Distribution of Mg II absorbers in along QSO lines of sight

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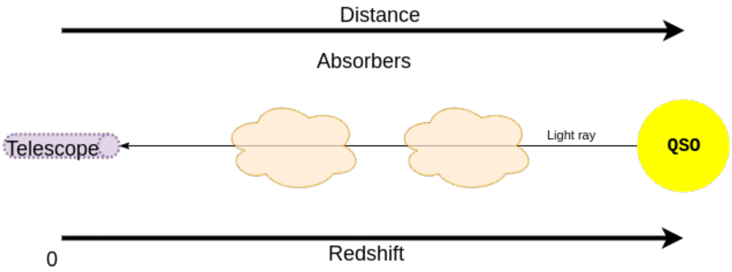

Figure: The absorption system

- Mg II ions have been known to be tracers of neutral gas.
- One of the strongest lines and thus easily spotted.
- Specifically looking at the doublet 2796-2803 Å

Mg II absorbers along QSO sightlines II

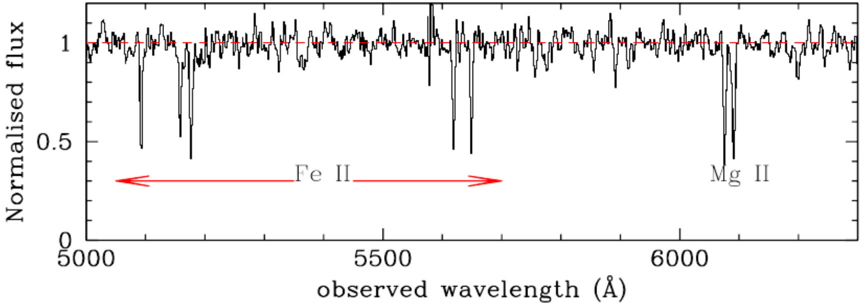

Figure: Mg II absorbers in QSO spectrum. Note the wavelength of the Mg II lines. They have been redshifted to nearly 6100 Åfrom their rest wavelength of 2800 Å. *Source: R. Srianand, private communication*

QSO sightlines

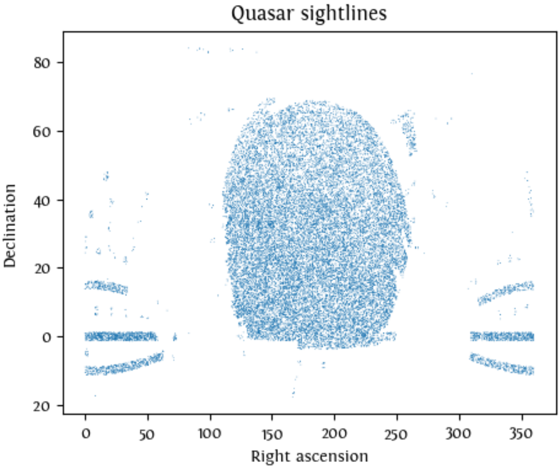

Figure: All QSO sightlines considered

Goals of this project

- To study the distribution of Mg II absorbers in redshift space
- To model this distribution and hence make inferences on the distribution of dark matter halos

Understanding the relationship between cold gas and dark matter halos would help understand structure formation better.

Work in progress

Modelling the distribution of absorbers

Work to be done

Modelling the **clustering** of absorbers as well

Background universe

The cosmological principle

The universe is homogeneous and isotropic.

- True at large enough scales: Of the order of 100 MPc.
- Evolution governed by the FLRW equations.

$$\begin{aligned} H^2 &= H_0^2\left[\frac{\Omega_{m0}}{a^3}+\frac{\Omega_{r0}}{a^4}+\Omega_{\Lambda 0}+\frac{1-\Omega_0}{a^2}\right] \\ \frac{\ddot{a}}{a} &= -\frac{H_0^2}{2}[\frac{3P}{\rho_{cr_0}}+\Omega] \end{aligned} \tag{1}$$

- The early universe being largely homogeneous and isotropic is reflected in the CMB.
- Temperature fluctuations are of the order of 10^{-5} of the average.

Cosmological perturbation theory

- Small fluctuations allow for a perturbative treatment.
- Since I am only interested in structures much smaller than the Hubble radius, **I can use Newtonian theory**.

