2022 12 26 Galaxy II

2022년 12월 25일 일요일 오후 10:07

Back to Galaxies

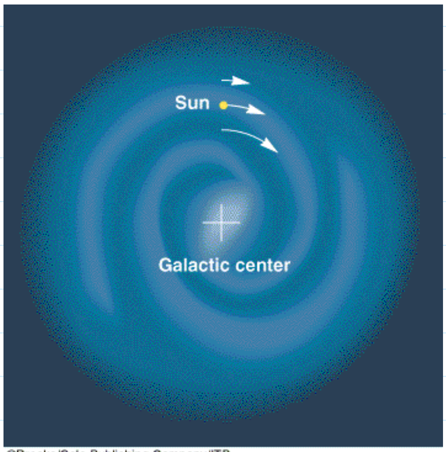
Spiral Galaxies

The Motion of Stars in the Sky
- All of the stars move.
- The motion is very slow, so it is difficult to detect.
- Best modern data comes again from Hipparcos measurements
- The fastest moving star on the sky is Barnard's star (RA269.4, Dec4.5)
  - A line joining your eyes and the star defines the **line-of-sight** direction.
  - The plane perpendicular to the line-of-sight is called the **plane of the sky**.

- The component of the velocity in the line of sight can be measured by the Doppler shift of the light:
  $v_r = c \times \frac{\delta\lambda}{\lambda}$
  - **Stars**: Doppler shifts of stellar absorption lines
  - **Ionized Gas**: emission lines from HII regions
  - **Atomic Hydrogen (HI) Gas**:
    - Cold H clouds emit a **radio emission line** at a wavelength of **21-cm**
    - Can trace nearly the entire disk beyond where the stars have begun to thin out.

- The component of the velocity in the plane of the sky is called proper motion.
  Usually term **proper velicty** refers to **angular velocity**.
- The proper motion of stars causes the constellations to change their shape.
- Measure proper motion by measuring the angular change in position of the star over some period of time.

Motion of Stars in the Milky Way
- In the 1920's, two astronomers, Jan Oort and Bertil Linblad measured the velocities of stars near the Sun.
- and found that the stars and our Sun all orbit around the galactic centre.
- Today's accepted value for the distance between the centre of the galaxy and the Sun is **8 kpc**, although there could be about 10% error in this measurement.



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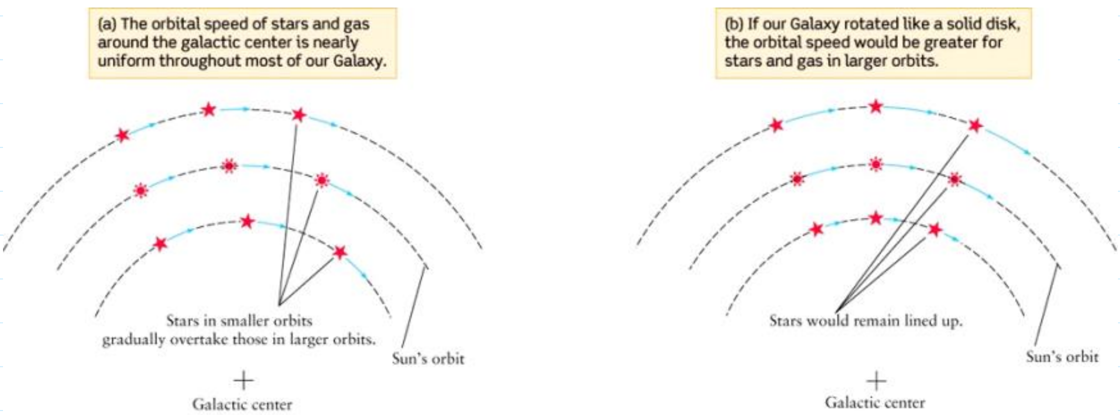
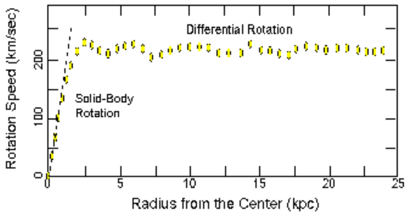


- The motion of the stars around the galactic centre is not rigid body rotation.

Actually, linear velocity **V**, not angular velocity of stars, seems to be the same
$V = \omega R = const \rightarrow \omega = const/R$

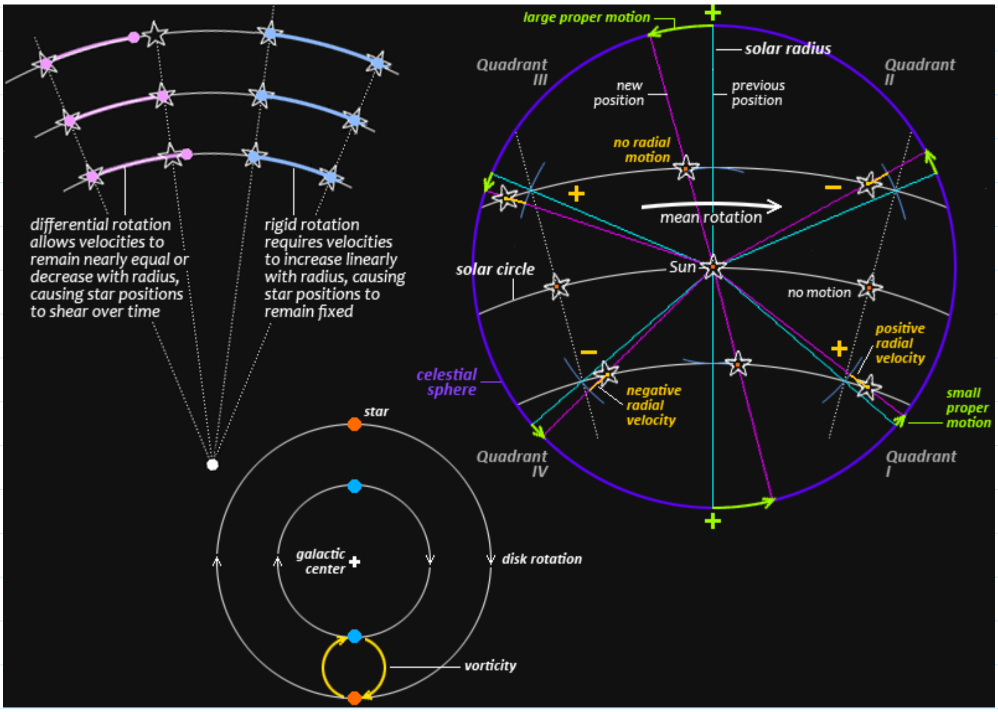


Inner Parts: Solid-Body Rotation

- Orbital speed increases with radius.   Rise from Zero to few 100 km/sec
- Orbital period is constant.

Outer Parts: Differential Rotation

- Orbital speed is nearly constant with radius at a few 100 km/sec
- Orbital period increases with radius



출처: <http://www.handprint.com/ASTRO/galaxy.html>

- The motion of the stars is
differential rotation: the stars closer to the centre have a shorter orbital period than the stars further out.

Circular Motion of the Sun

- The velocity of a star moving in a circle around the galactic centre is
  $V = 2\pi R/P$
  where
  R = 8.0 kpc=distance from the galactic centre to the star (Sun)
  P = orbital period of the star.
  V = 220 km/s for the sun:
- the Sun's orbital period.
  $P = 2\pi R/V = 2\pi\, 8.0 \times 3.086 \times 10^{16}$ km/(220 km/s) = 7.1×10^{15} s = 2.2×10^{8} years.
  The Sun takes 220 million years to make one full orbit.
- The Sun is 4.5 billion years old.
- The number of orbits made by the Sun since it was born is:
  Number of orbits = 4.5×10^{9} / 2.4×10^{8} = 19 orbits.

Peculiar Motion of the Sun

- The motion of the Sun is approximately a circle around the galactic centre.
- There is a small deviation from this motion which is called peculiar velocity.
- The Sun's peculiar velocity is 20 km/s at an angle of about 45 ° from the galactic centre towards

the constellation Hercules.

The Motion of other Stars

- The stars move approximately on circular orbits about the galactic centre along with small peculiar velocities.
- For most stars, the velocities range 200~250 km/s.
- The plot of velocity versus distance from the centre of the galaxy is called a **rotation curve**.
- The most important feature of the rotation curve is that the velocity of stars far away from the galactic centre stays at a large value near 220 km/s.
- This is not what was expected, because there is almost no stars at 16kpc, where we still see 220 km/s rotational velocity.

According to Kepler's Laws, the velocity on circular orbit that encompasses all gravitation mass is

$$V(R)=\sqrt{\frac{GM(R)}{R}} \quad \text{or} \quad \omega(R)=\sqrt{\frac{GM(R)}{R^3}}$$

i.e

$V \sim 1/\sqrt{R}$ if M(R) only "in" (M=const (ρ=0) "out")

$\sim$ const if M(R)($\sim\rho R^3$)~R or $\rho\sim 1/R^2$

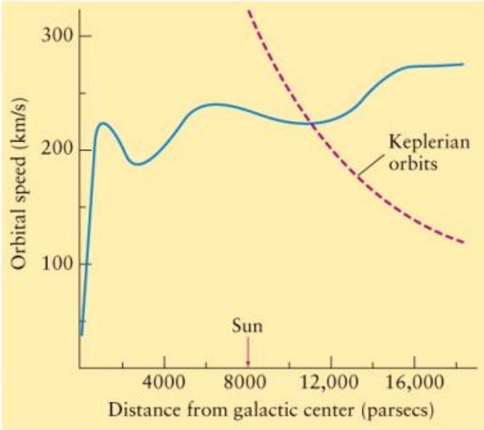
$\sim$ R if $\rho\sim$const

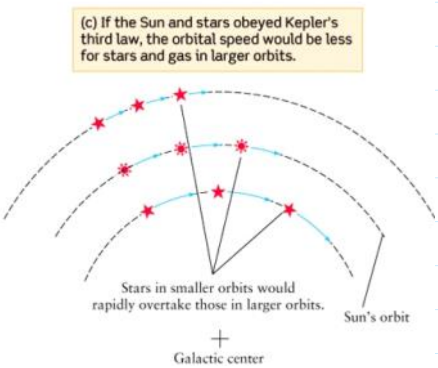
or angular velocity should behave as

ω(R)~$1/\sqrt{R^3}$ if M(R) is concentrated inside

~1/R if M(R)($\sim\rho R^3$)~R or $\rho\sim 1/R^2$

~const if M(R)($\sim\rho R^3$)~R^3 or $\rho\sim$const





- Most of a galaxy's light comes from the central region.
- If most of the mass of the galaxy is concentrated in the centre, then stars further from the centre would move at a slower velocity than stars closer to the centre.

Ex) The solar system

b Sb (M81)

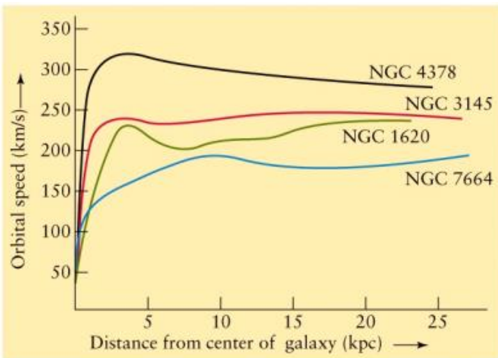
Rotation Curves of Other Spiral Galaxies

- In spiral galaxies the velocities of stars far from the centre are much faster than expected.
- This suggests that there is more mass in the galaxy than what we can see.

$\rho\sim$const inside

$\rho\sim 1/R^2$ outside

- We call this mass **dark matter** since we can't see it.



Dark Matter

- Estimate the mass of the Milky Way by using Kepler's laws of motion.
- The Sun only feels the gravitational attraction from the parts of the galaxy which are closer to the centre than the Sun is.
- The gravitational attraction between the Sun and the rest of the galaxy is as though the inner part of the galaxy were compressed to a point at the centre of the galaxy.

