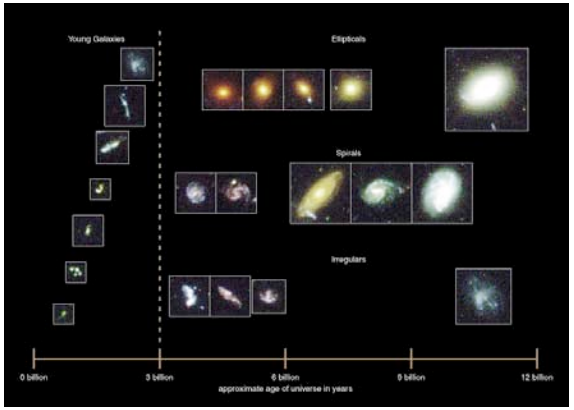
Galaxy Evolution…

- …is the study of how galaxies form and how they change over time.
- As was the case with stars…
  - we can not observe an individual galaxy evolve
  - but we can observe different galaxies at various stages of their life cycles



- This is made easier by virtue of lookback time.
- We can plot a "family album" for each type of galaxy.
- The greater the redshift...
  - the younger the galaxy!

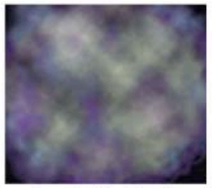
Modeling Galaxy Formation

- With our current telescope technology…
  - we are unable to see back to the time when galaxies first formed
  - we must rely on theoretical (computer) models to describe how galaxies formed
- The following assumptions are made when constructing these models:
  1. the Universe was uniformly filled with Hydrogen & Helium gas for the first million years after the Big Bang (called **Dark Ages**)
  2. this uniformity was not quite perfect; some regions of the Universe were slightly denser than others (called **Primordial Fluctuations**)
- All of the H & He gas expanded with the Universe at first.
  - after about a billion years, the denser regions slowed down and began to collapse under self-gravity (our familiar **gravitational collapse**!)
  - the collapsing gas became **protogalactic clouds**

Modeling Galaxy Formation

- As a protogalactic cloud collapses, its gravitational potential energy heats up gas and then is "radiated away".
  - Gas gets colder as radiation takes energy away with it from the cloud. **Energy Stolen**!
  - stars begin to form in the coldest, molecular cloud cores
  - same physics as when ionized and atomic ISM condenses into molecular clouds and forms star in the star-gas-star cycle of the Milky Way
- Conservation of angular momentum
  - caused remaining gas to rotate faster and flatten…star formation continues in disk
  - with no gas left in the spheroid, no new stars are formed and only old, red stars remain

Modeling Galaxy Formation



(a) A protagalactic cloud contains only hydrogen and helium gas.

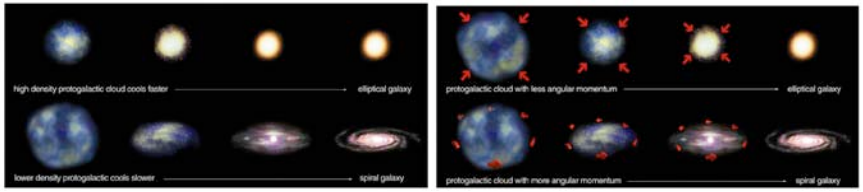
(b) Halo stars begin to form as the protogalactic cloud collapses.

(c) Conservation of angular momentum ensures that the remaining gas flattens into a spinning disk.

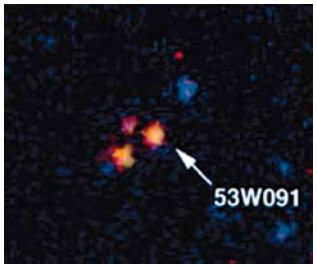
(d) Billions of years later, the star–gas–star cycle supports ongoing star formation within the disk. The lack of gas in the halo precludes further star formation outside the disk.

What Determines Galaxy Type?