Newtonian limit

The gravitational field obeys Poisson's equation. In terms of co-moving coordinates:

$$\nabla_x^2 \phi = 4\pi G a^2 \rho + 3a\ddot{a} \tag{2}$$

Assuming the universe to be filled with fluid,

$$\frac{\partial \rho}{\partial t}_x + 3H\rho + \frac{1}{a}\nabla_x(\rho \mathbf{v}) = 0 \qquad \text{(continuity eqn.)}$$

$$\frac{\partial \mathbf{v}}{\partial t}_x + H\mathbf{v} + \frac{(\mathbf{v}.\nabla_\mathbf{x})\mathbf{v}}{a} = -\left(\frac{\nabla_x P}{\rho a} + \frac{\nabla_x \phi}{a}\right) \qquad \text{(Euler eqn.)}$$

Linear perturbation theory

Defining the density contrast as $\delta = \rho/\rho_b - 1$, and combining the Euler and continuity equations in a matter dominated universe, we get:

$$\partial_t^2\delta + 2H\partial_t\delta = \frac{\nabla^2 P}{\rho_b a^2} + \frac{1}{a^2}\nabla.(1+\delta)\nabla\phi + \frac{1}{a^2}\partial_i\partial_j[(1+\delta)v^i v^j] \tag{3}$$

Linear order: The Meszaros equation

$$\partial_t^2\delta + 2H\partial_t\delta = \frac{1}{a^2}(\frac{\nabla^2 P}{\rho_b} + 4\pi G\rho_b\delta) \tag{4}$$

Jean's length:

$$\lambda_J = \sqrt{\frac{\pi}{G\rho_b}}c_s \tag{5}$$

Perturbations of wavelength greater than this grow while the others die out.

Non-linear theory: Spherical collapse I

A spherically symmetric, uniformly overdense region is considered. By conservation of energy,

$$\frac{\dot{r}^2}{2} - \frac{GM}{r} = E \tag{6}$$

Starting from a point where $\dot{r}$ was nearly Hr, the region behaves as if it were a closed universe by itself.

$$r = X(1 - \cos\Theta), t + T = Y(\Theta - \sin\Theta), X^3 = GMY^2$$

Equation of a cycloid!

Non-linear theory: Spherical collapse II

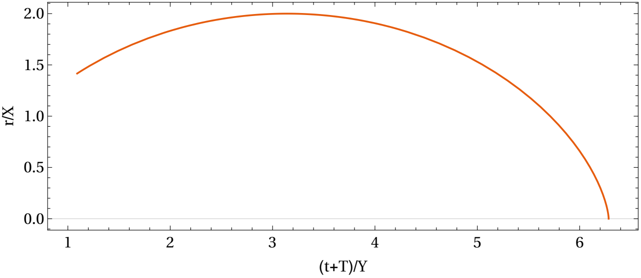

Figure: Evolution of a spherically overdense region.

Of course, collapse stops before $r = 0$ because of pressure generated by fluid. The system **virializes** and comes to a halt at $r = r_{max}/2$ with a density of $170\rho_b(t_{coll})$ in a matter dominated universe.

Halo mass function: Beyond Press-Schechter

The Millennium simulations showed the errors in the Press-Schechter halo mass function (HMF). A general HMF could be defined as

Sheth-Tormen Fitting function

$$\frac{dn}{dM} = -f(\sigma)\frac{\rho_m}{M}\frac{d\log\sigma}{dM}$$
$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2} \qquad (7)$$

- ρ_m: Mean background density
- σ: Std. dev. of linear power spectrum

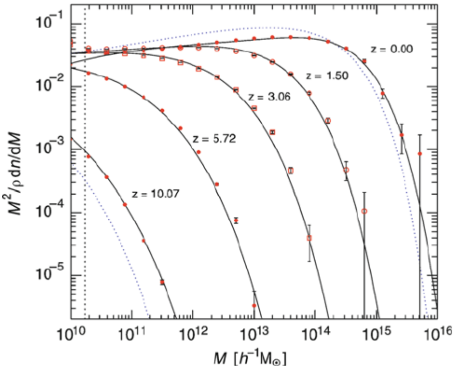

Figure: Results from the Millennium simulation. The dotted line represents Press-Schechter. *Source: Schneider, Extragalactic Astronomy and Cosmology, Ch. 7, Fig. 7.10*