- Kepler's law for motion in the galaxy:
$$M_{galaxy} = \frac{4\pi^2}{G}\frac{R^3}{P^2} = \frac{RV^2}{G}$$
- **Example:** Milky Way

  At the Orbit of the Sun:

  R=8 kpc, V_{rot}=220 km/sec   gives: M = 0.9×10^{11} M_{sun} inside R=8 kpc

  Gas Cloud in Outer Disk:

  R=16 kpc, V_{rot}=275 km/sec   gives: M=2.8×10^{11} M_{sun} inside R=16 kpc
- When we look at a star at double the distance from the galactic centre, we find that the mass contained within its orbit is double the mass within the Sun's orbit.
- However, when we look at this region, it looks like it has much less mass than this.
- Judging from the large circular velocity of stars far from the galactic centre, we can only see about 10% of the Milky Way's mass!

The Dark Halo

- It seems from the motion of stars that most of the Milky Way's mass is invisible.
- This dark matter seems to be distributed in a sphere around the disk of the galaxy.
- This sphere is called the dark halo.
- The only visible objects in the dark halo are a few globular clusters and a few stray stars.
- Neither the globular clusters nor the stars have enough mass to account for the halo's mass.

Possible Candidates for Dark Matter

1. Dust and cold hydrogen clouds: We know that dust blocks out light and that cold hydrogen doesn't give off much visible light.
   - However, dust will emit infrared light, so our infrared telescopes show where the dust is and there isn't enough.
   - hydrogen clouds emit 21 cm wavelength radio waves which we would detect if they were there.
   - No evidence for significant amounts of dust or H in the halo.
2. MACHOs: MAssive Compact Halo Objects = dim objects like Jupiter-like planets, white dwarfs, neutron stars and black holes.
   - A number of these have been discovered when they pass in front of background stars and "lense" them gravitationally.
   - These MACHOs can account for approximately 10% of the dark matter in the halo.
3. WIMPs: Weakly Interacting Massive Particles = particles which don't interact well with others
   - An example of a Weakly Interacting Particle is the neutrino.
   - A neutrino can pass through a thousand light-years of lead before interacting with a lead atom.
   - Hundreds of billions of neutrinos pass through every square inch of your body per second, all coming from the Sun without you noticing.
   - Because the neutrino interacts very weakly, it is very difficult to detect.
   - If there is some other particle similar to the neutrino, but with a higher mass, it would be a WIMP.
   - The WIMPy hypothesis is that the dark halo is filled with WIMPs of some unspecified type.
   - Nobody has ever detected any of these exotic particles (except for the neutrino).

Spiral Structure

Observations of other Spiral Galaxies show:

- Stars are found with equal density everywhere in the disk.
- Young type O and B stars, however, are only found in the spiral shaped arms.
- Type O stars are about 10,000 times more luminous than the Sun, so the light from these stars dominates the picture of a spiral galaxy, making it look like a spiral.
- To summarize, The spiral arms are regular, spiral-shaped patterns of hot stars, star clusters, gas & dust.
- The concentration of dark dust lanes and cool molecular clouds (the birthplace of stars) is largest in the spiral arms.
- Hydrogen regions which glow red after being ionized by young O

and B stars are mainly found in the spiral arms.

Conclusions:

- Spiral arms are the sites of star formation.
- After being born in a spiral arm, a star moves out of the arm.
- Old stars (like the Sun) need not be in an arm and won't usually be found inside of their birth arm. (It can complete about ~50 orbits around the Galaxy before becoming a white dwarf.)
- Type O and B stars have very short life-spans, only about 10 – 100 Myr, so they don't have time to move out of their birth arm. (will only move ~10-20° along their oribts before dying)
- Spiral Arm Tracers: The followings are rarely if ever found outside of spiral arms.
  - O &B Stars
  - HII Regions (star forming regions lit up by hot O & B stars)
  - Giant Molecular Clouds
  - Hydrogen Gas and Dust Clouds

Mapping the Spiral Structure of the Milky Way

- Since spiral arms are the location of star-birth, we can map the location of the arms by mapping the location of O-B stars and ionized hydrogen regions.
- This works for small distances (out to about 3 kpc) since the light from these objects is mainly visible light which is obscured by dust.
- For larger distance mapping of arms, we should look for radio waves emitted by gas in the arms which are not obscured by dust.
- Neutral Hydrogen atom and Carbon Monoxide emit radio waves.
- H and CO is concentrated in the spiral arms, so if we can find the distance out to H and CO clouds we can map the structure of the spiral arms.

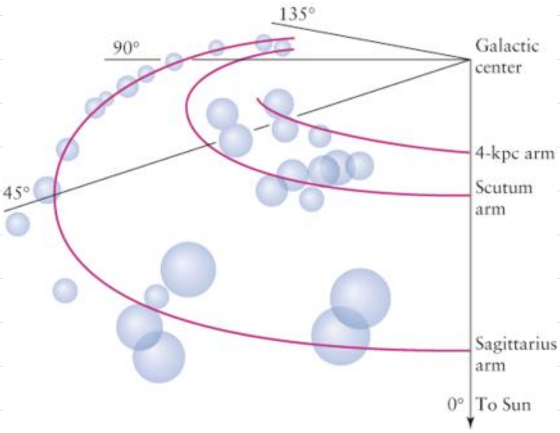


Figure 18-21

Neutral Hydrogen Maps

- Neutral Hydrogen atom at rest emits a photon with 21 cm wavelength when the electron spin flips.
- If the Hydrogen cloud is moving within our line-of-sight, the emission line will be either redshifted or blueshifted.
- We can determine the radial velocity (line-of-sight velocity) of H clouds.
- Since we already know the rotation curve for our galaxy, we can use trigonometry to reconstruct the locations of the spiral arms.

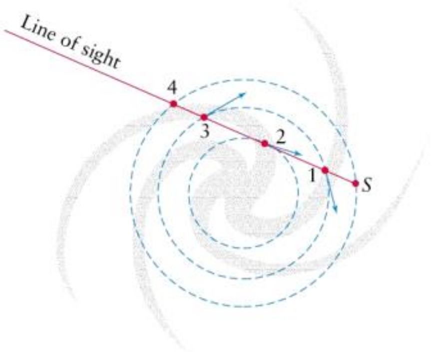
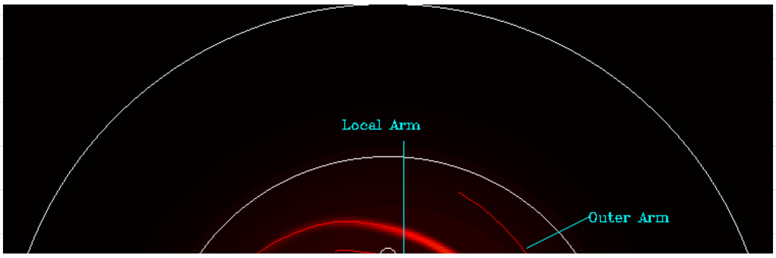


Figure 23-13

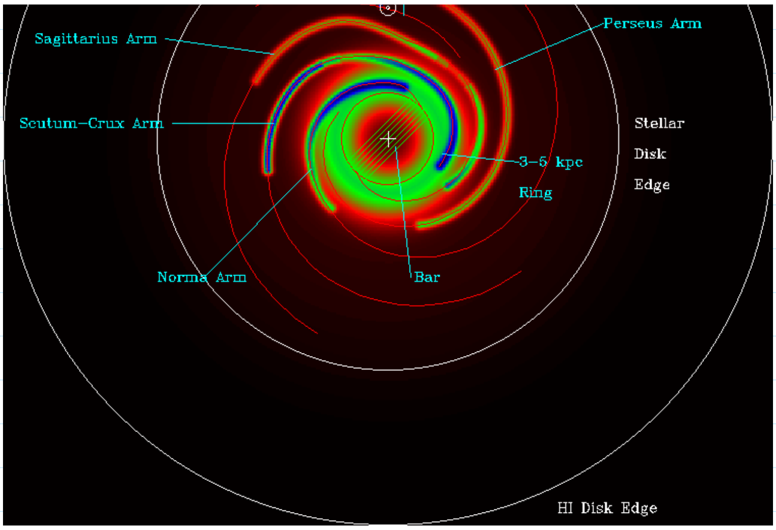
Actually, one needs to combine different observation to be more certain

Schematic Diagram of Spiral Structure in the Milky Way

- Most stars are within a circle of radius 15 kpc from the centre.
- Most Hydrogen is found



within a circle of radius 25 kpc from the centre.

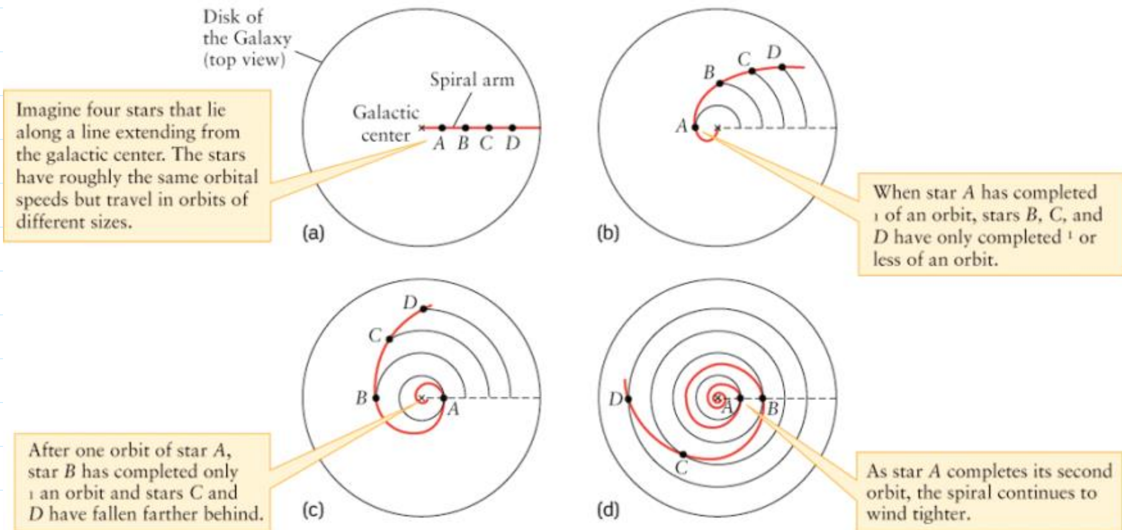


What is the origin of spiral arms in spiral galaxies ?

First of all:

Spiral arms cannot be made from the same material throughout the galaxy history.

Reason -- winding problem



- Galaxy like Milky Way made ~200 revolutions through its lifetime. Material spirals arms would be very tightly wound

Density-Wave Theory of Spiral Arms

- A spiral arm is just a region where the density of gas is little bit higher than average.
- This spiral arm is called a density wave and travels slowly in a circular motion around the galactic centre.
- Interstellar dust and gas move in circles at a much larger speed and collide with the density
- wave.
- When the gas enters the density wave region, it is compressed and stars begin to form.
- The newly born stars continue to move at fast speeds and eventually leave the spiral arm.
- O and B type stars don't live for long, so they never move far from their birth arm.
- Lower mass stars live longer and have plenty of time to move to regions between the arms.
- Density wave move slower than stars, so stars, dust and HI catches up from behind, but new stars are born at the front of the wave.

