THE LYMAN-ALPHA FOREST

Problems with Galaxies as Tracers of Structure

- Sparse, one per few Mpc^3 on average.
- Hard to predict galaxy clustering theoretically because the physics of galaxy formation is complicated and galaxies are extremely overdense.
- At least at high redshift, the effects of bias conspire to erase differences in the underlying mass distributions predicted by different cosmological models.

The Lyman-alpha Forest

- Picket fence pattern of absorption lines seen in spectra of QSOs, blueward of Lyα emission line [which is observed at wavelength $\lambda_{\mathrm{em}} = 1216 \times (1 + z_{\mathrm{QSO}})$Å].
- Caused by Lyα absorption from intervening concentrations of neutral hydrogen. Observed wavelength of absorption line is $\lambda_{\mathrm{abs}} = 1216 \times (1 + z_{\mathrm{abs}})$Å.
- Sensitive to small amounts of neutral hydrogen.

$$\tau_c = 2.52 \left(\frac{N_{\mathrm{HI}}}{10^{14}\mathrm{cm}^{-2}} \right) \left(\frac{30 \text{ km s}^{-1}}{b} \right),$$

where N_{HI} is the neutral hydrogen column density and b is the width of the absorption line. The disk of a typical spiral galaxy has $N_{\mathrm{HI}} \sim 10^{20}\mathrm{cm}^{-2}$.

- From the ground, one can observe the Lyα forest at $z \sim 2 - 4.5$. The HIRES spectrograph on Keck gives superb, high resolution, high signal-to-noise spectra. HST gives lower resolution data at $z < 2$.

Results From Simulations

In simulations of CDM models that include gas dynamics and photoionization:

- The basic observed features of the Lyα forest fall out "for free."
- The forest is caused mainly by low density, highly photoionized gas.
- At least in some cases, models match observed number of lines over a wide dynamic range (6-8 orders of magnitude) in column density.

Physics and Approximations

- It is easiest to think of the high-z Lyα forest as a *continuous* phenomenon rather than a collection of lines.
- Hydrodynamic simulations include all the relevant physics, but their results for the high-z Lyα forest can be described with fairly good accuracy by simple approximations.
- Most absorption in the hydro simulations is produced by gas with $\rho/\bar{\rho} < 10$ (because this low density gas fills most of the volume). Most of this gas is unshocked and lies on the temperature-density relation $T \propto (\rho/\bar{\rho})^{0.6}$ because of the interplay between adiabatic cooling and photoionization heating.

- PM approximation: Run N-body simulation using PM code (or other N-body code). Assume gas traces dark matter. Compute gas densities and assume all gas lies on temperature-density relation (i.e., ignore shock heating and radiative cooling). Make spectra.
- Fluctuating Gunn-Peterson Approximation:

$$\tau = 0.172 \left(\frac{\rho}{\bar{\rho}}\right)^{2-0.7\gamma} \left(1+\frac{dv_{\rm pec}}{H(z)dx}\right)^{-1} \left(\frac{1+z}{4}\right)^{6} \left(\frac{H(z)/H_0}{5.51}\right)^{-1} h^{-1} \times \left(\frac{\Omega_{\rm b}h^2}{0.0125}\right)^{2} \left(\frac{\overline{T}}{10^4\ {\rm K}}\right)^{-0.7} \left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{-1},$$

where $T = \overline{T}(\rho/\bar{\rho})^{\gamma}$ and

$$H(z)/H_0 = \left[\Omega_0(1+z)^3 + (1-\Omega_0-\lambda_0)(1+z)^2 + \lambda_0\right]^{1/2}.$$

Ignores shock heating, collisional ionization, and thermal broadening.

Testing cosmological models with the Lyα forest

- Good observational data probing wide range of redshifts.
- Continuous density maps along (sparse) lines of sight.
- Lyα optical depth is tied in direct and simple way to underlying density and velocity fields.
- *Physics is straightforward.* Robust predictions can be achieved with numerical simulations.
- Drawing conclusions requires:
  - Good statistical methods (borrow from large scale structure).
  - Careful match between observational and theoretical analyses.
  - Understanding of numerical resolution effects.

References

An up-to-date review of observations and theory of the Lyα forest is
Rauch 1998, ARAA, 36, 267

General discussion of simulations of the Lyα forest (and galaxy formation) along the lines emphasized in this lecture is
Weinberg, Katz, & Hernquist 1998, in Origins, ASP Conference Series 148, p. 21, astro-ph/9708213
Weinberg et al. 1999, in Evolution of Large Scale Structure: From Recombination to Garching, in press, astro-ph/9810142

There are many papers by various groups on simulations of the Lyα forest, including:
Hernquist, Katz, Weinberg, & Miralda-Escudé 1996, ApJ, 457, L51
Miralda-Escudé, Cen, Ostriker, & Rauch 1996, ApJ, 471, 582
Bryan, Machacek, Anninos, & Norman 1999, ApJ, 517, 13
Theuns, Leonard, Efstathiou, Pearce, & Thomas, 1998, MNRAS, 301, 478