Lecture 16: Galaxy Formation and Evolution
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Hubble’s Tuning Fork: Why do we have different types of galaxies?

Our best models for galaxy formation assume:

• Matter originally filled all of space almost uniformly
• Gravity of denser regions pulled in surrounding matter

Formation of the Cosmic Web

http://cosmicweb.uchicago.edu/filaments.html
Within this cosmic web are isolated galaxies, small groups of galaxies and large clusters of galaxies.....

All Matter (Baryonic and Dark Matter) is Organized into a Cosmic Web

Spiral galaxies are often found in groups of galaxies (up to a few dozen galaxies)

Elliptical galaxies are much more common in huge clusters of galaxies with hundreds to thousands of galaxies.

Abell 1689
Galaxies are Star Making Machines

Gas falls in from cosmic web

Winds from supernova and black holes blow out gas and limit star formation

Stars and elements are manufactured in galactic disk

Traditional View of Galaxy Formation

Galaxies formed from protogalactic clouds

H and He gases in these clouds formed the first stars

Supernova explosions from first stars kept much of the gas from forming stars

Leftover gas settled into spinning disk

Conservation of angular momentum
Spin: Initial angular momentum of protogalactic cloud could determine size of resulting disk

Density: Elliptical galaxies could come from dense protogalactic clouds that were able to cool and form stars before gas settled into a disk

Telescopes are time machines

Since it takes light time to travel from a galaxy to the Earth, we can observe galaxy evolution by looking at more and more distant galaxies.

One of the major challenges in astronomy is to construct a picture of galaxy formation by observing galaxies at different epochs in the history of the Universe.

Hubble’s Law (know this!!!!)

We can measure distances by the redshift of a galaxy.

By looking at a single patch of sky, we can see galaxies at many different distances
Measuring the Shift

Change in wavelength = wavelength x velocity / speed of light

\[ Z = \frac{\Delta \lambda}{\lambda} = \frac{v}{c} \] if \( v \) much smaller than the speed of light

\[ Z = \Delta \lambda / \lambda = \sqrt{\frac{1+v/c}{1-v/c}-1} \]

Collisions were much more likely early in time, because galaxies were closer together.

Many of the galaxies we see at great distances (and early times) indeed look violently disturbed.
Distant Red Ellipticals

- Observations of some distant red elliptical galaxies support the idea that most of their stars formed very early in the history of the universe.
- These elliptical seem to be parts of clusters of galaxies.

Star Formation over the History of the Universe

We still can’t directly observe the earliest galaxies: we need to rely on simulations to guide us until observations become possible.

http://luca.as.arizona.edu/~oppen/IGM/general.html
Galaxy Formation in the Cosmic Web

Map of Streams of Stars around our Galaxy

If we map the distribution of distant stars surrounding our galaxy, we find streams of stars: these are satellite galaxies being cannibalized by the Milky Way.

Johnston & Bullock

What are starbursts?

Starburst galaxies can have high luminosities (10^{12} solar luminosities - about 100 times of our galaxy).

They are forming stars so quickly (10 - 100 times faster than the rate of our galaxy) they would use up all their gas in less than a billion years. Thus we expect that there is a burst of star formation.

Starbursts may be triggered by encounters with other galaxies.

Most of the energy radiated in the infrared
Galactic Winds
Intensity of supernova explosions in starburst galaxies can drive galactic winds.
A galactic wind in a small galaxy can drive away most of its gas.
This can slow down star formation until the star burst is over.

What happens when galaxies collide?
The stars don’t collide, galaxies interact through gravity and collision of gas clouds in the ISM.

Galaxy collisions take millions to billions of years.
We use computer simulations to speed up time!

Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical galaxy.
M81 & M82: Interacting Galaxies

Atomic Hydrogen Gas Surrounding M81 and M82

These Galaxies are Interacting: M81, M82, and NGC 3077 (located 10 million light years away from the Earth)

Gas Rich Mergers

Gas Rich Mergers and Disk Galaxy Formation

Galaxy formation simulations created at the

N-body shop

made of quantity galaxies

key: gas - green new stars - blue old stars - red
credits:
Fabio Governato (University of Washington)
Ajayon Brooks (University of Washington)
James Mihos (McMaster University)
Tom Quinn (University of Washington)
Chris Brook (University of Washington)
Simulation run on Columbia (NASA Advanced Supercomputing)
contact: fabio@astro.washington.edu

http://www.astro.washington.edu/users/fabio/movies/Merger.mpg
Making Elliptical Galaxies from Spiral Galaxies.

Modeling such collisions on a computer shows how galaxies at the center of a cluster merge to form a giant elliptical galaxy. Question – where does the gas go? Is it used up in violent star formation. Or are such mergers “dry” – i.e. most of the molecular gas is gone. http://galaxydynamics.org/galacticencounters.html

Collisions may explain why elliptical galaxies tend to be found where galaxies are closer together.

Giant elliptical galaxies at the centers of clusters seem to have consumed a number of smaller galaxies.