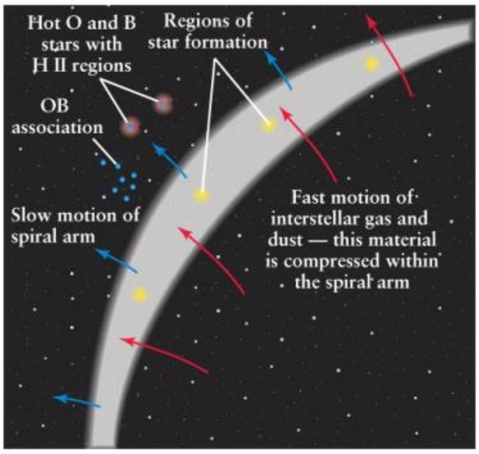
The Self-Propagating Star-Formation Model

M81 Grand Design galaxy

M101 "Pinwheel" flocullent galaxy

- **Grand design-like spirals** are result of the density waves.
- Much less regular, **flocculent spirals** may need a different mechanism.
- **Self propagating star formation** model works as follows
  - Star formation begins in some dense molecular cloud in the disk that does not yet have spirals
  - Radiation and stellar winds from first born stars compress matter around. Star formation is triggered in newly compressed regions.
  - Massive stars explode as supernovae, compressing gas and trigerring star formation in larger region
  - This cloud of newly formed stars is sheared by differential rotation looking like short spiral arms
  - Bright O and B stars are short lived, so during their lifetime the spiral does not wind much, and as birght stars die, disappear from view.
  - Somewhere else new star formation starts ...

출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect24/lecture24.html>



Galactic Collisions and Evolution

Key Ideas

I. Tidal Interactions between Galaxies:

Ia) Close Tidal Encounters

Splash encounters

II Galaxy-Galaxy Collisions

IIa) Starbursts induced by interactions

I. Mergers & Galactic Cannibalism

Fate of the Milky Way & Andromeda?

Elbow Room

Galaxies are large compared to the distances between them:

- Most galaxies are separated by only ~20 times their diameters.
- By comparison, most stars are separated by ~10^7 times their diameters.

Galaxies are likely to encounter other galaxies a few times over their histories.

Collisions

- The bigger an object is, the easier it is to collide with it.
- It is easier for a collision to occur if there is a large density of objects (in other words, lots of objects in a small volume).
- Consider two objects with the same radius R separated by a distance d.
- The probability of a collision in the time it take to fly over distance "d" is approximately $(R/d)^2$

Collisions between Stars : **very low probability for any collision**

- The distance between star systems is generally rather large compared to the size of the star.
- For instance: The Sun's radius is $R_{Sun} = 7 \times 10^5$ km.
- The distance to the nearest star system (Alpha Centauri) is about 1pc = 3×10^{13} km
- The distance between the Sun and our nearest neighbour is 4×10^7 times larger than the radius of the Sun.
- The chance that the Sun will collide with another star is very tiny.
- In a Globular Cluster stars are much closer to each other. A typical separation is 0.1 pc. This is still 4 million times larger than the Sun.
- Some stars (Red Supergiants) are much larger than the Sun. It is possible for a Supergiant to be 1000 x larger than the Sun. This provides a larger target than the Sun, but is still much smaller than the typical interstellar distances.

Collisions between Galaxies

- The distances between galaxies in a cluster or a group are relatively small compared to the sizes of the galaxies.
- For instance: The Milky Way's visible disk has a diameter of 30 kpc.
- The distance to the Large Magellenic Cloud (LMC) is about 50 – 60 kpc, no more than 2x the diameter of the Milky Way. (The LMC is only 7 kpc in diameter.)
- The distance to the Andromeda Galaxy is 770 kpc, only about 20x the diameter of the Milky Way.
- Collisions between galaxies in our Local Group are very likely.
- Most galaxies probably undergo at least one significant collision in their lifetimes. This is likely the future of our Milky Way when it collides with the Andromeda Galaxy.
- Andromeda and the Milky Way are moving towards each other with a relative velocity of 120 km/s. We will probably collide in about 6 billion years.

Galaxies in galaxy clusters and large scale Web

- Evolution of the structure in the Universe assembles small objects into the large ones.
- The motion under gravitational forces is not random, but leads to formation of galactic clusters with galaxies flowing into such concetration along filamentary web.
- Galactic interaction and mergers is not accident, but inevitable development.

Ex) The Virgo Cluster : the closest, rich cluster

(A rich cluster has more than 1000 galaxies in it.)

- The giant elliptical galaxy M87 at the centre of Virgo.
- Two other giant elliptical galaxies, M84 and M86 are in the upper-right-hand corner of the image.
- The diameter ≈ 3 Mpc, ∴ the galaxies are closer to each other on average than in the Local Group.
- Rich clusters are composed of mainly elliptical galaxies and lenticular galaxies. This suggests that **when galaxies collide, elliptical galaxies may result**.

Click the image for movie

Ex) The Giant Elliptical Galaxy M87

- At the centres of rich clusters lie giant elliptical galaxies.
- Giant elliptical galaxies are about 20 times larger than typical galaxies.
- The Giant elliptical galaxies may be the remains of many galaxy collisions occuring near the centre of a rich cluster.

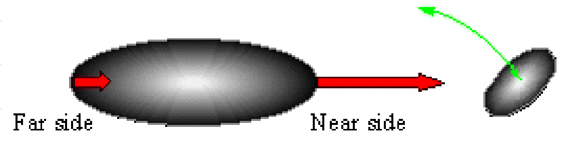
- M87 in Virgo has a diameter which is approximately 700 kpc.
- Remember, the distance between the Milky Way and Andromeda is about 700 kpc.

I. Tidal Interactions between Galaxies

- Because of the large sizes of the galaxies, two galaxies passing near each other raise **mutual tides**.
- These tides distort the shapes of the galaxies
- Gives rise to dramatic effects **without** direct collision.
- Many "peculiar galaxies" are interacting pairs.

Ia) Close Tidal Encounters

Raising Tides



Tidal stretching along the encounter line.

- Near side feels stronger gravitational pull from the companion
- Far side feels weaker gravitational pull and lags behind the near side.

Ex1) Whirlpool Galaxy Color Photo (17k), an example of a tidally interacting pair.
Credit: NOAO/AURA/NSF

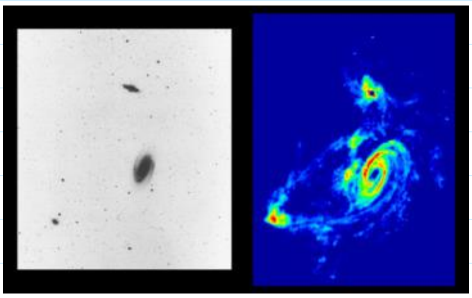
II. Galaxy Collisions

- When two galaxies collide, their dark matter, gas and dust clouds hit each other and can be flung out of the galaxies.
- This produces long tidal tails of matter
- This may produce large spiral arms.
- This can strip the galaxies of their gas.
- We see evidence of this when we view rich clusters and see evidence of hot **intracluster gas**.
- Intracluster gas is gas within the cluster (but not in a galaxy) which glows at X-ray wavelengths since the gas is over one million Kelvin.


Click the image for movie

II a) Tidal interaction: Starburst Galaxies

- When galaxies come close to each other but miss, the tidal deformation can trigger a burst of star formation.
- In this case a **star-burst** galaxy is formed.
- An example is the galaxy **M82** which seems to have narrowly missed colliding with the spiral galaxy **M81**.



Ex2) The M81 group of galaxies

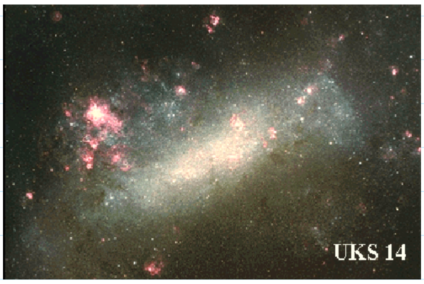
- This image shows the 3 galaxies in the M81 group.
- The left image shows the visible light where the galaxies

appear disconnected.
- The radio image (on the right) shows streams of hydrogen connecting the galaxies.
- M82 (the star-burst galaxy) is the upper-most galaxy.

(Pogge) Case of intense star formation in a galaxy.
- Millions of O & B stars greatly enhance the brightness of the galaxy.
- Exhausts the available gas in a few Myrs.
- Many supernovae can drive fast "superwinds" blowing out of the galaxies.

The most intense starbursts occur in violently interacting galaxy pairs.

Ex) Large Magellenic Cloud (LMC)



- The LMC has an irregular shape because the tidal force of the Milky Way is distorting it violently.
- The red ionized hydrogen regions and young, blue star clusters are evidence that star formation is occuring.
- The stars in the LMC have a very low metal content.
- This suggests that star formation in the LMC is a recent phenomenon, and is occuring because of the disruption caused by the Milky Way.

II b) Galaxy-Galaxy Collisions

Rare direct collisions have more dramatic effects:
- Tides raised are stronger, giving greater tidal distortion
- Tear off huge "Tidal Bridges" of stars & gas
- Stars pass through **without** colliding, but
- Gas clouds collide, leading to a massive **starburst** in the galaxy disks.

Ex3) [Image of "The Antennae", a directly colliding galaxy pair. Blue stars indicate sites of recent massive star formation, and dark dust clouds can be seen in silhouette against the inner parts of the two galaxies. OSU Galaxy Survey Image.]

III. Galaxy Mergers

If two colliding galaxies can dissipate enough orbital energy:
- Wreckage merges into a single galaxy.
- Gas clouds collide and form new stars.
- Some portion of the old stars are ejected from the system (carry off orbital energy).

Mergers may play a pivotal role in the formation ("assembly") of galaxies.
- There are many photographs of galaxies caught in the act of merging.
- One of the most famous is called The Antennae.
- The Antennae was formed from the collision of two similar sized spiral galaxies.
- These images of the Antennae show the star formation which is occuring as a result of the collision.
- Dust has been funnelled into the central regions of the galaxies causing them to look red.
- The regions of star-formation are blue from the glow of the hot type O and B stars.
- The scale bars on the right-hand images are 1,500 light-years across.

IV. Galactic Cannibalism

Slow encounter between a large & a small galaxy:
- Smaller galaxy gets torn apart by the tides from the larger galaxy.
- Gas and stars get incorporated into the larger galaxy.
- Nuclei of the galaxies slowly spiral together.

May be the way giant Ellipticals grow.
- When two galaxies merge, a larger galaxy results

Stellar Populations
- Surveys of stars in our galaxy (and others such as Andromeda) show that there are two main populations of stars.
- The two populations are called Population I and Population II.
- The populations are divided by chemical composition.
- Both populations are composed of mainly Hydrogen and Helium.

- Nuclei of the galaxies slowly spiral together.

May be the way giant Ellipticals grow.

- When two galaxies merge, a larger galaxy results.
- Over time, very large galaxies can form inside of rich clusters.
- When a small galaxy merges with a much larger galaxy, the larger galaxy effectively "eats" the smaller one.
- During a merger of this sort, the larger galaxy is unaffected by the collision, while the smaller one is disrupted.
- This process is called galactic cannibalism and probably explains the formation of giant ellipticals at the centres of rich clusters.

- The two populations are called Population I and Population II.
- The populations are divided by chemical composition.
- Both populations are composed of mainly Hydrogen and Helium.
- The main difference is in the fraction of heavier elements, such as Carbon, Oxygen, Iron, etc. (In Astronomy, all elements heavier than Helium are called metals.)

Population I

- Population I stars are stars with a high abundance of metals.
- The Sun is a Population I star.
- Population I stars include young type O and B main sequence stars.
- Since O and B stars are bluish in colour and are the most luminous types of stars, their light tends to dominate any group of stars. This makes groups of Pop I stars to appear somewhat blue in colour.
- Poplulation I stars are mainly found in the disk of the galaxy.

