Galaxies: Structure, formation and evolution

Lecture 8

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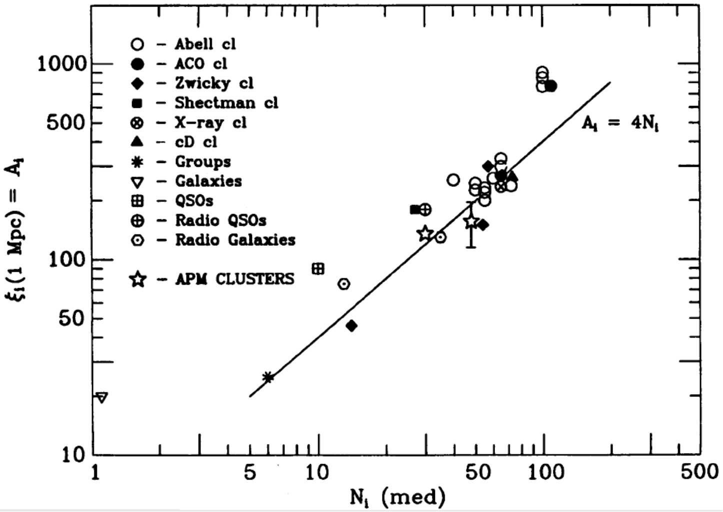
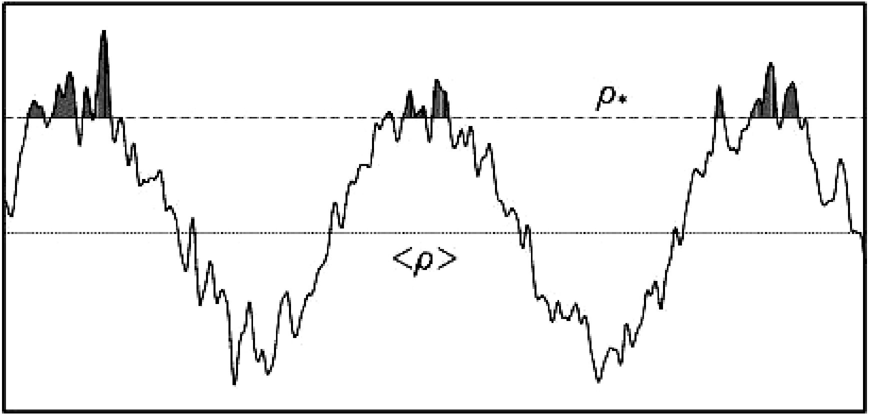
Cluster correlation function



Clusters are more strongly correlated than individual galaxies and rich ones are more clustered than poor ones. Why?

Biasing



See Kaiser (1984) and Bardeen et al. (1996)

Biasing in galaxies

Bardeen et al. (1996) show that for a Gaussian distribution of initial mass density fluctuations, the peaks which first collapse to form galaxies will be more clustered than the underlying mass distribution.

Large Scale Structure of galaxies

- A range of structures: galaxies (10 kpc), groups (0.3 - 1 Mpc), clusters (few Mpc), superclusters (10 - 100 Mpc)
- Redshift surveys are used to map LSS $\gtrsim 3 \times 10^6$ galaxies now
- LSS quantified through 2-point correlation function, well fit by a power-law: $\gamma \sim 1.8$, $r_0 \sim$ few Mpc. Equivalent description: power spectrum $P(k)$
- CDM models fit the data over a very broad range of scales
- Objects of different types have different clustering strengths and more massive structures, cluster more strongly

Question

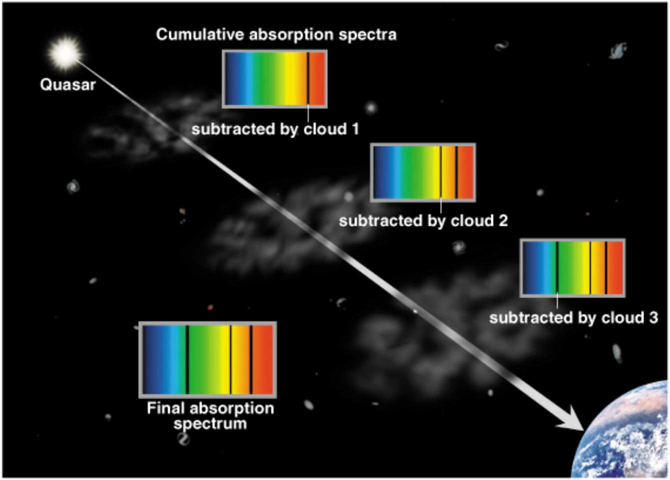
There is one major component of the baryonic large scale structure that we have ignored so far

