LARGE SCALE STRUCTURE AND GALAXY CLUSTERS

Galaxy Redshift Surveys

- Basic tool for mapping large scale structure in the local universe. Measure redshift-distances to all galaxies satisfying some criteria (e.g., optical apparent magnitude limit) in some area of sky.
- Large optical redshift surveys
  - CfA redshift survey: $\sim 12,000$ galaxies, reasonably large solid angles in North and South Galactic caps, only partly published. Geller, Huchra, and collaborators.
  - Las Campanas redshift survey: $\sim 25,000$ galaxies, six $1.5°$ thick slices, public. Shectman, Schechter, Oemler, Kirshner, and collaborators.
- Infrared-selected galaxy surveys: a succession of surveys of galaxies selected over nearly the full sky based on IRAS 60- and/or 100-micron fluxes. The most extensive is the (completed but not yet published) PSCZ catalog of 15,000 galaxies in the IRAS point-source catalog with 60-micron flux greater than 0.6 Jy (by Saunders and many collaborators).
- Future large surveys
  - 2dF Survey: 250,000 galaxies in southern hemisphere, from the AAT. Selected from photographic plates.
  - Sloan Digital Sky Survey: 10^6 galaxies and 10^5 quasars over π steradians in the North Galactic Cap, from a dedicated telescope in New Mexico. Selected from the survey's own, five-band, CCD photometry.
  - Survey of $\sim 100,000$ galaxies over most of the sky selected from the 2MASS survey.

Variance of Mass Fluctuations

The variance of fluctuations of the mass density field smoothed (or averaged) over volumes ("windows") of characteristic radius R is

$$\begin{aligned}\sigma^2(R) &= \int_0^\infty P(k) 4\pi k^2 dk\, \tilde{W}^2(kR) \\ &= \int_0^\infty \Delta^2(k) d\ln k\, \tilde{W}^2(kR),\end{aligned}$$

where $\Delta^2(k) \equiv 4\pi k^3 P(k)$.

The Fourier transform of the window function satisfies

$$\begin{aligned}\tilde{W} &\approx 1 \qquad 2\pi kR \ll 1 \\ \tilde{W} &\approx 0 \qquad 2\pi kR \gg 1.\end{aligned}$$

For a power spectrum $P(k) \propto k^n$ with $n > -3$, $\sigma^2(R)$ increases towards smaller scales and is dominated by waves with $k \sim 1/(2\pi R)$.

Clustering Statistics

To go beyond a "beauty contest" comparison of models to data, one uses galaxy clustering statistics. Many have been proposed and applied, including:

- The galaxy power spectrum $P(k)$.
- Its Fourier transform, the galaxy autocorrelation function $\xi(r)$, the probability in excess of random of finding a pair of galaxies with separation r.
- Higher-order correlation functions, which tell the probability of finding triples, quadruples, and so forth. These have Fourier analogs: the bispectrum, trispectrum, etc.
- Counts-in-cells distributions: the probability distribution $P_V(N)$ for finding N galaxies in a volume V. Essentially equivalent is the probability distribution function (PDF), the probability $P(\delta)$ of finding galaxy density contrast δ after smoothing with a filter of volume V.
- Topology: the connectedness of isodensity contour surfaces at different smoothing scales.

Although the true distribution of galaxies should be statistically isotropic, peculiar velocities distort all of these measures, making the line of sight a preferred direction. These redshift-space distortions can be used to infer the average magnitude of peculiar velocities induced by the gravity of observed structures, and from this the value of Ω.

Biased Galaxy Formation

Sounds easy. Use simulations to compute clustering statistics. Compare to observations. Rule out models.

The problem: N-body simulations predict the distribution of mass. We observe the distribution of galaxies. To go from one to the other we need assumptions about (or a theory of) galaxy formation.

Plausible assumptions:

- Galaxies trace mass (choose a random subset of N-body particles).
- Galaxies form more efficiently in high density regions, and are therefore more strongly clustered than the underlying mass distribution (choose a biased subest of N-body particles).

One characteristic quantity of a biased model is the bias factor $b(R) \equiv \sigma_{\rm gal}(R)/\sigma_{\rm mass}(R)$, but this could in principle depend on R, and b alone does not give a complete description of the operation of bias (many models can have the same b but predict different clustering).

Approaches to the Biased Galaxy Formation Problem

1. Compute bias from first principles, using simulations with gas dynamics and star formation.
   - Probably the ultimate solution, but numerically tough.
   - Might prove sensitive to uncertain star formation physics.
2. Use high-resolution N-body simulations that resolve galaxy-mass dark halos. Assume that each

halo hosts one galaxy.

- Still pretty tough numerically, since one needs high force and mass resolution to follow galaxy-mass halos that fall into larger mass halos.
- Neglects the influence of gas dynamics on the dark matter dynamics.
- Requires an assumption about the relation between dark halo mass and galaxy luminosity.