Observed distribution

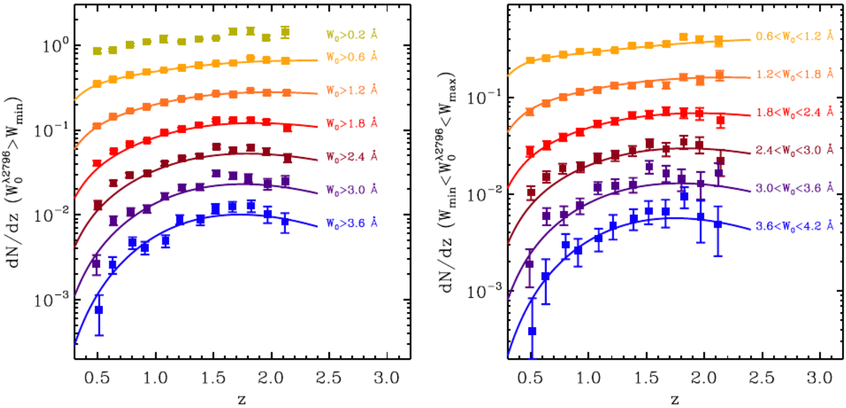

Figure: Cumulative (left) and differential (right) incidence rates dN/dz of Mg II absorbers. The solid lines show the best-fit parametrisation. The redshift evolution is much stronger for stronger absorbers. *Source: Zhu-Menard 2013, ApJ 770:130*

Halo-Absorber model: Tinker & Chen 2008

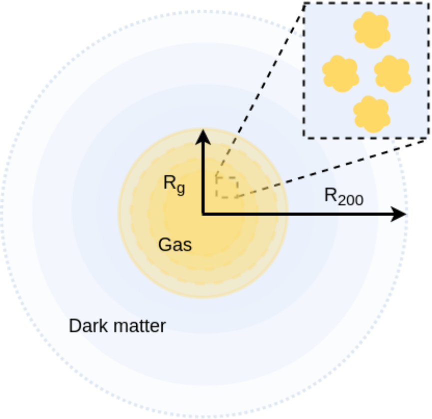

Figure: The classical model proposed by Tinker and Chen 2008, ApJ 679:1218

Halo-Absorber model

Halo: Has **NFW mass** profile.
Radius defined through:

$$M = 200\rho_m \frac{4}{3}\pi R_{200}^3$$

Gas: Arranged in clumps within R_g.
Distribution of clumps is of the form:

$$\rho_g = f_g G_0/(r^2 + a_h^2)$$
$$G_0 = \frac{M(< R_g)/4\pi}{R_g - a_h \arctan(R_g/a_h)}$$

Probability density of REW

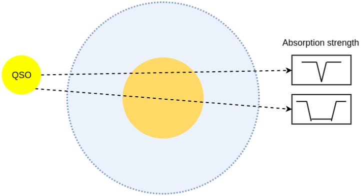

Figure: Absorption strength depends on impact parameter and gas distribution properties

REW vs impact parameter

$$
\begin{aligned}
W_r(s|M) &= \frac{W_0 \sigma_{cl} f_g}{M_{cl}} \frac{2G_0}{\sqrt{s^2 + a_h^2}} \times \\
&\quad \arctan \frac{R_g^2 - s^2}{s^2 + a_h^2} \\
&= A_w \frac{2G_0}{\sqrt{s^2 + a_h^2}} \arctan \frac{R_g^2 - s^2}{s^2 + a_h^2}
\end{aligned}
$$

$$
\begin{aligned}
P(W_r|M)dW_r &= \kappa_g(M) P(s|M) ds \\
P(W_r|M) &= \kappa_g(M) \frac{2s(W_r|M)}{R_g^2} \frac{ds}{dW_r}
\end{aligned} \tag{8}
$$

Number density of absorbers

Absorber distribution

$$\frac{d^2N}{dW_r dl} = \int dM \times \text{Number density of halos} \times \text{Total cross section} \times P(W_r|M) \quad (9)$$

$$\frac{d^2N}{dW_r dl} = \int dM \frac{dN}{dM} \pi R_g^2 P(W_r|M)$$

$$\frac{dN}{dz} = \frac{dl}{dz} \int dW_r \frac{d^2N}{dW_r dl}$$

Current state of work

- Speeding up the integral for $d^2N/dW_r dl$
- Checking for numerical errors

Currently, computed dN/dz is a decreasing function of redshift, unlike Zhu-Menard's observations.

References

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3. **T. Padmanabhan**, *Structure formation in the universe*, Cambridge 1993
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