The Development of Structure in the Universe: The Big Picture

Ay21
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Wilkinson Microwave Anisotropy Probe (WMAP) 2003
Growth of Perturbations After Recombination

Pressure on baryons from its strong coupling to the radiation field before recombination is too high for their inhomogeneities to grow (undergo only "acoustic oscillations")

Something was there that was not strongly coupled and whose inhomogeneities must have had a "head start" by the time recombination occurred (they must have become non-relativistic at early times)

![Diagram](https://via.placeholder.com/150)

baryons fall into the dark matter potential wells after they are de-coupled from the radiation (pressure drops by a huge factor!)

The First Astronomical Objects?

- around z~25-30, the largest dark matter concentrations (~10^5 M_{sun}) have collected enough gas to form a single star (each!)
- some time later, say z~10-15, the first small galaxies (~10^8 M_{sun}) are able to sustain star formation
  - can they be detected?? [maybe; James Webb Space Telescope]
- gradually these small halos merge together to form bigger ones, and to support larger star formation rates
  "hierarchical structure formation", a "bottom-up" process
the first stars

Simulation: Tom Abel (PSU), Greg Bryan (Oxford), Mike Norman (UCSD)
Viz: Ralf Kähler (AEI, ZIB), Bob Patterson, Stuart Levy, Donna Cox (NCSA), Tom Abel (PSU)
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Formation of a Galaxy Group (U Chicago Computational Cosmology)
What are the Baryons Doing?

The progress of structure formation depends on both the amount and the nature of dark matter. Many possibilities have been ruled out in just the last few years...
“Biased” Galaxy Formation

Galaxies form preferentially in the densest regions in the dark matter distribution, and these regions will be naturally strongly correlated with one another.

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\textbf{One also expects that the amount of “clustering” will depend on the mass of the collapsed object}

Expect that the brightest, or the most massive, objects at any cosmic epoch represent an “amplified” version of the dark matter distribution (e.g., galaxy clusters clump with one another more strongly than typical galaxies do).
Large Scale Structure of the Universe: The Dark Matter Distribution

"Recipe" for Galaxy Formation

- "collapsed" dark matter halo (~85% of total mass)
- gaseous baryons (~15% of mass)
- gas cooling (further collapse of baryons)
- energy input via star formation, supernova explosions, black hole accretion ("Feedback")

Potential well formed by gravity of (primarily) dark matter
Example of “Feedback”

**Simulation:** Tiziana Di Matteo (MPE/CMU), Volker Springel (MPE) & Lars Hernquist (Harvard)

- “Feedback” (heating and expulsion of gas) from quasar activity regulates star formation and black hole growth
- Recent computer simulations of galaxy formation show that black holes may be needed to reproduce some observations

Galaxy Formation: When, Where, How?

- So, when do galaxies become observable, and what should they look like?
- Growth of dark matter structure seems reasonably well understood, but do we understand all that we need to know?
- How does the “fossil record” agree with observations of distant galaxies?
Inferences from the “fossil record” of stars in nearby galaxies

The Fossil Record Versus Cold Dark Matter Cosmology

- Perceived conflicts everywhere when CDM meant $\Omega_m=1$
  - Presence of old, quiescent elliptical galaxies
  - Lack of strong evolution in appearance of large galaxies to $z\sim1$
  - Lack of dynamical evidence for large matter density
  - But alternatives to CDM were not physically compelling, searches for “primeval galaxies” generally gave null results.