Population II

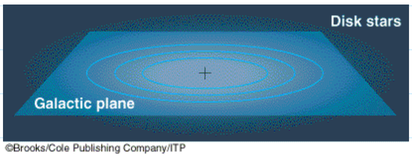
- Population II stars are stars with a low abundance of metals.
- The heavy elements are only about 3% as abundant as in the Sun.
- Only older type K and M main sequence stars, as well as red giants are part of Pop II.
- These stars are all red in colour.
- Pop II stars are generally found in the central bulge of the galaxy, the globular clusters (in the halo) and in stray stars in the spherical halo.

Stellar Evolution and the Populations

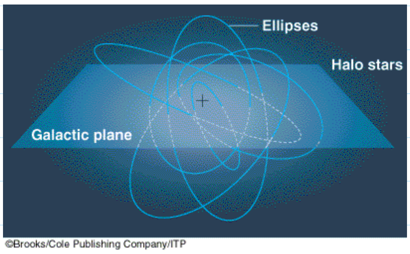
- The two types of populations can be understood if the galaxy was initially composed of only Hydrogen and Helium.
- The Milky Way probably formed 10 – 15 billion years ago.
- The first stars which formed had almost no heavy elements. These will be the Pop II stars.
- Over the course of the first 5 billion years the high mass stars (Type O to type F) in the first generation will have evolved off of the main sequence.
- These stars will either evolve into planetary nebulae and white dwarfs or explode in supernovae.
- Either type of evolution will enrich the interstellar medium with higher mass elements.
- After 10 billion years, only the low mass main sequence star (K and M) will still be burning Hydrogen.
- Today, we would only expect to see type K and M main sequence stars as members of Pop II.
- The population I stars (like the Sun) form from the remains of the older stars and have more Carbon, Oxygen and Iron than the previous generation.
- Within the disk of Pop I stars, there is a gradient of heavy element abundance. The highest fraction of heavy elements are in the centre and the metals decrease outwards.

Galactic Evolution

- The location of Pop I and II stars provides some clues about the evolution of the Milky Way.
- The oldest stars (Pop II) occur mainly in the spherical halo and in the central nuclear bulge.
- The youngest stars (Pop I) are mainly seen in the galactic disk.
- In addition, the disk stars mainly move in circles around the galactic centre, and are confined to the disk.
- Stars in the spherical halo orbit the galactic centre, but on elliptical orbits which are not confined to the disk.
- Stars in the central bulge move in randomly oriented orbits within the bulge.



Motion of Pop I stars



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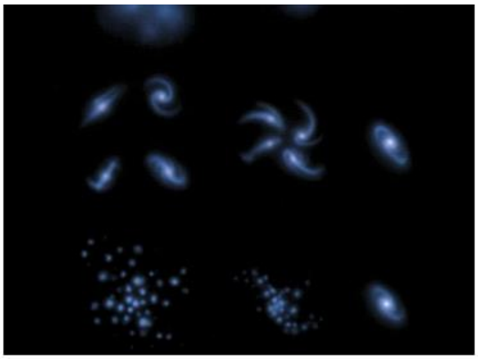
Motion of Pop II stars

A Possible History of the Milky Way

1. Either one large spherical gas cloud, or a number of

smaller gas clouds started to form stars.
   - Star formation took place through-out the whole cloud(s).
   - The original cloud is mainly H and He.
2. If smaller clouds exist they merge with each other to form a larger cloud. The whole system slowly begins to collapse.
   - Any small rotation of the original cloud(s) is amplified during the collapse due to angular momentum conservation.
   - The slow gravitational collapse will tend to produce a region of higher stellar density near the centre.
   - The angular momentum will flatten the distribution of gas.
   - The old stars left behind in the halo will have orbits similar to their orbits before the collapse.
3. In the disk of gas which rotates rapidly, a second generation of stars can form.



출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect25/lecture25.html>

The Milky Way & Andromeda

The Milky Way (us) and Andromeda are perhaps on a collision course.

- Moving towards each other at ~120 km/sec
- In ~3-4 Gyr, they will have a close encounter
- Tidally distort & merge after ~1-2 Gyr

Eventually, only 1 galaxy would remain behind, most likely an Elliptical galaxy.

This idea is controversial: it depends on knowing the tangential motion of the Milky Way relative to Andromeda, which cannot be measured reliably until the next generation of astrometric satellites. [Coincidentally, the collision timescale quoted above is also the timescale on which the Sun will be evolving away from the Main Sequence if the scenario described above unfolds on the timescales indicated. See John Dubinski's The Metamorphosis of the Local Group page for more details.]

Redshifted Galaxies

Redshifted Spiral Nebulae

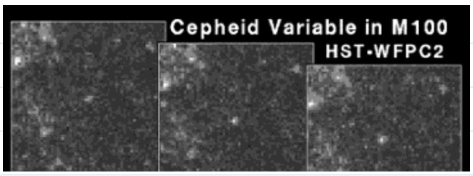
- 1914 – Vesto Slipher examined the spectra of 15 spiral "nebulae" and found that 11 out of 15 had redshifted spectral lines, meaning that the "spiral nebulae" were moving away from the Earth.

Redshifted Galaxies

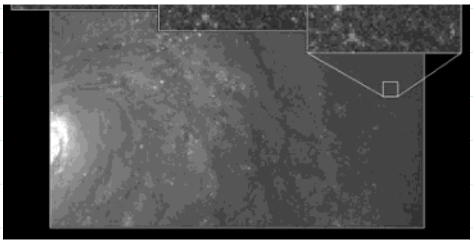
- In 1923, Edwin Hubble measured the distance to galaxy Andromeda and showed that the distance to Andromeda is bigger than the Milky Way. This showed that the spiral nebulae are really large spiral star systems outside of our galaxy.
- Hubble (with Humason) observed the spectra of the Cepheid variables in the galaxies.
- By observing the pulsation period of the Cepheid variable stars, they could calculate the distance to the galaxies.
- They also measure the Doppler shifts of spectral lines and interpreted them as velocities of the galaxies. All Doppler shifts were to the red.
- When they plotted velocity versus distance they found strong relation between the two :
  Galaxies move away from us and more distance galaxies have larger recess velocity

Cepheid Variable Stars Used for Distance Measurements

- The Hubble Space Telescope was used to observe the spiral galaxy M100.
- The inset photos show the Cepheid variable star over a period of a few days.



- The distance to M100 is 17 Mpc.
- This is the same method which Hubble used to find the distances to galaxies.
- One of the major projects that the Hubble Space Telescope was built for was the observation of Cepheid Variable stars in far away galaxies.



Redshift of Galaxies

- When we look at a galaxy, we expect to see a spectrum similar to the stars inside of it.
- The stars have dark absorption lines corresponding to the elements in their atmospheres.
- If the galaxy is moving either towards us or away from us, the spectrum of the galaxy will be Doppler shifted due to the motion.
- Define the redshift = z by the equation (lambda denotes wavelength)

z = (lambdaobserved - lambdalab)/lambdalab=$\delta\lambda/\lambda$

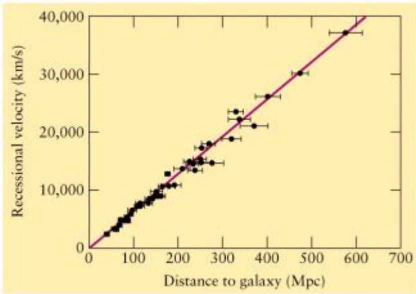
- This is defined so that if the object is moving away from us, the observed wavelength will be longer than expected and **z** will be positive.
- From the Doppler shift formula,

$$\frac{v}{c}=\frac{\delta\lambda}{\lambda}$$

the velocity of the galaxy is

$\frac{v}{c}=z=\frac{\delta\lambda}{\lambda}$ or v = c z where c = speed of light

Hubble's Law



- Hubble and Humason found a peculiar correlation in the distance and redshift data.

-the larger the distance a galaxy is away from us, the larger the redshift of its spectral lines.

- If the redshift is due to a relative velocity between the galaxy and ourselves, this shows that the further away a galaxy is from us, the faster it moves away from us.
- This is known as **Hubbles' Law** (although Humason also showed this).
- the Universe is expanding uniformly and that the distance between all galaxies is increasing everywhere. ⇝ leading to the "Big Bang Model"
- The mathematical statement of Hubble's law is

v = H₀ d **or** d= H_0^{-1} v

where

v = relative velocity of galaxy away from us measured in km/s

d = distance to the galaxy measured in Mpc

H_0 ≈ 70 km/s/Mpc≡ $100h$ km/s/Mpc, $h = 0.7$ (* unit of H₀:1/time)

Hubble "constant" (=Hubble parameter at present (H(t=t_{present}))

= the expansion rate at the present time

(H_0 ≈ $100h$ km/s/Mpc≡ $z_0 h$ 3x10^5km/s/Mpc ($z_0=\frac{100\text{km/s}}{3\text{x}10^5\text{km/s}}$ =0.33x10^{-3})

=$z_0 h$ 1ly/yr/Mpc=$z_0 h$ $\frac{1}{3.26}$pc/yr/Mpc= $\frac{h\ \text{pc}/(3\text{x}3.26\text{x}10^3 yr)}{\text{Mpc}}=\frac{h\ \text{ly}/(3\text{x}10^3 yr)}{3.26\text{Mly}}=\frac{h\ \text{ly}/(3\times 3.26\text{x}10^3 yr)}{\text{Mly}}$

=h/(0.978x10^4x10^6yr)=1/1.397x10^{10}yr

the Hubble Time

t_H =1/H_0 The inverse of the Hubble Constant

t_H = 1/H_0=$3/h\times 10^{17}$ s = $1/h\times 10^{10}$ yr≈ 14 Gyr

Or t_H = 1/H_0 = (3.26/$z_0 h$)Mpc yr/pc =(3.26/$z_0 h$) Myr=(0.978x10^4/h) Myr

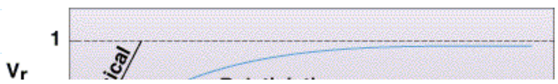
the time since a linear cosmic expansion has begun

(extrapolating a linear Hubble Law back to time t = 0);

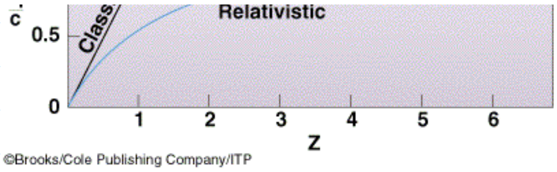
it is thus related to the age of the Universe from the Big-Bang to today.

Warning about large values of z

- Many far away galaxies have redshifts greater than 1.



- This does not mean that the galaxies move faster than light.
- The Doppler shift formula is only valid for small speeds much less than light.
- For speeds which are a large fraction of the speed of light a more complicated relation between z and speed is needed.
- When the correct relativistic formula is used large redshifts are allowed.



