Computing Our Universe, Structure IV **David Weinberg**

GALAXY FORMATION AND BIAS, AT LOW AND HIGH REDSHIFT

Galaxy Formation and Star Formation

Adding gas dynamics and realistic cooling to simulations leads to the formation of dense globs of cold gas, with masses and sizes similar to those of galaxies.

One can add a star formation algorithm to simulations that converts these globs of cold gas into collisionless stars. The KWH algorithm allows dense, cooling, Jeans unstable gas to turn into stars at a rate

$$\frac{d\rho_*}{dt} = -\frac{d\rho_g}{dt} = \frac{c_* \rho_g}{t_g},$$

where t_g is the local cooling time or dynamical time (whichever is larger).

Star formation adds energy from supernova feedback to the surrounding medium. Unfortunately, it is far from clear what is the most appropriate way to do this in simulations, since the effect of this energy depends on the structure of the ISM on scales that are unresolved.

With our prescription, the simulated galaxy population is similar with or without star formation.

Resolution and Photoionization, a Cautionary Tale

It is easy to artificially suppress galaxy formation with inadequate resolution.

When we added photoionization to our "standard" simulation, we found that it suppressed the formation of even fairly massive galaxies. But tests with higher resolution showed that this suppression was a numerical artifact, a result of underestimating the mass density.

This is a case where, at the lower resolution, adding a real physical effect (photoionization) made the simulation *less* accurate because of the interplay between physics and resolution.

Computing Bias

- Straightforward in principle: do large simulations with gas dynamics and compare the clustering of the simulated galaxies to the clustering of the dark matter.
- Hard to simultaneously get adequate resolution and sufficient volume for statistics. Also physical uncertainties associated with star formation and feedback.
- Cen, Ostriker, and collaborators have studied bias using simulations with adequate volume but insufficient resolution.
- We have studied bias using simulations with (probably) adequate resolution, but the small simulation volumes (11 h^{-1}Mpc on a side) severely limit the statistical robustness of our results. We are currently running a simulation with 144^3 particles in a 50 h^{-1}Mpc box, which has evolved to $z \sim 0.5$. It should be a good simulation for studying bias in the LCDM model.
- The VIRGO consortium has recently completed an SPH simulation of LCDM using 128^3 particles

in a volume of 100 Mpc and used it to study bias (Pearce et al., ApJL in press, astro-ph/9905160).

High Redshift Galaxies

Explosion of observational data in last 3 years thanks to multi-color selection, follow-up spectroscopy with large telescopes (especially the LRIS instrument on Keck) to confirm redshifts.

Star formation rate can be estimated from rest-frame UV (observed frame optical) luminosity, but the estimate depends on the assumed stellar initial mass function and dust extinction correction.

Basic observational results:

- Substantial population of star-forming galaxies at $z = 3$.
- Inferred star formation history of the universe, peaking at $z \sim 1-2$ (dust extinction is a major uncertainty here).
- Clustering of $z = 3$ galaxies is almost as strong as clustering of $z = 0$ galaxies.

Numerical results:

- Predicted baryon mass functions and UV luminosity functions.
- Reasonable match to inferred high-redshift star formation rate; simulations perhaps predict too much star formation.
- The high-redshift galaxy population is highly biased, and the *galaxy* clustering does not depend strongly on the underlying mass clustering. Implications:
  - Simulations can explain the strong observed galaxy clustering.
  - High-z galaxy clustering isn't a good way to distinguish between cosmological models, but it does test the theory of galaxy formation.

Individual Galaxy Simulations

Another class of galaxy formation simulations: zoom in on a single object selected from a larger scale simulation.

- Get reasonable objects with bulges and exponential disks.
- Disks appear to be too small, as though lumpy collapse is transferring too much angular momentum from the gas to the dark halo.

Issues in Simulations of Galaxy Formation

- Effect of limited numerical resolution.
- Importance of feedback.

It seems that the simulations tend to produce too much cold gas, too much angular momentum loss. Is the explanation of this problem numerical artifacts, inadequate modeling of the "micro"-physics (like star formation and feedback), or an error in the assumed cosmological model?

References

Our work on galaxy formation is described in
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Weinberg, Katz, & Hernquist 1998, in Origins, ASP Conference Series 148, p. 21, astro-ph9708213

Our work on high redshift galaxies and their clustering is described in the Origins paper and in
Katz, Hernquist, & Weinberg 1998, in Highly Redshifted Radio Lines, astro-ph/9801074
Katz, Hernquist, & Weinberg 1998, ApJ, in press , astro-ph/9806257

The Cen & Ostriker work on galaxy bias is described in
Blanton, Cen, Ostriker, & Strauss 1998, ApJ, in press, astro-ph/9807029
Cen & Ostriker 1992, ApJ, 399, L113
Cen & Ostriker 1993, ApJ, 417, 415
Cen & Ostriker 1998, ApJ, submitted, astro-ph/9809370

A nice review of individual galaxy simulations and of the SPH simulation method is
Steinmetz 1996, in Dark Matter in the Universe, astro-ph/9512013