3. Use parametrized models in large-scale, lower resolution N-body simulations. Try to constrain these models using multiple observations.
   - Trade-off between Ω and b. Can constrain $\Omega^{0.6}/b$, but hard to determine them separately.
   - Things are simpler at large scales: bias still operates, but the results are less sensitive to the details of the models. The 2dF and Sloan surveys should therefore help unravel the problem.
   - There should eventually be fruitful interaction between approach 2 and approach 1.

Galaxy Clusters

Important feature: approximately in virial/hydrostatic equilibrium. Can estimate masses from galaxy motions, X-ray data (e.g., virial temperature). Also from weak lensing.

Can compare N-body (or analytic) predictions directly to "measured" masses. Results subject to any systematic uncertainties in mass measurements.

Matching the (standard estimates of the) cluster mass function leads to an effective constraint: $\sigma_8\Omega^{0.5} \approx 0.5$. This constraint relies on the assumption of Gaussian initial fluctuations.

Combined with $\sigma_{8,\mathrm{gal}} = 1$ for optical galaxies, this constraint implies $b_8 \approx 2\Omega^{0.5}$.

Redshift-space distortion analyses lead to a similar result, though some analyses give higher b values and some lower.

Can also compare predictions and observations of the clustering of clusters themselves, e.g., the cluster autocorrelation function $\xi_{cc}(r)$. The advantage is that the theoretical prediction is not sensitive to the detailed assumptions about galaxy formation (i.e., to bias). One assumes only that the largest virialized objects have sufficient concentrations of galaxies to be identified as clusters.

The Death of "Standard" CDM

In the mid-1980s, the standard version of the CDM scenario assumed $\Omega = 1$, $h = 0.5$, and a scale-invariant ($n_p = 1$) inflationary power spectrum. The normalization of the power spectrum (σ_8) was a free parameter.

Various large scale structure observations suggested that the shape of the CDM power spectrum with these parameters was too shallow on the scales $10 - 100\ h^{-1}$Mpc.

The death knell came from COBE. Normalizing the power spectrum to match the COBE fluctuations implies $\sigma_8 = 1.2$, which is clearly incompatible with the cluster mass function for $\Omega = 1$.

A number of solutions have been proposed:

- TCDM: tilt the inflationary power spectrum to $n_p < 1$.
- τCDM: delay equalization with a decaying τ neutrino.
- CHDM: add hot dark matter (neutrinos) to the cold dark matter.
- OCDM: lower Ω, with an open universe.
- LCDM: lower Ω, with a flat universe and cosmological constant.

Any of these changes goes in the direction of making the power spectrum steeper and reducing the predicted cluster masses. However, each model invokes different changes to the fundamental physics.

Hydrodynamic Simulations of Galaxy Clusters

Goals:

- Predict observables directly, not just total mass and dark matter distribution.
- Include the influence of gas on cluster dynamics.
- Understand the physics of cluster formation.

Two general types:

1. Simulate the cluster population, using a large scale box, uniformly sampled.

   Goals:
   - X-ray luminosity function.
   - X-ray temperature function.
   - Luminosity-temperature relation.

   Challenges:
   - Getting enough resolution, especially for X-ray luminosities or for any cooling effects.
   - Getting large enough box for decent statistics.
2. Simulate an individual cluster, using a coarsely sampled large scale box and high resolution in the region that will form the cluster.

   Goals:
   - Temperature and luminosity profiles.
   - Galaxy distribution and velocities.
   - Substructure in X-rays and galaxies.

   Challenges:
   - Still hard to get enough resolution.
   - Big computational effort yields only one cluster, not statistical results.

A caveat: Many cluster simulations do not include cooling and star formation; these simulations are often described as "adiabatic," though a more appropriate term would be "non-radiative."

The justification is that the cooling time of the intracluster gas observed in present day galaxy clusters is longer than the Hubble time, except in the cluster cores. However, it is not clear that ignoring radiative cooling and star formation throughout the history of the cluster's formation gives one the right answer in the end, even outside of the core.

References

This is a huge field, and no small number of references will summarize it. Many of my own prejudices and opinions on large scale structure are expressed in

Weinberg & Cole 1992, MNRAS, 259, 652

Weinberg 1995, in Wide Field Spectroscopy and the Distant Universe, astro-ph/9409094

Cole, Weinberg, Frenk, & Ratra 1997, MNRAS, 289, 37

Some recent papers on cluster simulations include

Moore, Governato, Quinn, Stadel, and Lake 1998, ApJ, 499, L5

Bryan & Norman 1998, ApJ, 495, 80

Mohr, Evrard, Fabricant, & Geller 1995, ApJ, 447, 8

Metzler & Evrard 1994, ApJ, 437, 564

Suginohara & Ostriker 1998, ApJ, 507, 16

A soon-to-be forthcoming opus by Lewis, Babul, Katz, Hernquist, Quinn, and Weinberg