Hubble's Law as a tool for finding distances

- Can use the Hubble's law to find the distances to galaxies. : $v = H_0 d = c\,z$
- Basic idea: It is easy to measure z.
- Distance is then given by:

$d = H_0^{-1} v = zc\, H_0^{-1}$ Ex)

$$\frac{c}{H_0} = \frac{3\times10^5 \text{km/s}}{100h \text{ km/s/Mpc}} = \frac{3\times10^3 \text{Mpc}}{h} = \frac{10^4 \text{Mly}}{h}$$

$1/H_0 = (3.26/z_0 h)\text{Mpc yr/pc} = (0.978\text{x}10^4/h)\ \text{Myr} = (0.978/h)\ 10\ \text{Gyr}$
$c/H_0 = (0.978\text{x}10^4/h)\ \text{Mly} = (9.78/h)\ \text{Gly}$

$d = z\frac{10^4 \text{Mly}}{h}$

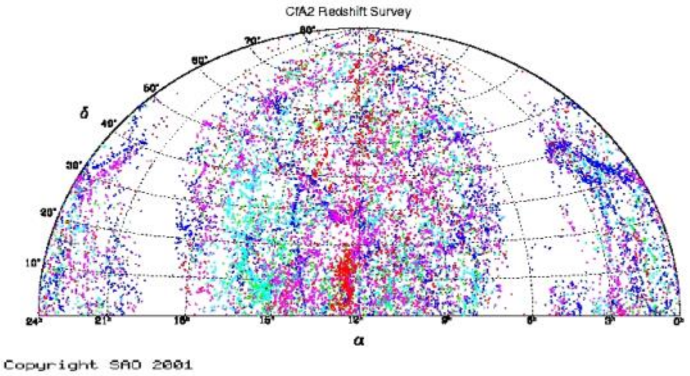
z=0.1 ⇝ $d=1{,}000h^{-1}$ Mly, z=0.32 ⇝ d= h^{-1} Gpc
z=0.01⇝ $d=100h^{-1}$ Mly, z=0.032 ⇝ $d=100h^{-1}$ Mpc,
z=0.001⇝ $d=10h^{-1}$ Mly, z=0.0032 ⇝ $d=10h^{-1}$ Mpc,

Redshift Surveys of the Universe

- The Center for Astrophysics **(CfA)** **Redshift Survey** at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, was the first attempt to map the large-scale structure of the universe.
- The first redshift survey began in 1977. A 3-dimensional map of that part of the Universe could thus be produced. This initial data collection was completed by 1982.
- The second survey (CfA2) was started in 1985 by John Huchra and Margaret Geller and measured the redshifts of 18,000 bright galaxies in the Northern sky by 1995ㅠ.

- In the diagram below, each point represents a galaxy in the northern celestial hemisphere that is brighter than an apparent blue magnitude of 15.5 and with a measured redshift inside 15,000 km/s. The nearest galaxies are shown in red, followed by blue, magenta, cyan and green.

- The blank areas running more or less north-south and looping over the north celestial pole with no galaxies are called the "Zone of Avoidance" and is merely the location of the Milky Way's disk which blocks out the light of galaxies due to dust extinction when looking through the Milky Way.
- The nearest galaxies are shown in red, followed by blue, magenta, cyan and green.
- This redshift survey shows that at scales of 200 Mpc, galaxies are grouped into large superclusters.
- The large red area at the center of the map (12 hours, +10 degrees) is the dense central region of the Virgo Cluster of galaxies which is the core of the Local Supercluster.
- The dark blue points which dominate the RHS of the map (0-4 hours +30 to +40 degrees) show the location of the Pisces-Perseus Supercluster.
- The light blue (cyan) points at 15 hours running almost from the equator to +40 degrees declination are the Hercules Supercluster.



The CfA Redshift Survey

Colour	Max z	Max d
Red	0.01	43 Mpc
Blue	0.02	86 Mpc
Magenta	0.03	129 Mpc
Cyan	0.04	171 Mpc
Green	0.05	214 Mpc

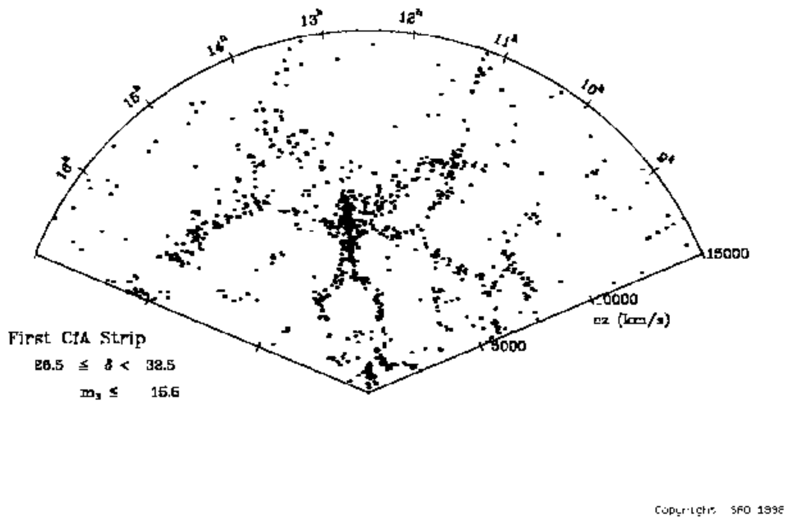
- Data from the second CfA survey showed that galaxies were not evenly distributed but clustered on the spherical surfaces of empty "voids".
- The project also made the 1989 discovery of the *Great Wall*, a supercluster of galaxies surrounded by voids.
- that surprised astronomers because its size was larger than could be produced by gravitational collapse since the beginning of the universe.
- Since then, superclusters have been described as artifacts of quantum fluctuations in the inflationary epoch of the universe.

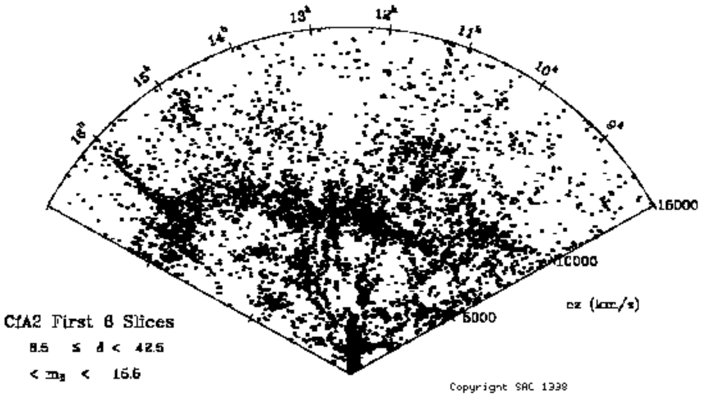
출처: <https://lweb.cfa.harvard.edu/~dfabricant/huchra/zcat/>
출처: <https://en.wikipedia.org/wiki/CfA_Redshift_Survey>

The first slice of the CfA Survey.

- Below is the "slice of the Universe" that represents the first set of observations done for the CfA Redshift Survey in 1985
- These are spectroscopic observations of about 1100 galaxies in a strip on the sky 6 degrees wide and about 130 degrees long. We are at the apex of the wedge.
- The outer arc of the plot is at a distance of about 700 Mly.

출처: <https://lweb.cfa.harvard.edu/~dfabricant/huchra/zcat/>





Here's the map with six contiguous 6 degree slices in the northern galactic cap.
the ``Great Wall,'' : The structure running all the way across between 8 hours and 17 hours RA and 5,000 and 10,000 km/s. Its dimensions are about 600x250x30 million light years, sort of like a giant quilt of galaxies across the sky.
출처: <https://lweb.cfa.harvard.edu/~dfabricant/huchra/zcat/>

Modern Redshift Survey: The Cosmic Web

- There are several modern galaxy redshift survey that aim for depth and/or full sky coverage. It covers the sky in the sequence of wedge-like slices.

Prominent example is Sload Digital Sky survey(SDSS)

The **Sloan Digital Sky Survey** or **SDSS**

- is a major multi-spectral imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States.
- The project was named after the Alfred P. Sloan Foundation, which contributed significant funding.
- The Astrophysical Research Consortium (ARC) was established with the University of Washington and Princeton University and with the New Mexico State University and Washington State University.
- In 1991 the Sloan Foundation granted the ARC funding for the construction of equipment.

Operation

- Data collection began in 2000;
  the final imaging data release (DR9) covers over 35% of the sky,
  With 1 billion photometric observations, and 4 million spectra.
- The galaxy with a median redshift of z = 0.1; luminous red galaxies as far as z = 0.7,
  and for quasars as far as z = 5, beyond a redshift z = 6.
- Data release 8 (DR8), in January 2011, covering over 35% of the full sky.
  Data release 9 (DR9), on 31 July 2012, includes the 1st results from the Baryon Oscillation Spectroscopic Survey (BOSS). objects in the Universe 7 billion years ago.
  Data release 10 (DR10), on 31 July 2013, the first results from the APO Galactic Evolution Experiment (APOGEE), also including new BOSS spectra of galaxies and quasars.
  In July 2020, published the largest, most detailed 3D map of the universe so far, and provided data which supports the theory of a flat geometry of the universe and confirms that different regions seem to be expanding at different speeds.

Observations

- SDSS uses a dedicated 2.5 m wide-angle optical telescope;
- from 1998 to 2009 it observed in both imaging and spectroscopic modes.
- The imaging camera retired in late 2009, since then, entirely in spectroscopic mode.
- Every night the telescope produces about 200 GB of data.

Phases

SDSS-I: 2000–2005

SDSS-II: 2005–2008

- extending the observations to explore the structure and stellar makeup of the Milky Way, the SEGUE and the Sloan Supernova Survey, which watches after supernova Ia events to measure the distances to far objects.

Sloan Legacy Survey

- The Sloan Legacy Survey covers over 7,500 square degrees of the Northern Galactic Cap with data from nearly 2 million objects and spectra from over 800,000 galaxies and 100,000 quasars.
- The information on the **position and distance** of the objects has allowed the large-scale structure of the Universe, with its voids and filaments, to be investigated for the first time.
- Almost all data were obtained in SDSS-I, but a small part was finished in SDSS-II.

Sloan Extension for Galactic Understanding and Exploration (SEGUE)

- The Sloan Extension for Galactic Understanding and Exploration obtained spectra of 240,000 stars (with typical radial velocity of 10 km/s) in order to create a detailed **three-dimensional map of the Milky Way**.
- this survey are publicly available as part of SDSS Data Release 7 (DR7).

Sloan Supernova Survey from 2005 to 2008

- The project discovered more than 500 type Ia supernovae, Running until the end of the year 2007, the Supernova Survey searched for Type Ia supernovae. In 2014 an even larger catalogue was released containing 10,258 variable and transient sources.

SDSS III: 2008–2014

- In mid-2008, SDSS-III was started. It comprised four separate surveys:

APO Galactic Evolution Experiment (APOGEE)

- The APO Galactic Evolution Experiment (APOGEE) used high-resolution, high signal-to-noise infrared spectroscopy to penetrate the dust that obscures the inner Galaxy.[21] APOGEE surveyed 100,000 red giant stars across the full range of the galactic bulge, bar, disk, and halo. APOGEE planned to collect data from 2011 to 2014, with first release of data in July 2013.

Baryon Oscillation Spectroscopic Survey (BOSS)

- The SDSS-III's Baryon Oscillation Spectroscopic Survey (BOSS) was designed to measure the expansion rate of the Universe. It mapped the spatial distribution of luminous red galaxies (LRGs) and quasars to determine their spatial distribution and detect the characteristic scale imprinted by baryon acoustic oscillations in the early universe. Sound waves that propagate in the early universe, like spreading ripples in a pond, imprint a characteristic scale on the positions of galaxies relative to each other. It was announced that BOSS had measured the scale of the universe to an accuracy of one percent, and was completed in Spring 2014.

Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS)

- The Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS) monitored the radial velocities of 11,000 bright stars, with the precision and cadence needed to detect gas giant planets that have orbital periods ranging from several hours to two years. This ground-based Doppler survey [25] used the SDSS telescope and new multi-object Doppler instruments to monitor radial velocities.[25]
- The main goal of the project was to generate a large-scale, statistically well-defined sample of giant planets.
- The project started in the fall of 2008, and continued until spring 2014.[25][28]

SEGUE-2

- The original Sloan Extension for Galactic Understanding and Exploration (SEGUE-1) obtained spectra of nearly 240,000 stars of a range of spectral types. Building on this success, SEGUE-2 spectroscopically observed around 120,000 stars, focusing on the in situ stellar halo of the Milky Way, from distances of 10 to 60 kpc. SEGUE-2 doubled the sample size of SEGUE-1.

SDSS IV: 2014–2020

- The latest generation of the SDSS (SDSS-IV, 2014–2020) is extending precision cosmological measurements to a critical early phase of cosmic history (eBOSS), expanding its infrared spectroscopic survey of the Galaxy (APOGEE-2), and to make spatially resolved maps of individual galaxies (MaNGA).

