 \, T^{-0.7}}{\text{ionizing photon flux}} \qquad \delta = \Delta\rho_b/\rho_b$$

Tempertuare fluctuations tied to density fluctuations:
$T = \bar{T}(z)(1+\delta)^{\gamma(z)-1}$, $\gamma(z \sim 3) \sim 1.6$
Photon flux fluctuations from quasar number density fluctuations.....

Optical depth at redshift z

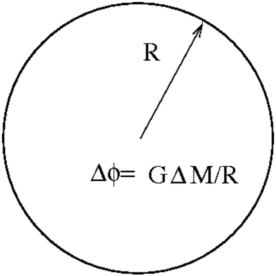
$$\tau(z) \propto \Omega_{\mathrm{B}}^2 \frac{(1+z)^6 \bar{T}(z)^{-0.7}}{H(z) J_\gamma(z)} \frac{(1+\delta(z))^\beta}{(1+\eta(z))^1} \qquad \eta \equiv \frac{v_p'(z)}{H(z)}$$

where $\beta = 2 - 0.7(\gamma(z) - 1) \sim 1.6$.
Formula assumes well defined $v_p(z)$ (no thermal broadening!).
To determine lower limit on Ω_{B}:

- Measure $\tau(z)$ averaged over Δz.
- Calculate $H(z)$ (cosmological model)
- Calculate $\bar{T}(z)$ and $\gamma(z)$ (simulations)
- Get lower limit on $J_\gamma(z)$ by counting UV sources (quasars)
- Model density and η fluctuations + thermal broadening

Note: With increasing $\langle \delta^2 \rangle$, $\tau(z)$ first increases then decreases (because of shielding)

Linear growth $\Rightarrow \langle\delta^2\rangle \sim \langle\eta^2\rangle$



Spherical perturbation of radius R.

$$\Delta\phi = \frac{G\Delta M}{R} \sim G\rho\frac{\Delta\rho}{\rho}R^2$$

Friedman eqn $\Rightarrow G\rho \sim H^2 = 1/D_H^2$

$$\delta \equiv \frac{\Delta\rho}{\rho} \sim \Delta\phi\left(\frac{D_H}{R}\right)^2 \qquad (1)$$

Peculiar velocities from excess Newtonian acceleration acting over one Hubble time:

$$\Delta a = \frac{\Delta\phi}{R} \quad \Rightarrow \Delta v = \Delta\phi\frac{D_H}{R} \quad \Rightarrow \eta \equiv \frac{\Delta v/R}{H} = \Delta\phi\left(\frac{D_H}{R}\right)^2$$

Numerical factors and updated cosmology

$$\tau(z) \propto \Omega_{\rm B}^2 \frac{(1+z)^6\,\bar{T}(z)^{-0.7}}{H(z)J_\gamma(z)}\;\frac{(1+\delta(z))^\beta}{(1+\eta(z))^1} \qquad \eta \equiv \frac{v_p'(z)}{H(z)}$$

Uniform density:

$$\tau_u = 2.31\times 10^{-4}\frac{(1+z)^{4.5}}{\sqrt{\Omega_{\rm M}h^2}}\;T_4^{-0.7}\,\Gamma_{-12}^{-1}\;\left(\frac{\Omega_{\rm B}h^2}{0.0125}\right)^2$$

where

$T_4 = \overline{T}/10^4$ K

Γ_{-12} = ionization rate$/10^{-12}\ \mathrm{sec}^{-1}$

Solve for Ω_B

Uniform density:

$$\frac{\Omega_\mathrm{B} h^2}{0.0125} = 65.8 \, \frac{(\Omega_\mathrm{M} h^2)^{1/4}}{(1+z)^{9/4}} \; T_4^{0.35} \, \Gamma_{-12}^{1/2} \, \tau(z)^{1/2}$$

Non-uniform

$$\frac{\Omega_\mathrm{B} h^2}{0.0125} = 65.8 \, \frac{(\Omega_\mathrm{M} h^2)^{1/4}}{(1+z)^{9/4}} \; T_4^{0.35} \, \Gamma_{-12}^{1/2} \, X_W^{(1-\beta)/2\beta} \left[\int_0^\infty \tau^\beta P(\tau) d\tau \right]^{1/2\beta}$$

$\sqrt{\tau(z)}$ replaced by a probability weighted integral over τ and a "fudge factor" $X_W \sim 1$ taking into account velocity effects and determined by simulations.

$\Omega_{\rm B} h^2$ conclusion (1997)

$\Omega_{\rm B} h^2 > 0.018$ (Planck: $\Omega_{\rm B} h^2 = 0.0222$)

All (known) approximations are conservative:

- Uses "reasonable estimate" of UV flux from known sources. Extra sources would increase $\Omega_{\rm B} h^2$.
- Assumes all regions with $\tau > 3$ have $\tau = 3$. (conservative)
- Shock-heated baryons and compact objects not included

Historical notes:

- Limit interesting in 1997 because of deuterium controversy.
- Cosmologists in 1997 were more comfortable with $\Omega_k \neq 0$ than with $\Omega_\Lambda \neq 0$.