- *Not Solid Yet*, but we can explore two options:
  - the initial conditions of the protogalactic cloud; i.e. destined from birth
  - later interactions with other galaxies; i.e. a life-altering conversion
- Two plausible explanations regarding the birth properties of the protogalactic cloud:
  - Protogalactic spin…the initial angular momentum determines how fast the cloud will form a disk before it is completely turned into stars
  - Protogalactic cooling…the initial density determines how fast the cloud can form stars before it collapses into a disk



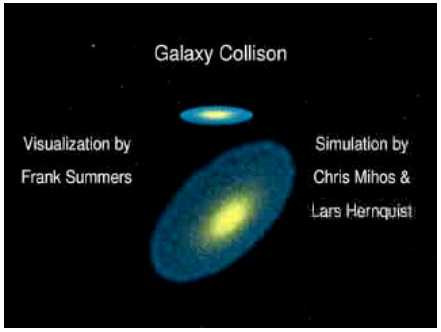
What Determines Galaxy Type?



- This giant elliptical provides evidence for the protogalactic cooling explanation.
  - it is very distant (young) and very red, even accounting for redshift
  - white and blue stars are missing
  - Explosive, instantaneous starformation occurred at very early times
  - star formation has ceased very early in the galaxy's history
  - no gas will be left to form a disk
- Galaxy Interactions
  - when two spiral galaxies collide
  - tidal forces randomize the orbits of stars
  - gas either falls to the center to form stars
  - or it is stripped out of the galaxies
  - the disk is removed
- The galaxy becomes an elliptical.

When Spirals Collide

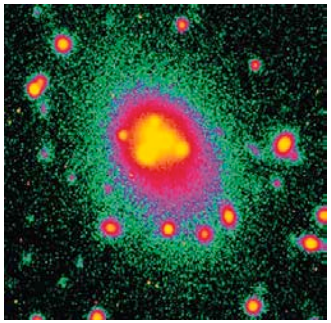
Model of Galaxy Interaction



Movie. Click to play.

The Role of Galaxy Clusters

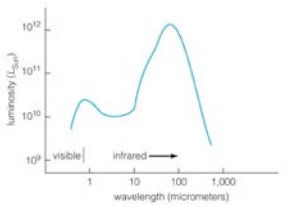
- Galaxy clusters provide evidence that some galaxies are shaped by interactions:
  - elliptical galaxies are more common in cluster centers
  - collisions will occur more often in crowded cluster centers
  - **central dominant (CD) galaxies** are gigantic ellipticals found in cluster centers
  - they grow large by consuming other galaxies



- These CD galaxies often contain tightly bound clumps of stars.
- They are probably the leftover cores of galaxies which were *cannibalized* by the CD.
- Some CD galaxies are more than 10 times as massive as the Milky Way.
  - making them the largest galaxies in the Universe!

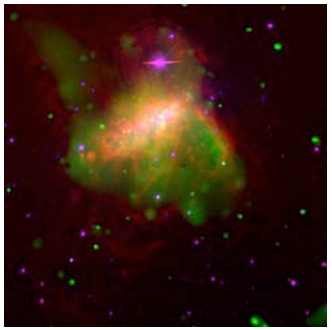
Unusual Galaxies I: Starburst Galaxies

- An average of 1 new star per year forms in the Milky Way.
- We observe some galaxies with a star-forming rate of 100 per yr.
- We call them **starburst galaxies**.
  - infrared image of Arp 220 ⟶



- They look normal in visible light (10^{10} $L_{\odot}$ like Milky Way).
  - but they are 100 times brighter in infrared light
  - molecular clouds block the visible/UV light from new stars
  - dust in the clouds absorbs this light and reemits the energy as infrared light
- With such a fast rate of star formation, the galaxy will use up its gas..
  - in only a few 100 million years
  - starburst phase is temporary in light of fact that galaxy is billions of years old

Starburst Galaxies



- 100 times star-forming rate also means 100 times supernova rate.
  - ISM is full of hot superbubbles
  - supernovae continue to pump energy into the superbubbles
- The hot (10^{7}–10^{8} K) gas breaks out
  - and a **galactic wind** streams from galaxy
  - NGC 1569 (X-ray–green; visible–red)