APO Galactic Evolution Experiment (APOGEE-2)

- A stellar survey of the Milky Way, with two major components: a northern survey using the bright time at APO, and a southern survey using the 2.5m du Pont Telescope at Las Campanas.

extended Baryon Oscillation Spectroscopic Survey (eBOSS)[edit]

- A cosmological survey of quasars and galaxies, also encompassing subprograms to survey variable objects (TDSS) and X-Ray sources (SPIDERS).

Mapping Nearby Galaxies at APO (MaNGA)

- MaNGA (Mapping Nearby Galaxies at Apache Point Observatory), explored the detailed internal structure of nearly 10,000 nearby galaxies from 2014 to spring of 2020. Earlier SDSS surveys only allowed spectra to be observed from the center of galaxies. By using two-dimensional arrays of optical fibers bundled together into a hexagonal shape, MaNGA was able to use spatially resolved spectroscopy to construct maps of the areas within galaxies, allowing deeper analysis of their structure, such as radial velocities and star formation regions.

SDSS-V: 2020–current

- Apache Point Observatory in New Mexico began to gather data for SDSS-V in October 2020. Apache Point is scheduled to be converted by mid-2021 from plug plates (aluminum plates with manually-placed holes for starlight to shine through) to small automated robot arms, with Las Campanas Observatory in Chile following later in the year. The Milky Way Mapper survey will target the spectra of six million stars. The Black Hole Mapper survey will target galaxies to indirectly analyze their supermassive black holes. The Local Volume Mapper will target nearby galaxies to analyze their clouds of interstellar gas.[34][35]

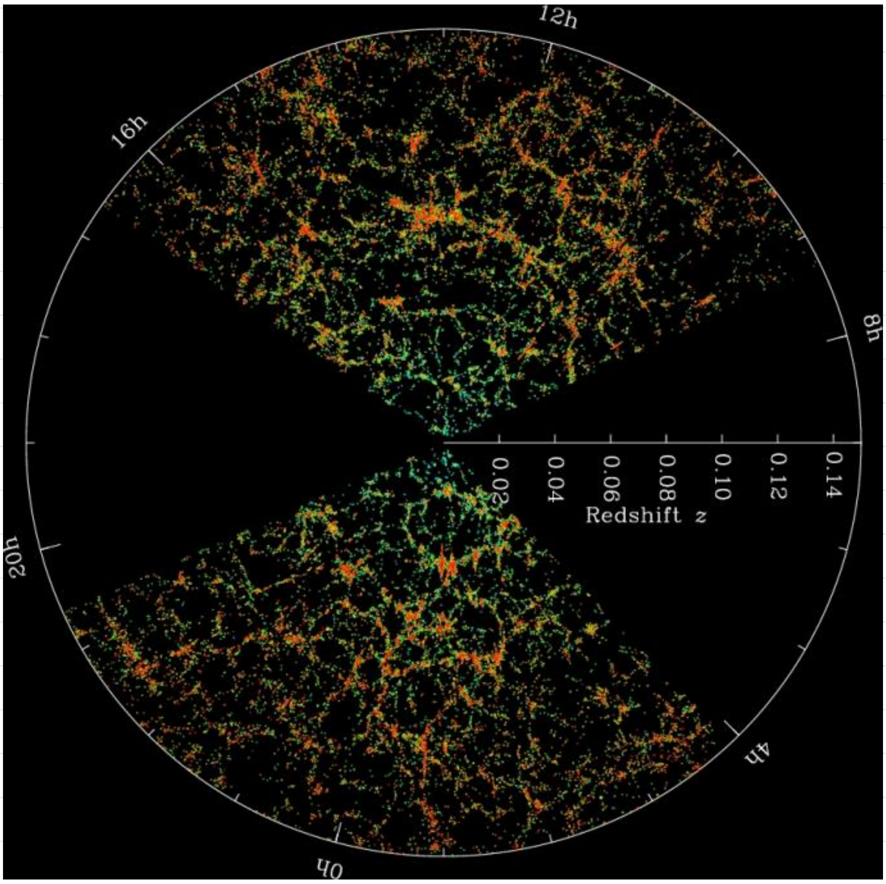
Results

- The SDSS website has a full list of these publications covering distant quasars at the limits of the observable universe, the distribution of galaxies, the properties of stars in our own galaxy and also subjects such as dark matter and dark energy in the universe.

Maps

- Based on the release of Data Release 9 a new 3D map of massive galaxies and distant black holes was published on August 8, 2012.

출처: <https://en.wikipedia.org/wiki/Sloan_Digital_Sky_Survey>



Large scale structure in the northern equatorial slice of the SDSS main galaxy redshift sample. The slice is 2.5 degrees thick, and galaxies are color-coded by g-r color.

출처: <https://classic.sdss.org/legacy/index.html>

Another example is 2DF survey

the **2dF Galaxy Redshift Survey** (Two-degree-Field Galaxy Redshift Survey), **2dF** or **2dFGRS**

- is a redshift survey conducted by the Australian Astronomical Observatory (AAO) with the 3.9m Anglo-Australian Telescope between 1997 and 11 April 2002.
- The data from this survey were made public on 30 June 2003.
- The survey determined the large-scale structure in two large slices of the Universe to a depth of around 2.5 billion light years (redshift ~ 0.2). It was the world's largest redshift survey between 1998 (overtaking Las Campanas Redshift Survey) and 2003 (overtaken by the Sloan Digital Sky Survey).
- The 2dF survey covered an area of about 1500 square degrees, surveying regions in both the north and the south galactic poles.
- The name derives from the fact that the survey instrument has a 2 degree diameter field of view.
- 232,155 were galaxies (221,414 with good quality spectra), 12,311 are stars, and 125 are quasi-stellar objects (quasars). The survey necessitated 272 required nights of observation, spread over 5 years.
- The survey was carried out with the 4 metre Anglo-Australian Telescope, with the **2dF instrument** installed at the primary focus permitting the observation of a field of 2 degrees per pointing.
- The limiting apparent magnitude of the survey is 19.5, covering objects with a redshift mostly within less than z=0.3 and a median redshift of 0.11. The largest redshift observed by the survey corresponds to a distance of 600 h^{-1} Mpc.

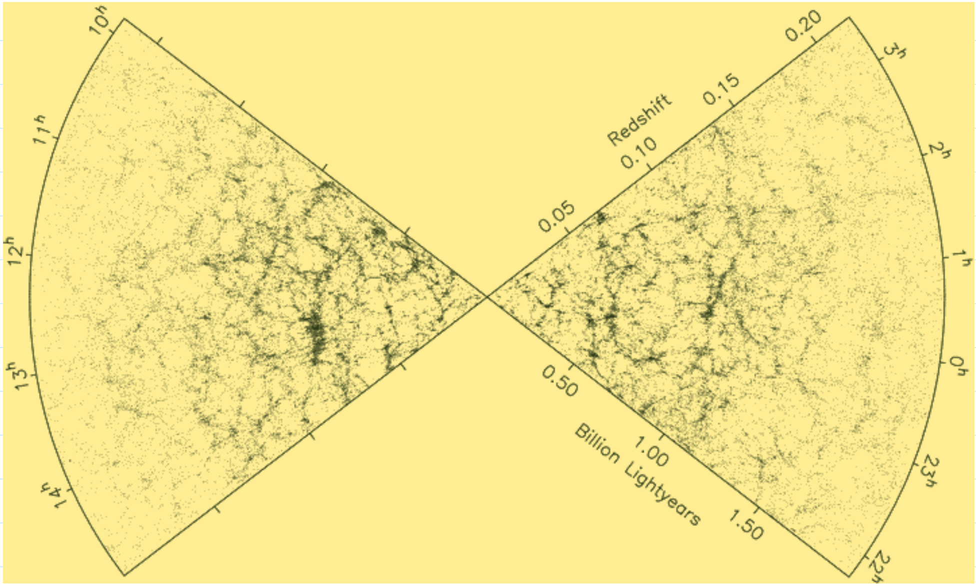
Survey results[edit]

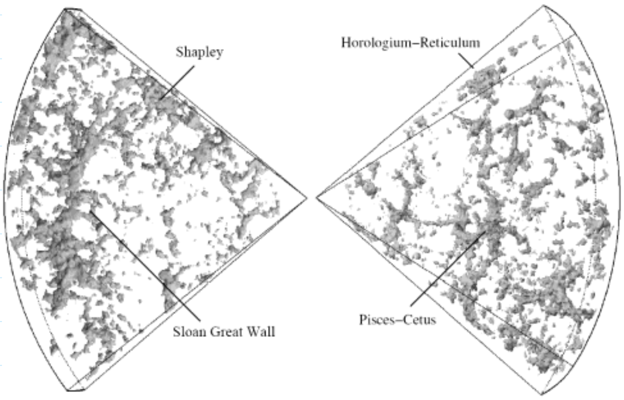
The principal results obtained for the field of cosmology by the 2dF survey are:

- The measurement of the density parameter of non-relativistic matter (baryonic matter plus dark matter plus massive neutrinos)
- The detection of Baryon acoustic oscillations, and as a consequence the relationship between the density of baryonic matter and dark matter
- Limits on the contribution of massive neutrinos to dark matter, putting a limit on the sum of the masses of the three families of neutrinos at 1.8 eV.

- The 2dF survey also yields a unique view on our local cosmic environment. In the figure a 3-D reconstruction of the inner parts of the survey is shown, revealing an impressive view on the cosmic structures in the nearby universe. Several superclusters stand out, such as the Sloan Great Wall, one of the largest structures in the universe known to date (see also Huge-LQG).

출처: <https://en.wikipedia.org/wiki/2dF_Galaxy_Redshift_Survey>

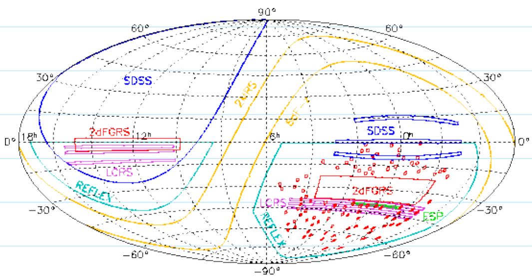




Three-dimensional DTFE reconstruction of the inner parts of the 2dF Galaxy Redshift Survey.

The figure reveals an impressive view on the cosmic structures in the nearby universe. Several superclusters stand out, such as the Sloan Great Wall, once known as the largest structure in the universe until discovery of the Huge-LQG in January 2013.
This picture was featured on 7 November 2007 on Astronomy Picture of the Day (APOD).
출처: <https://en.wikipedia.org/wiki/2dF_Galaxy_Redshift_Survey#/media/File:2dfdtfe.gif>

- This produces a "wedge" shaped diagram with us at the vertex.
- Distance away from us increases along the straight lines of the wedge.
- This diagram shows the distribution of about 930000 galaxies out to a distance of 600 Mpc.
- The Galaxies form filamentary structures woven in the web-like pattern over great distances, with large **Voids** between them. Hence we speak about **the Cosmic Web**

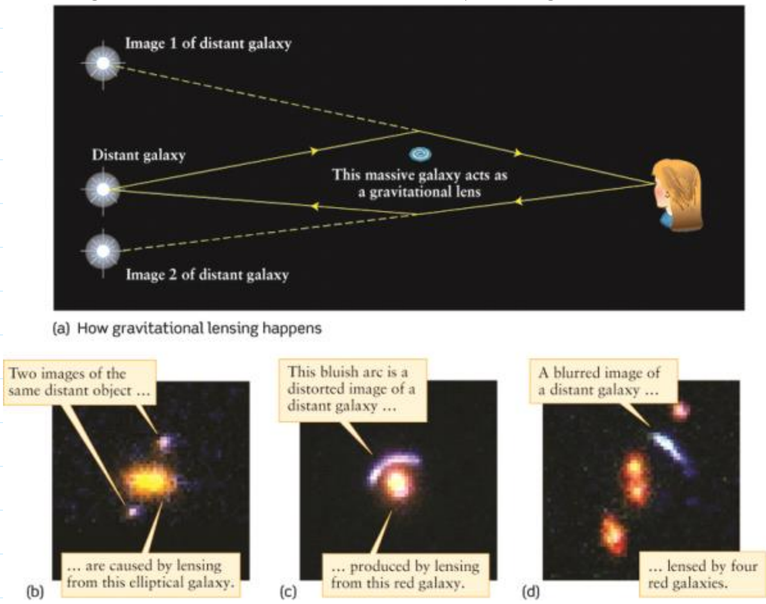


The areas of the sky covered by various surveys mentioned in the text

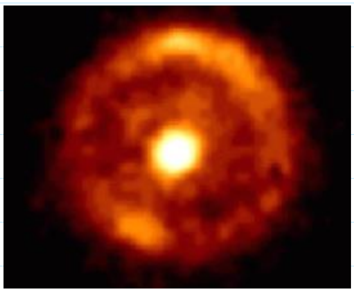
출처: <https://www.atnf.csiro.au/pasa/17_3/colless/paper/node2.html>

Gravitational Lensing

- When light travels near a massive object, the gravitational field of the object bends the path of the light creating a gravitational lens.
- The gravitational lens can create multiple images or distorted images of a background object emitting the light.