Shells of stars observed around some elliptical galaxies are probably the remains of past collisions.
What have we learned?

- How do we observe the life histories of galaxies?
  - Deep observations of the universe are showing us the history of galaxies because we are seeing galaxies as they were at different ages.

- How did galaxies form?
  - Our best models for galaxy formation assume that gravity made galaxies out of regions of the early universe that were slightly denser than their surroundings. The gas collapsed to form galaxies. Galaxies continue to cannibalize smaller galaxies and draw in gas as they evolve.

- What determines the morphologies of galaxies?
  - Gravity plus angular momentum leads to the formation of large disk galaxies (spiral galaxies) by pulling in gas from the cosmic web and through cannibalizing smaller galaxies.
  - Collisions and mergers can play a major role in galaxy growth and can induce starbursts. It is still being argued how important they are in spiral galaxy formation.
  - Mergers can transform spiral galaxies into an elliptical galaxy – thus elliptical galaxies are typically found in the centers of galaxy clusters. Collisions thought to be very important in elliptical galaxy formation.

- What are starbursts?
  - A starburst galaxy is transforming its gas into stars much more rapidly than a normal galaxy, can be triggered by interactions between galaxies.
  - Winds from starbursts may blow out gas and limit star formation.

How do Black Holes Affect Galaxy Evolution?

QUASAR stands for QUASi-stellar radio source.

First identified as bright radio sources - without visible counterparts

In 1962 Maarten Schmidt identified a “star” coincident with the radio source and obtained a spectrum. He discovered it was not a star, and named it a QUASAR.

The highly redshifted spectra of the quasars indicated large distances (billions of light years!)

From brightness and distance we find that luminosities of some quasars are \( >10^{12} L_{\odot} \)

Variability shows that all this energy comes from region smaller than solar system
Quasars powerfully radiate energy over a very wide range of wavelengths, indicating that they contain matter with a wide range of temperatures.

**Thought Question**

What can you conclude from the fact that quasars usually have very large redshifts?

A. They are generally very distant
B. They were more common early in time
C. Galaxy collisions might turn them on
D. Nearby galaxies might hold dead quasars

**What are QUASARS?**

If the center of a galaxy is unusually bright we call it an **active galactic nucleus or AGN**.

Quasars are the most luminous examples of AGN that were found only in the early universe.

Are found at distances of 12.7 billion light years to 800 million light years.

None are found near the Milky Way.

**Thought Question**

What can you conclude from the fact that quasars usually have very large redshifts?

A. They are generally very distant
B. They were more common early in time
C. Galaxy collisions might turn them on
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*All of the above!*
Radio galaxies contain active nuclei shooting out vast jets of plasma that emits radio waves coming from electrons moving at near light speed.

The lobes of radio galaxies can extend over hundreds of millions of light years.

Characteristics of Active Galaxies

- Luminosity can be enormous (>10^{12} L_{\text{Sun}})
- Luminosity can rapidly vary (comes from a space smaller than solar system)
- Emit energy over a wide range of wavelengths (contain matter with wide temperature range)
- Some drive jets of plasma at near light speed
An active galactic nucleus can shoot out blobs of plasma moving at nearly the speed of light.

Speed of ejection suggests that a black hole is present.

Accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars.

Energy from a Black Hole

- Gravitational potential energy of matter falling into black hole turns into kinetic energy.
- Friction in accretion disk turns kinetic energy into thermal energy (heat).
- Heat produces thermal radiation (photons).
- This process can convert 10-40% of $E = mc^2$ into radiation.
- QUASARs may swallow the equivalent of 10 stars per year to generate their power.

Jets are thought to come from twisting of magnetic field in the inner part of accretion disk.
Orbital speed and distance of gas orbiting center of M87 indicate a black hole with mass of 3 billion $M_{\text{Sun}}$

Many nearby galaxies – perhaps all of them – have supermassive black holes at their centers.

These black holes seem to be dormant active galactic nuclei.

All galaxies may have passed through a quasar-like stage earlier in time.

Galaxies around quasars sometimes appear disturbed by collisions. These may be AGN which are being fueled by gas funneled into the center of galaxies in these collisions.

These events were much more frequent when galaxies were closer together, thus Quasars were much more common in the past.

Mass of a galaxy’s central black hole is closely related to mass of its bulge.

Development of central black hole must be somehow related to galaxy evolution.
What have we learned?

- What are quasars and active galactic nuclei?
  - Active galactic nuclei are very bright objects seen in the centers of some galaxies, and quasars are the most luminous type.

- What is the power source for quasars and other active galactic nuclei?
  - The only model that adequately explains the observations holds that supermassive black holes are the power source.

- Do supermassive black holes really exist?
  - Observations of stars and gas clouds orbiting at the centers of galaxies indicate that many galaxies, and perhaps all of them, have supermassive black holes.

- Are black holes important in galaxy formation?
  - There is a relationship between bulge size and black holes size.

Epilogue:
Formation of galaxies with feedback from galactic winds (from supernovae and black holes)

http://luca.as.arizona.edu/~oppen/IGM/general.html