- Starburst galaxies are irregular in type.
  - lots of dusty molecular clouds and usually two distinct clumps of stars
- This suggests that the starburst is caused by the collision of two spiral galaxies.
  - although a close encounter could trigger starburst, e.g. Large Magellanic Cloud

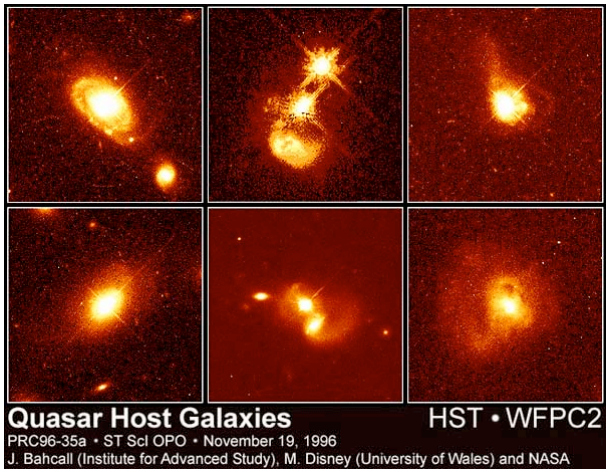
Unusual Galaxies II: Quasars

- In the early 1960s, Maarten Schmidt identified the radio source 3C 273 with a faint, **blue star**.
  - the "star's" spectrum displayed emission lines
  - the wavelengths of these lines matched no know element
- Schmidt realized that the emission lines belonged to Hydrogen, but they were highly redshifted.
- This object is very (> 10^{10} light years) far away.
  - But, what? How come we can see "stars" that distant??
  - other such objects were subsequently discovered
  - they were called *quasi-stellar radio sources* or **quasars** for short
- The farther away we look out in distance, the farther back we look in *time*!
- Quasars exist only in the *early* Universe!

Quasars…

- are extremely luminous.
  - 10^{40} watts
  - 1,000 brighter than the entire Milky Way Galaxy
- are extremely variable.
  - luminosity changes < 1 hour
  - implies they have **a very small size**
- have redshifted emission lines.
  - greatest is 6.8 times the rest wavelength

Hubble ST shows us that quasars do live in galaxies…they are Active Galactic Nuclei!



Unusual Galaxies III: Active Galactic Nuclei (AGN)

- Seyfert Galaxies
  - spiral galaxies with an incredibly bright, star-like center (nucleus)
  - they are very bright in the infrared
  - their spectra show strong **emission** lines

Circinus

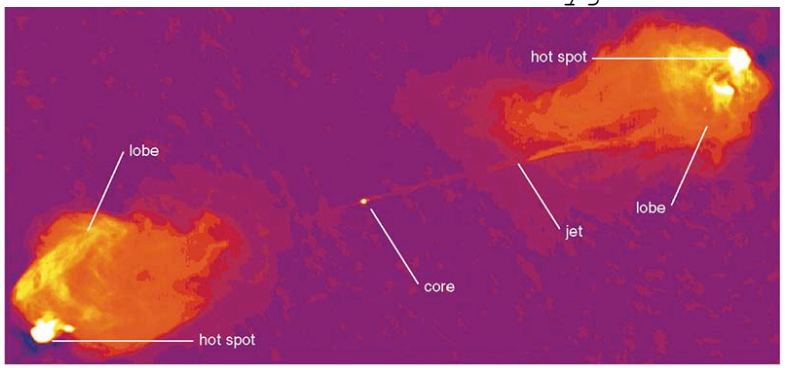
The luminosity can vary by as much as the entire brightness of the Milky Way Galaxy!!