The Einstein Ring



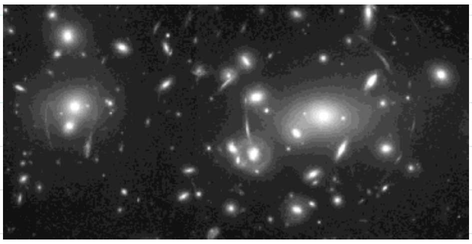
- If there is a perfect alignment between the source, lens and the observer, the image of the source looks like a ring.
- This ring is called an **Einstein Ring**
- The angular radius of the ring depends on the distance to the lens (d) and the mass of the lens (M):

  angular radius = $(2GM/(dc^2))^{1/2}$
- If our telescope can't resolve the small angular size of the Einstein Ring, we just see the image's brightness increase. This is called microlensing.
- By examining the image, it is possible to find the mass of the lensing object.
- The bright central region is a nearby galaxy, whose mass acts as a lens for the further away galaxy.
- The image of the far-away galaxy is distorted into a ring shape.

A Galaxy Cluster acting as a Lens

- The Galaxy Cluster Abell 2218 is about 1000 Mpc = Gpc away from us.

- This cluster is acting as a lens.
- Galaxies much further away are lensed by the mass of the cluster into little arc-shapes.
- The lensed arcs are images of galaxies which are 5 - 10 Gpc away.

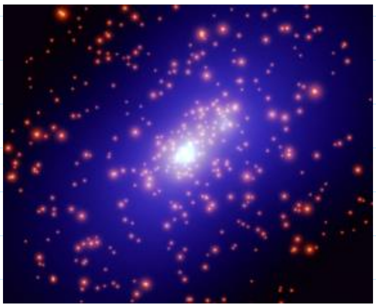


Present record redshift for a galaxy

- The ovals show the location of very faint distorted images of a galaxy with z=7.
- The galaxy is about 13 billion light years away from us

Gravitational Lensing Reveals Dark Matter

- Gravitational lensing of the far away blue galaxy in the bottom left photo is caused by the mass in the galaxy cluster CL0024. The cluster of galaxies **CL0024+17** is located in Pisces, and about 4 billion light years distant.
- The galaxies of CL0024 are yellow in the bottom left photo.
- By tracing the paths of light rays we can infer where the mass of the cluster is from the location of the images of the blue galaxy.
- The bottom-right photo shows the inferred location of the cluster's mass in blue.
- The visible galaxies are orange.
- This method infers that 80% of the cluster's mass is not seen in the photo.

Importance of Lensing

- The observation of lensing is important for two reasons.
- The lensing shows us where invisible mass in a cluster lies.
- The lensing allows us to study distorted images of very young galaxies.

- The general trend of all of these studies is that we only see a small fraction (about 1/10) of the mass of the universe.

Active Galaxies & Quasars

출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect26/lecture26.html>

Key Ideas

Active Galactic Nuclei (AGN)

Powerful energy sources in the nuclei of some galaxies.

Types of Active Galaxies:

Quasars
Blazars
Seyfert Galaxies
Radio Galaxies

Power source:

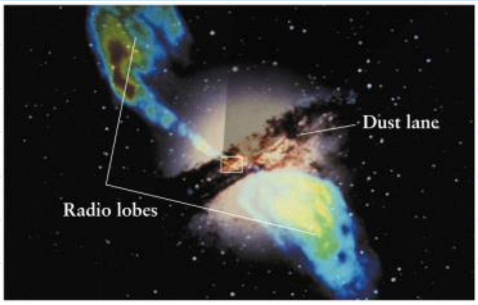
Accretion of matter by Supermassive Black Holes

I. Normal Galaxies Versus Active Galaxies

Ia) Properties of "Normal" Galaxies

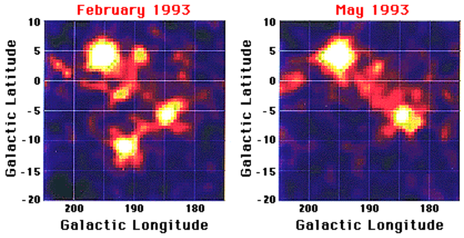
- Most of the galaxies are normal galaxies.
  Ex) All the galaxies in the Local Group are normal galaxies.
- Normal galaxies have total luminosities up to about $10^{11} L_{Sun}$.
- The spectrum of a galaxy is mainly the sum of the spectra of all the stars (absorption spectrum) as well as the dust and Hydrogen gas.
- The luminosity of a normal galaxy does not change much over short periods of time.

Ib) Properties of Active Galaxies



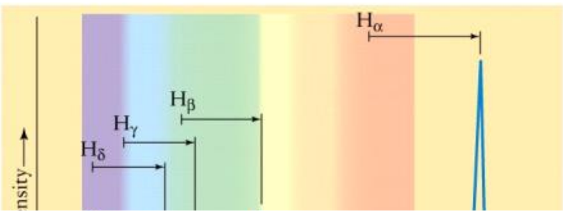
- Active Galaxies are typically more luminous than normal galaxies ranging from $10^{11} L_{Sun}$ to $10^{15} L_{Sun}$.
- The spectrum of an active galaxy includes features usually not seen in the spectrum of stars including: Hydrogen emission lines; radio synchrotron emission; x-rays
- The active galaxy nucleus is much brighter than the that of a normal galaxy.
- The active galaxies often have gigantic jets pointing out of the galaxy.
- The luminosity of an active galaxy can change by a factor of 2 over a short period of time (such as a few days).
- Some different types of active galaxies are: Radio Galaxies, Seyfert Galaxies, BL Lac Objects (also known as Blazars), and Quasars.

Ex) Rapid Variability



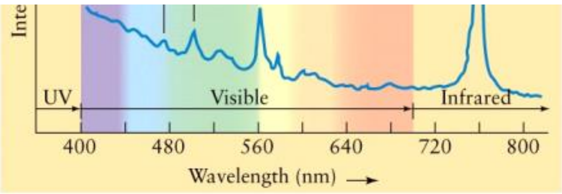
- This gamma-ray picture of the active galaxy PKS0528 shows large changes over only 3 months of observations.

Ex) Emission Lines



- Instead of seeing absorption lines (as in a regular galaxy) we see emission lines in the spectrum of the quasar 3C 273.
- In addition, the Balmer series of Hydrogen lines have all been redshifted.

- Hubble's law would imply that this quasar is very far away, so it must be very luminous since we can see it.



Galactic Nuclei

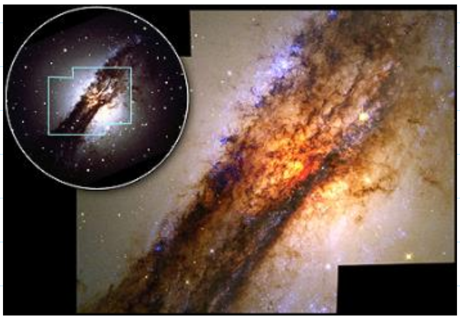
Normal Galaxies:	**Active Galactic Nuclei**
• Dense central star cluster	About 1% of all galaxies,bright compact **active nuclei**.
a composite **stellar absorp-line**	Strong, broad **emis line** (hot, dense, highly excited gas)
May show **weak** nebular emis line	
	Rapidly Variable ⇝ small (a few light days across)

II. Radio Galaxies

- All galaxies emit radio waves. For normal galaxies, radio emission corresponds to a small fraction of the total energy emitted by the galaxy.
- For **Radio Galaxies**, the energy emitted at radio wavelengths is 0.1 to 10 times the energy emitted at visible wavelengths.
- Most radio galaxies are either elliptical or giant elliptical galaxies.
- The radio emission comes from a tiny bright source in the nucleus of the galaxy as well as large jets which are often larger than the galaxy.
- The radio emission comes from the synchrotron mechanism where rapidly moving electrons spiral around magnetic field lines.

Centaurus A

- The galaxy Centaurus A at about 3 Mpc is the closest active galaxy to us.
- This galaxy is an elliptical galaxy with a dusty disk.
- These images are taken at visible wavelengths.
- This image shows a close-up of the nucleus showing the star-formation occuring inside the dusty nucleus.



II a) Radio Emission from Centaurus A

- The combined light image from visible, IR & radio waves.
- The IR is coloured red,
- the centre of the elliptical galaxy appears very similar to a small barred spiral galaxy with a radius of about 3 kpc!
- The radio emission originates from giant jets perpendicular to the dusty disk.
- The length of the radio jets are about 10 kpc, extending out much further than the visible part.

II b) X-ray Emission from Centaurus A

- blue = x-ray emission (Chandra space X-ray Observatory)
- yellowish = submm (APEX, Chile)
- This X-ray image of Centaurus A shows the bright nucleus and a jet extending outwards.
- The X-ray emission is in the same location as the radio jets.

III. Seyfert Galaxies

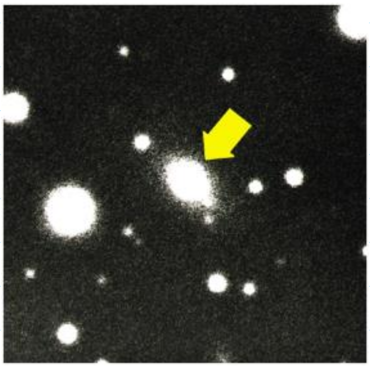
- Carl Seyfert identified 6 galaxies with strong, broad emission lines from a compact, bright galaxy nucleus (1943)
- Seyfert Galaxies are spiral galaxies with an unusually bright nucleus.
- The nucleus is much bluer than a normal nucleus.
- Emission lines are present, showing that very hot ionized gas is present.
- The gas in the central region orbits the centre very rapidly.
- The luminosity of the nucleus changes rapidly over the course of days and weeks.
- A Seyfert Galaxy is an example of a galaxy with an active nucleus.

Some Examples of Seyfert Galaxies (Visible Light)

NGC 7742

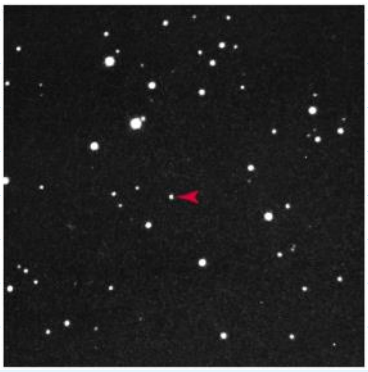
Circinus Galaxy

IV. Blazars (BL Lac Objects)



- The first Blazar identified was first thought to be a variable star and given the name BL Lacertae.
- All objects similar to this first blazar are called either BL Lac objects or Blazars.
- BL Lac objects appear to be star-like point sources in early photos.
- Their spectra show no emission lines, only continous synchrotron emission.
- Longer exposure photos show that the Blazars are the very bright nuclei of faint elliptical galaxies.

