Lecture 38: Galaxy Formation
Section 26-9

Key Ideas
Observations of Galaxies
    Key Questions
Current Picture of Galaxy Formation
    Mergers & Rotation Important
Testing Theory of Galaxy Formation
    Fossils in the Milky Way
    High redshift observations
Frontiers of Research

Major Types of Galaxies: Spirals, Ellipticals & Irregulars

Spiral Galaxies
Look different edge-on and face-on\
Thin disk
Spiral arms in disk
Mix of old and young stars (old stars in halo, young and old stars in the disk)

Elliptical Galaxies
No organized rotation
No thin disk
Little gas or dust but lots of old stars

Irregular Galaxies
Come in all shapes
Small percentage of bright galaxies, but a larger percentage of dwarfs
Lots of gas and young stars

Morphology-Density Relation
Clusters have a lot more ellipticals compared to isolated galaxies in the "field". The shapes of galaxies ("morphology") depends on the density of their environment.

Properties of Galaxies at the Present Time

Type of Galaxy	Gas	Stars	Rotation	Dark Matter	Dwarfs
Spiral	Some	Mix of old and young	Important	Yes	No
Elliptical	No	Mostly old	Not important	Yes	dE dSph
Irregular	Lots	Both old and young, lots of young	Not important	Yes	dIrr

Key Questions

Why do galaxies have different shapes?
Why does galaxy type depend on environment?
Why do different galaxies have different kinds of stars? Different amounts of gas?
How do galaxy types change over time?

Current Picture of Galaxy Formation

Galaxies form from the bottom-up
    Start off small and merge to become bigger
Rotation is important
    Rotation leads to flat, thin disks
    Disruption of rotation leads to ellipticals
Mergers are important
    "Major merger" – galaxies are about equal mass
    "Minor merger" – 1 galaxy smaller than the other – aka "galactic cannibalism"

Galaxies in a Cosmological Context

Galaxies do not form in true isolation. They form along filaments, in superclusters, clusters, and groups.

Recipe for Galaxy Formation

Step 1: Gravity starts to win in the battle against cosmic expansion
    Wins for small masses first
Step 2: Gravity pulls gas and dark matter together
    Little things come together to make big things
Step 3: Gas pulled together into giant molecular clouds. Star formation begins.

Rotation – Crucial Ingredient

See Figure 26-32a
Galaxies much more extended originally.
Rotation makes spiral galaxies with thin disk
Mergers destroy disks

Mergers – Crucial Ingredient

See Figure 26-32b, but including the idea that a major merger occurs, destroys the disk and ignites a starburst.

Computer Simulations

Gravity pulling gas and dark matter together is a complicated process
We study it by large computer simulations of many dark matter and gas particles
We can't model the formation of individual stars as part of galaxy formation yet.
Assume a recipe for how stars form, how supernova eject material and heat the gas, and other details.

What to Notice in the Simulations

Color-coded
- Green=gas
- Blue=young stars
- Yellow=middle-aged stars
- Red=old stars

High merger rate early
Tidal tails as galaxies merge
Rotation important for spiral
Major merger for elliptical

Simulations of the Formation of a Disk (=Spiral) and Elliptical Galaxy.

Point of View of Movies: you are riding along with one particular galaxy, not a "God's eye" view
See Matthias Steinmetz's web site for movies of the formation of spiral and elliptical galaxies
http://www.aip.de/People/MSteinmetz/E/movies.html

Mergers more common in clusters

The more galaxies – the more likely to merge

Effects in clusters

- Mergers (galactic cannibalism if a minor merger)
- Gas stripping
  - By gas in the cluster
  - By other galaxies (galaxy harassment)

Mergers more important for big galaxies, stripping and harassment more important for small galaxies.