Intergalactic medium (IGM) - baryons between galaxies

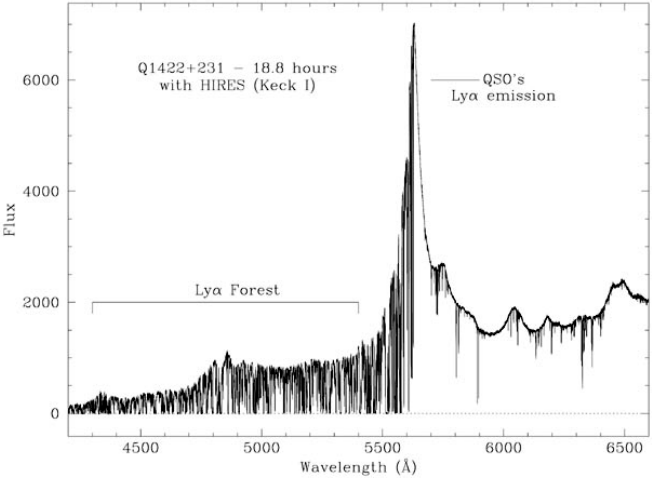
- Its density evolution follows the LSS formation, and the potential wells defined by the DM, forming a web of filaments, the “Cosmic Web”
- An important distinction is that this gas unaffiliated with galaxies samples the low-density regions, which are still in a linear regime
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation. Likewise, enriched gas is driven from galaxies through the radiatively and SN powered galactic winds, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other

How to observationally detect the IGM?

Absorption line systems



Quasar spectrum



Question

We saw that successful models of structure formation need to reproduce the observed correlation function/power spectrum on all length scales. Is there any other global observable, that models need to reproduce correctly?

Luminosity functions

The Luminosity Function specifies the relative number of galaxies at each luminosity.
The Luminosity function is a convolution of many different effects:

- primordial density fluctuations
- processes that destroy/create galaxies
- processes that change one type of galaxy into another (e.g. galaxy mergers)
- processes that transform mass into light

Observed LFs are fundamental observational quantities. Successful theories of galaxy formation/evolution must reproduce them.

The luminosity function

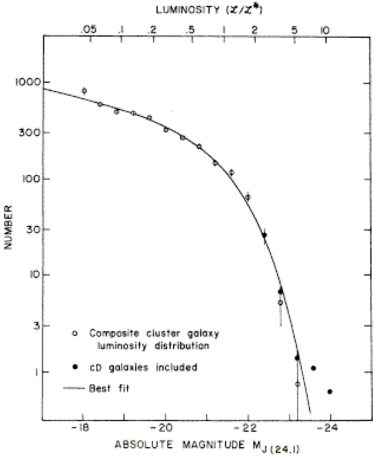


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Schecter Luminosity Function

In 1974, Press and Schechter calculated the mass distribution of clumps emerging from the young universe, and in 1976 Paul Schechter applied this function to fit the luminosity distribution of galaxies in Abell clusters.

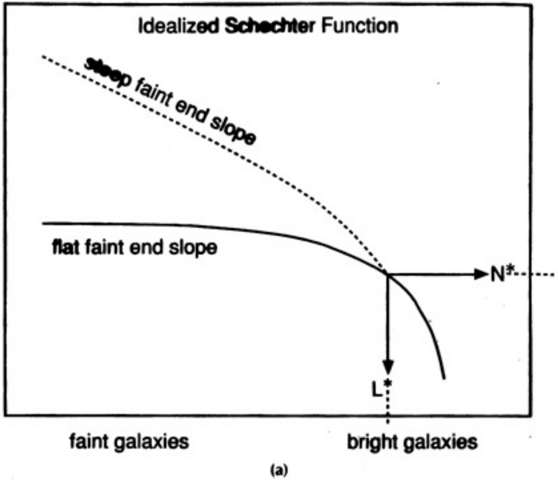
$$\phi(L)dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right) d\left(\frac{L}{L_*}\right) \qquad (1)$$

Function has two parts and three parameters.

Schecter Luminosity function

- L_* : luminosity that separates the low and high luminosity parts; $L_* \sim 10^{10} L_{B\odot} h^{-2}$, or $M_{B,*} \sim -19.7 + 5\log(h)$
- At low luminosity, ($L < L_*$): We have a power law with $\alpha \sim -0.8$ to -1.3 (“flat” to “steep”) lower luminosity galaxies are more common.
- At high luminosity, ($L > L_*$): We have an exponential cutoff, very luminous galaxies are very rare
- n_* : is a normalization, set at L_* $n_* \sim 0.02h^3$ Mpc^{-3} for the total galaxy population. Depending on context, n_* can be a number; a number per unit volume; or a probability. Note the implicit dependence on Hubble constant, via h^3.