- “New Cosmology” relaxes, but does not remove, discrepancies with cosmological models.
  - Rapid convergence on low-density, flat “CDM” model puts more pressure on understanding other, more complicated, physical processes.
Galaxy Formation: Important “facts” to be accounted for-

- The oldest and most massive galaxies are located in the densest environments (apparently at all cosmic epochs)
- Morphological transformations may be occurring
  - no “Hubble Sequence” beyond z~1 (7-8 Gyr ago)- just “train wrecks”
- The overall level of star formation in the Universe today is much smaller than when it was at its peak
- Galaxies are being found at high redshifts that already appear old and “quiescent”: a big puzzle for hierarchical structure formation!
  - lack of understanding of “baryonic” processes?
- Much larger proportion of galaxies with HUGE star formation rates as one goes back in time

Ab Initio Understanding of Galaxy Formation

- Begin with dark matter halos, with baryonic component according to Big Bang Nucleosynthesis/WMAP baryon density relative to $\Omega_m$
- Follow evolution of dark matter distribution using N-body models, or analytic calculations (given an assumed initial matter power spectrum).
- Baryon physics added "by hand" or with simple treatment of hydrodynamics (gas physics)
  - Star formation "recipes"
  - "Feedback" from star formation, AGN accretion power a major uncertainty
  - Hope to reproduce observed universe with simple physical prescriptions
- Goal is to naturally explain both the properties of individual galaxies, and their large-scale distribution.
- Problem: need both the large scale picture, and "sub-grid" physics, for complete understanding: it is a very hard problem!
- Galaxies should be thought of as a strongly evolving, non-linear map of dark matter distribution.
Galaxy Formation: What’s Wrong With This Picture?

Schematic diagram of the basic galaxy formation model (à la White and Rees 1978, from Baugh 2006).

Galaxy Formation: Theoretical “Predictions”

- The oldest and most massive galaxies should be found in the densest environments at all cosmic epochs
- Morphological transformations may be occurring (disk+disk=bulge/elliptical?)
- Galaxies will get increasingly smaller, less massive as one goes back in time
- Structure should be generally less well-developed as one goes back in time
**GALAXY FORMATION: High Peaks in the Matter Distribution**

Galaxies here are color-coded according to the cosmic epoch of their original collapse—**red** galaxies are the oldest, **blue** the youngest.

Galaxies in the most strongly clustered regions formed first.

Virgo consortium, 1999

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**Merger-Driven Star Formation**

- The dominant mode of star formation in the local universe is “quiescent”, in the disks of spiral galaxies
- Increasingly at high redshift (early times) star formation is occurring in objects that look “disturbed”
- The most spectacular objects at high redshift have star formation rates of \( >1000 \, M_\odot \) per year, so they could form an entire giant galaxy of stars in \( \sim 10^8 \) years
  - is this the same as “monolithic collapse” as in the early 1960s?
    - No, not really...
Galaxy Transformations

More likely scenario:

- bulges form from major mergers of gas-rich galaxies \(\Rightarrow\) huge bursts of star formation, AGN, supernovae
- disks are accreted slowly when things have "settled down" enough to allow it (no major mergers or accretion events to disturb thin disks)
- star formation is episodic during the early history of the universe
The process of galaxy formation is available via direct observations.

Does it agree with a) the fossil record or b) theoretical expectations?

Today…
Is the observable record of the history of structure formation consistent with the current cosmological paradigm?

Many new tools have become available in the last ~7-8 years that allow this question to be answered, in principle. Progress has been incredibly rapid...

Hubble Deep Field, Jan 1996

Universal Timeline

Best current estimate of the age of the universe

It appears that the era that dominates the assembly of stellar mass (and black hole accretion) was 9-12 Gyr ago

How do we know?
Practical Difficulties in Studying the Distant Universe

Distant galaxies are extremely faint, requiring very large telescope apertures to collect enough photons to detect them, and even larger apertures to acquire physical information.

The Milky Way if seen at 12 billion light years would have only 1% of the brightness of the dark night sky!

The observational "window" over which sensitive observations can be made from the ground is limited.

Recall:
- The UV is blocked by ozone in the atmosphere;
- much of the IR is blocked by water vapor;
- where it is not the sky background can be hundreds to thousands of times brighter than in the 0.3-0.9 micron "optimal window";
- much of the energy produced by star formation is "processed" by dust and re-radiated in the far-IR, where it is difficult to detect.