See simulation of a cluster forming (with lots of merging, etc.) at
http://hpcc.astro.washington.edu/faculty/trq

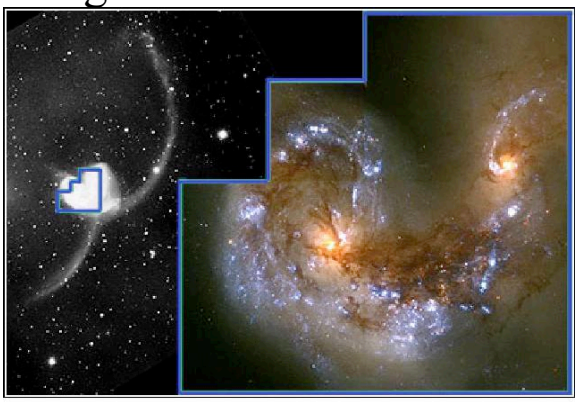
- Formation of a cluster of galaxies showing the dark matter
- Formation of a cluster of galaxies, showing the gas

Mergers Leave Clues

See Figure 26-27

Sometimes obvious clues, like bright tidal tails. As time passes since the merger, the tidal tails and starbursts fade. Deep images are required to see the faint traces of a mergers in what otherwise looks like an elliptical galaxies.

Mergers Cause Starbursts



Starbursts turn lots of gas into stars. Uses up the gas.

My Favorite Movie (of Galaxy Formation)

http://www.astro.washington.edu/stinson/nbody/galform/index.html

The 220 kiloparsec wide view of a galaxy

Testing the theory

Explain observed differences

Mergers common

- Tidal Tails and other distortions
- Smaller galaxies more common in past
- Spirals more common in the past

Star Formation histories

- Elliptical – all early
- Spirals – lots early, but continuing
- Clusters – lots of star formation early

How to Study Galaxy Formation

Fossil Record

- Look for the traces of how a galaxy formed in nearby galaxies

Time Machine

- Look at high redshift=high recession velocity=large lookback time
- Observing distant galaxies=observing young galaxies

"Fossils" in the Milky Way

We see old stars in the halo, young stars in the disk, just as in the simulations

We see the Milky Way merging with the Sagittarius dwarf.

Finding Fossils

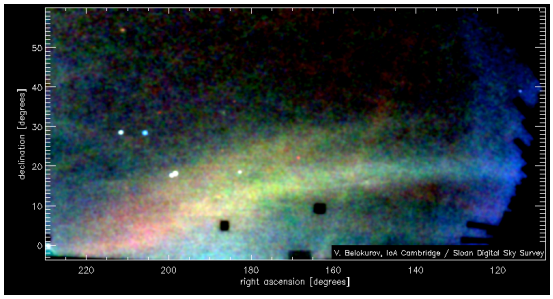
Finding the remnants of a nearby galaxy's formation can be tough

Lots of stars, so finding the few stars from a large merger challenging

Techniques

- Distances/colors/brightnesses for lots of stars
- Deep images of nearby galaxies

Field of Streams



See remains of little galaxies that have merged with the Milky Way.

Looking Back in Time

High Redshift=Very Young Galaxies

Observations of high redshift=very distant=very young objects show

- Lots of irregulars
- Lots of spirals
- Lots of dwarfs
- Lots of star formation in spirals

Agrees with the theory!

What we don't see at z=3

We don't see rich clusters full of ellipticals with old stars.
However, this is what some of the galaxies we see at high redshift will eventually look like.

Key Answers

Why do galaxies have different shapes?

- Different mergers/rotation

Why does galaxy type depend on environment?

- Mergers/harassment/stripping more common in clusters.

Why do different galaxies have different kinds of stars? Different amounts of gas?

- Same things that affect shape affect star formation. Mergers lead to elliptical shapes as well as starbursts which use up the gas.

How do galaxy types change over time?

- Galaxies are not one type throughout their history.

Frontiers of Research

Computer models do not agree exactly with what we see

- Too many dwarfs!

The role of active galactic nuclei (in particular, quasars) in galaxy formation.

- Eject gas and quench star formation?

The gory details of stellar birth and death on galactic scales.

Notes on the Final

7:30 -10:30 am on Monday March 12 in Orton 110
The final is cumulative
75 multiple-choice questions
    10-15 from the last three lectures
    60-65 from the rest of the material
Suggestion method for studying:
    Study the quizzes, essentially "retaking" them.
    I asked about the concepts I thought were important, sometimes as the right answer and sometimes as a distractor
    So if you know why the right answers are right and the wrong answers are wrong, you will have gotten the concepts.
A few questions will be taken directly from the earlier quizzes, but a few questions will be very similar, but with "low-mass" instead of "high-mass" or "O" instead of "M", etc. Read the questions carefully!