What each parameter does



Properties of the luminosity function

$$N_{(>L)} = \int_L^\infty \phi(L')dL' = n_*\Gamma(\alpha+1, L/L_*) \tag{2}$$

For $L \to 0$, the total number of galaxies, $N_{\rm tot} = n_*\Gamma(\alpha+1)$. What happens for $\alpha \leq -1$?
Integrating over luminosity,

$$L_{(>L)} = \int_L^\infty L'\phi(L')dL' = n_*L_*\Gamma(\alpha+2, L/L_*) \tag{3}$$

Different equivalent forms of the luminosity function

$\phi(L)$ per dL, (which is usually plotted $\log(\phi)$ vs $\log L$). $\phi(M)$ per dM where M is absolute magnitude, so this is effectively $d(\log L)$. Sometimes the cumulative LF is given: $N > L$ or $N < M$. So please check the axes on your plots.Observationally, it is also important to specify:

- whether the LF is for specific Hubble Types, or integrated over all Types
- whether the LF is for Field galaxies or Cluster galaxies (or whatever the environment is)
- the value of H_0, since ϕ varies as h^3 while L or M vary as h^{-2}

How to measure the luminosity function? in Clusters

All cluster galaxies are at the same distance.

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All cluster galaxies are at the same distance.

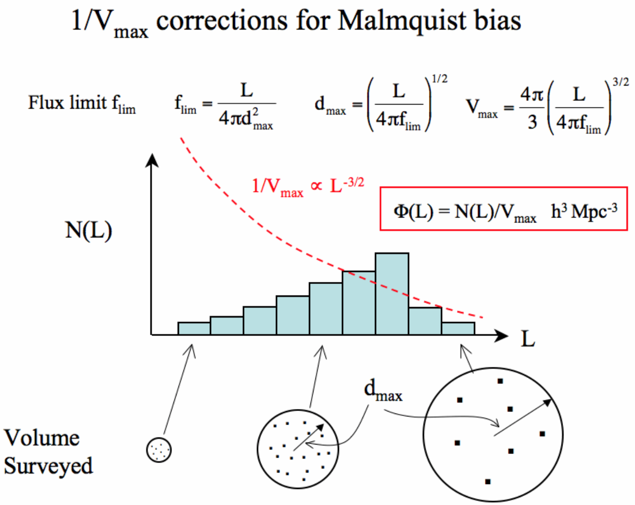
1. bin galaxies by apparent magnitude, down to some limit, to get $\phi(m)$
2. use cluster redshift (distance) to get $\phi(M)$
3. Fit a Schechter function to $\phi(M)$ by minimizing χ^2 to obtain M_* and α.

Complications arise principally from trying to eliminate fore/back-ground field galaxy contamination: here galaxy velocities are useful. Also dwarfs are often too faint to measure (except BCDs) because they have low SB. We need to apply statistical corrections to $N(m)$ using field samples.

Measuring the LF in the field

Obtain a **flux limited** sample: all galaxies brighter than given apparent magnitude limit. Use distances to calculate luminosity of each galaxy. Form a histogram of luminosity: $N(L)$.
However, each luminosity bin comes from a different survey volume (Malmquist bias) i.e. surveyed volume, $V_{max}(L)$, is small (large) for low (high) luminosity objects. So divide $N(L)$ by $V_{max}(L)$ to create $\phi(L)$ the density of objects at each luminosity. This now corrects the Malmquist bias and each luminosity samples the same effective volume.
Unfortunately, this method assumes a constant space density. When will this assumption be especially problematic?

Correcting Malmquist bias



Maximum likelihood method

See: Blanton et al. 2003, ApJ, 592, 819 *To estimate the luminosity function, we use a maximum likelihood method that allows for a general form for the shape of the luminosity function, fits for simple luminosity and number evolution, incorporates the flux uncertainties, and accounts for the flux limits of the survey.*
This is the method most commonly used today.

The V/V_{max} test to check for completeness

In addition to Malmquist bias, samples can be incomplete for other reasons: magnitude errors near m_{lim} include fainter galaxies and often magnitude corrections (e.g. for internal absorption) are only applied after the sample is defined. In practice, magnitude dependent weighting factors are applied to compensate for the incompleteness.

It is possible to check for completeness with the V/V_{max} test: For each galaxy, find the ratio V/V_{max} where: V is the volume out to that galaxy V_{max} is the volume out to d_{max}, the distance that the galaxy would be at the flux limit.

If the average of that ratio, $\langle V/Vmax \rangle = 0.5$ then the sample is complete Why 0.5?. We separate the sample into bins of apparent magnitude, When $\langle V/Vmax \rangle$ begins to deviate from 0.5 you've hit the completeness limit of the survey.

Unfortunately, this test also assumes a constant space density.