Active Galactic Nuclei

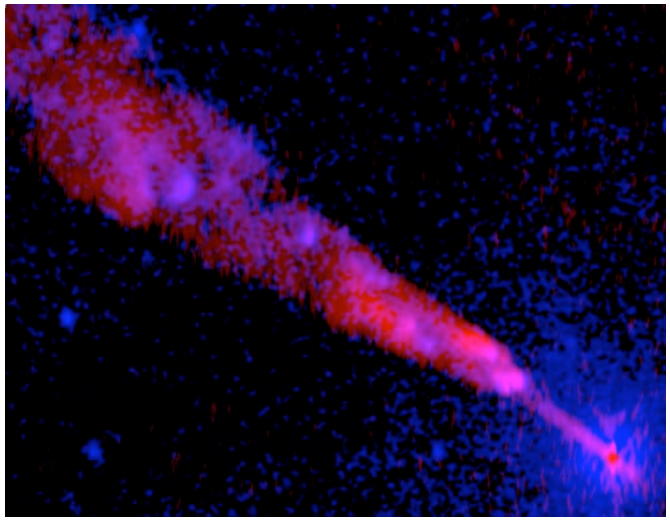
Radio Galaxies

- galaxies which emit large amounts of radio waves
- the radio emission come from *lobes* on either side of the galaxy; **not** the galaxy itself

Cygnus A



X-ray/Radio Image of Centaurus A



X-ray is blue; radio is red

What powers these Active Galactic Nuclei?

Hubble Space Telescope gave us a clue

NGC 4261

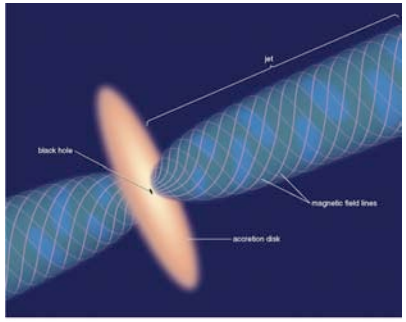
Active Galactic Nuclei

- The energy is generated from matter falling onto a **supermassive black hole**…
  - 1.2 x 10^9 $M_\odot$ for NGC 4261
  - 3 x 10^9 $M_\odot$ for M87
- …which is at the center (nucleus) of the galaxy.

- Matter swirls through an accretion disk before crossing over the event horizon.
- Gravitational pot. energy lost
  - = mc^2 the mass energy
  - 10 – 40% of this is radiated away
- Process is very efficient for generating energy.

Active Galactic Nuclei

- Formation of the Jets
  - magnetic fields in accretion disks are twisted
  - they pull charged particles out of the disk and accelerate them like a slingshot
  - particles bound to magnetic field; focused in a beam



- Orientation of beam determines what we see:
  - if beams points at us, we see a quasar
  - if not, the molecular clouds/dust of the galaxy block our view of the nucleus
  - so we see a radio galaxy
  - lobes are where jets impact intergalactic medium

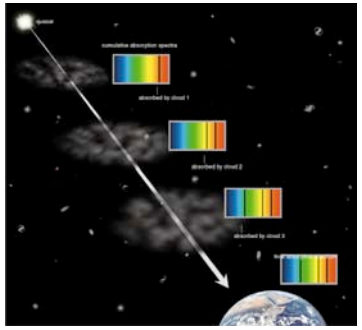
Active Galactic Nucleus

- Quasars are observed in the distant past (high redshift).
  - this implies that many galaxies had bright nuclei early in their histories, but those nuclei have since gone dormant
- So many galaxies which look "normal" today have supermassive black holes at their centers.
  - such as *Andromeda* and Milky Way?
  - Yes, probably.

Movie. Click to launch.

A "Forest" of Absorption Lines

- QUASAR AS A LIGHT HOUSE: As light from a quasar travels toward Earth…
  - it passes through intergalactic Hydrogen clouds and galaxies
  - each cloud leaves absorption lines at a *different* redshift on quasar spectrum
  - this is the only way we can "observe" protogalactic clouds



- Analysis so far has shown:
  - H lines at high redshift are broader than those at low
  - implies that the gas content of clouds/galaxies is higher in the early Universe
  - more heavy element lines are seen at low redshift
  - supports element enrichment of galaxies by supernovae
- These data support our models of galaxy evolution

Next Stop: Cosmic Web

- November 2
  - Clusters of Galaxies and Beyond (Chapter 22)
- November 4
  - Dark Matter and Dark Energy (Chapter 22)

- Quiz on November 9
- Homework handed out on November 9 (due Nov 16)