LECTURE 2

NUMERICAL STUDIES OF GALAXY FORMATION

1. Simulations of interactions and mergers
2. Galaxy formation in a cosmological context
3. Formation of individual galaxies
4. Photoionization and galaxy formation
5. Overview of results
6. High-redshift galaxies

Interactions and Mergers

Basic approach: set up equilibrium galaxies, let them interact with each other, or with perturbers in a cluster.
N-body or N-body + SPH.

Motivating questions:

- What role do interactions play in
  - determining/transforming galaxy morphologies?
  - fueling AGN activity?
  - fueling starbursts?
- Can mergers of disks form elliptical galaxies?
- Why do ellipticals lie on a fundamental plane?
- What happens to accreted dwarfs?
- How much lumpy accretion can disk galaxies tolerate?

Some Important Results

- Violent mergers of disks produce slowly rotating remnants with $R^{1/4}$-law profiles.
  Plausible mechanism for elliptical formation if gas dissipation increases central phase space density.
- Mergers have memory. Particles remember initial gravitational potential and angular momentum.
- Merging ellipticals "puff up" at level needed to move them within the fundamental plane.
- Interactions move gas in toward galaxy centers.
  Could fuel AGN/starburst activity.
- Weak encounters can produce tidal arms.
  But not if halos are too massive.
- Weak interactions in clusters, a.k.a. harassment, can produce remarkable morphological transformations.
- Satellites accreted into a spherical galaxy sink to the center in roughly a dynamical friction time.
- Disks can tolerate some satellite accretion, especially if they have gas to cool them down.

Galaxy Formation Simulations: Overview of Results

- White & Rees (1978) scenario works: dissipation produces dense objects that retain identity in larger groups.
- Sizes, overdensities, and baryon masses are in right ballpark for real galaxies.
- Fairly quiescent assembly history $\longrightarrow$ thin, exponential disks.
- Photoionization suppresses galaxy formation below $v_c \sim 40$ km/s, has little effect above $v_c \sim 75$ km/s.
- Using age of stellar population as surrogate for morphology, get reasonable morphology-density relation.

Problems:

- Too much cooling:
  $\Omega_\star$ too large.
  Central cluster galaxies too massive.
- Angular momentum transfer $\longrightarrow$ disks too small.

Possible implications:

- Some cooling gas forms baryonic dark matter.
- Need new cosmological model (e.g., warm dark matter).
- Feedback plays larger role.
- Numerical limitations are leading to spurious results.

High-Redshift Galaxies

Several variants of CDM produce healthy population of high-z galaxies.

Maybe too healthy.

High-z galaxies strongly biased relative to mass distribution.

Lyman-break galaxies detected to date should be tip of the iceberg: many more lower luminosity systems at $z = 3$, and significant population to $z = 6$ and beyond.

Comparison of Approaches

Strengths of semi-analytic approach

- Large dynamic range in halo mass
- Flexible treatment of star formation, feedback
- Parametrized treatments of mergers & morphological transformations
- Fast $\longrightarrow$ can explore wide parameter space
- Relatively simple to understand

Strengths of numerical approach

- Accurate treatment of hierarchical collapse and merging
- (Probably) more accurate treatment of galactic scale dissipation
- Appropriately messy
- Few tunable parameters (given cosmological model)
- Direct predictions of morphology, structure
- Spatial information

Future interactions

- N-body gravity + semi-analytic galaxies
- Use simulations to test/calibrate basic assumptions of SAMs
- Wider range of star formation and feedback prescriptions in simulations
- Detailed comparison of numerical and semi-analytic predictions for matched assumptions