V. Quasars (Quasi-Stellar Radio Sources)



- In the 1960's, radio astronomers found point (star)-like sources of radio emission.
- Photographs revealed slightly fuzzy or "quasi-stellar" objects at these locations.
- The spectra were bizarre and full of unrecognized broad emission lines.
- Named them **Quasars**, short for **Quasi-Stellar Radio Sources** (sometimes QSO, for **Quasi-Stellar Object**)
  - emitted radio waves and had strong emission lines, not a normal spectrum for a star.
  - In 1963 Martin Schmidt identified the emission lines of Hydrogen in the QSO named 3C 273 and showed that they were redshifted. The "fuzz" is the host galaxy in the glare of an intense active nucleus.

Note : Hubble's redshift law

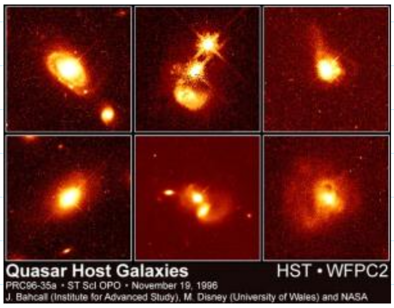
$$d = v/H_0 = cz/H_0 = z \times 4.3 \times 10^9 \text{ pc}$$

  - The redshift for 3C 273 is z = 0.158 1(6% the speed of light), the distance is 680 Mpc.
  - At the time, this was the largest redshift ever recorded.

- With this large distance, the luminosity of the quasar must be very large. Q: How?

a) Quasars are Active Galactic Nuclei (AGN)

- Later more powerful telescopes have shown that the QSOs have faint galaxies surrounding them, suggesting that the Quasars are the very bright nuclei of active galaxies.
- The brighter quasars have a luminosity of 10^{15} L_{Sun} ~ 100,000 x more luminous than the Milky Way.



b) The **Einstein Cross** (**Q2237+030** or **QSO 2237+0305**)

A Gravitationally Lensed Quasar

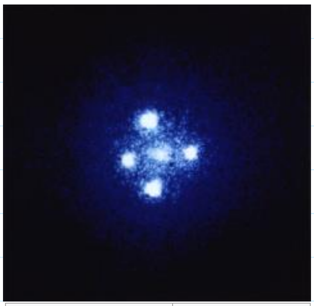
- Since quasars are far away from us, they can appear to be gravitationally lensed by a nearby galaxy.
- This picture (1985) is called the "Einstein Cross". The central bright spot in the centre is a "nearby" galaxy ZW 2237+030, Huchra's Lens with redshift z=0.0394 (400Mly)
- The four spots around the centre are four images of a background quasar QSO 2237+0305 with z=1.695(8Gly)
- The spectra of the four images are the same, showing that this is a gravitational lens.
- When the spectrum of the quasar changes, there is a time delay between when the changes occur due to the different distances that light has to travel for the different images.

- While gravitationally lensed light sources are often shaped into an Einstein ring, due to the elongated shape of the lensing galaxy and the quasar being off-centre, the images form a peculiar cross-shape instead.

- The apparent dimensions of the entire foreground galaxy are 0.87 × 0.34 arcminutes, while the apparent dimension of the cross in its centre accounts for only 1.6 × 1.6 arcseconds.

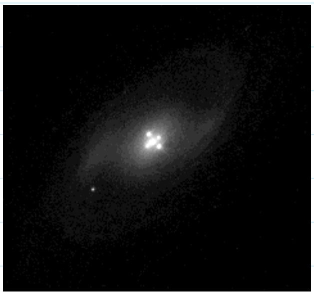
출처: <https://en.wikipedia.org/wiki/Einstein_Cross>

QSO 2237+0305



Constellation	Pegasus
Right ascension	22^h 40^m 30.3^s
Declination	+3° 21′ 31″
Redshift	1.695
Distance	8Gly (2.5Gpc)
Type	LeQ
Appar dim (V)	less than 2"
Appar mag (V)	16.78
Other	**designations**
LEDA 69457,	Z 378-15

출처: <https://en.wikipedia.org/wiki/Einstein_Cross>



Cosmic Beacons

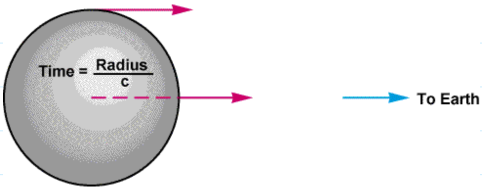
- Quasars are the most luminous objects in the Universe:
- Among the most distant objects in the Universe. Most distant is almost 4 Gpc away
- Probes of the Universe on very large scales.

6. Models of Active Galactic Nuclei

- All of the Active Galaxies (Seyferts, Radio Galaxies, Blazars, Quasars) have properties in common: bright nuclei and rapid variability.
- What can cause the nucleus of an active galaxy to be so powerful?

Time Variability

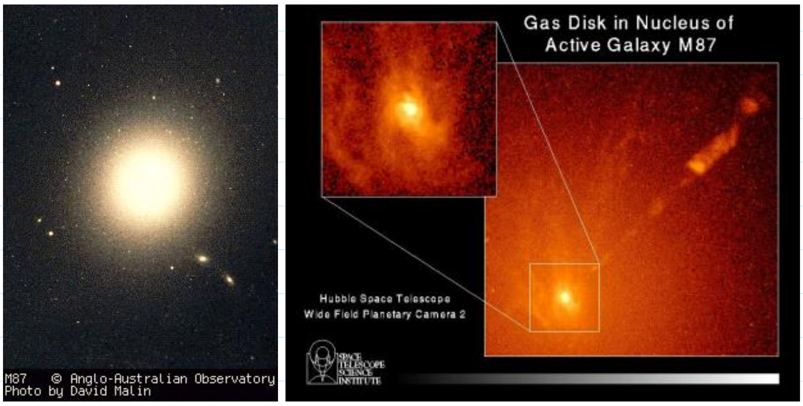
- The short time scales over which the nucleus changes its luminosity gives us information about its size.
- If the nucleus is a sphere with radius R, it takes a period of time
  t = R/c
  for light to cross the radius of the sphere.
- By measuring the period of time over which the nucleus changes its luminosity, we can find an upper limit to the size of the nucleus.
- For instance, if the nucleus changes its luminosity over the course of one day, the bright region must be smaller than one light-day in radius.



- The shortest variability timescales seen for active galaxies are on the order of hours, suggesting that the nuclei of these galaxies are smaller than a few light-hours.
- One light-hour corresponds to 7.2 AU.
- This means that the source of energy in the nucleus must be very small.

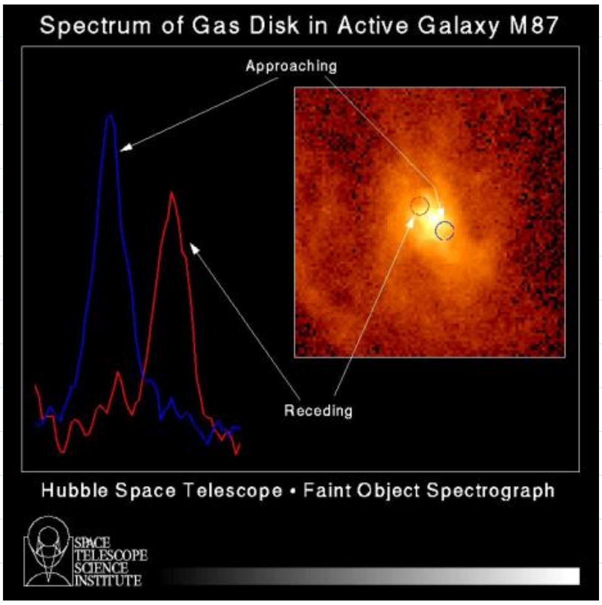
Orbital Speeds Near the Nucleus

- Gas moving in circular orbits near the nuclei of active galaxies has been observed.
- An example is the giant elliptical galaxy M87, which is also a radio galaxy with a jet.
- In the Hubble Space telescope of the central region, a disk and a jet are seen.
- A series of Radio images of the centre of the galaxy show that the bright energetic region is smaller than a light-year in diameter.



Evidence for a High-Mass Object in the Nucleus

- Spectra of gas clouds at a distance of
  20 pc = 6.2×10^{14} km = 4,100,000 AU
  from the centre were measured.
- The Doppler shifts showed that the gas orbits the centre at a speed of 550 km/s.
- Kepler's law gives us the mass of the central region.
- Orbital Period = P = 2 pi a/v
  = 2 pi x 6.2×10^{14} km/ 550 km/s = 7×10^{12} s
  = 220,000 years.
- Mass = a^3/P^2 = $(4{,}100{,}000)^3/(220{,}000)^2$
  = $1.4 \times 10^9\ M_{Sun}$

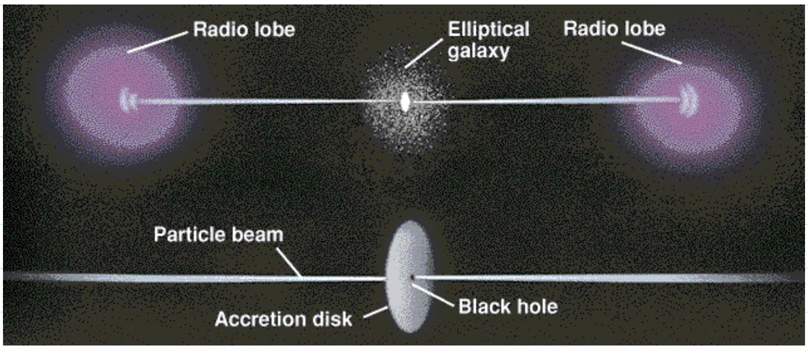


- A gigantic mass is found inside of a small region.

VI a) Black Holes as Engines for Active Galaxies

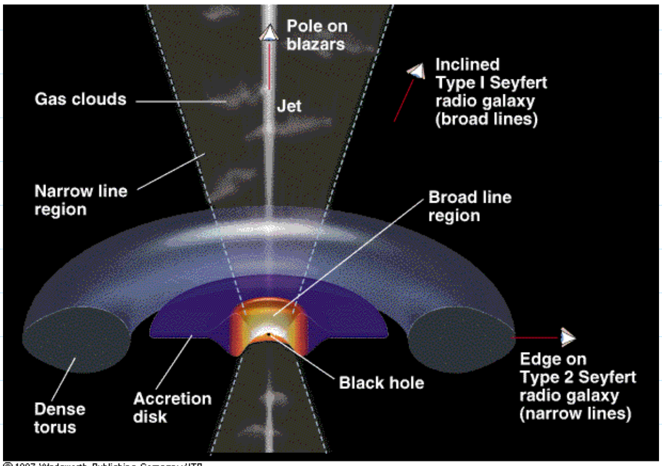
- a gigantic black hole (or Supermassive black hole) with a mass in the range of one million to one billion solar masses can also have an accretion disk which emits radiation.
- The basic model for all active galaxies is that a rotating supermassive black hole lies at the centre of the galaxy.
- The black hole has an accretion disk which emits radiation.
- The rapid rotation can also funnel material into jets which point along the axis of rotation, similar to what is seen in the

formation of stars.



VI b) Black Hole Model

- In more detailed black hole models, the types of phenomena are a result of the viewing angle.
- Blazars correspond galaxies with jets pointing right at us.
- Radio galaxies and Seyferts correspond to views of active galaxies which are inclined.
- The luminosity of the BH's accretion disk is proportional to the rate mass falls onto the disk.



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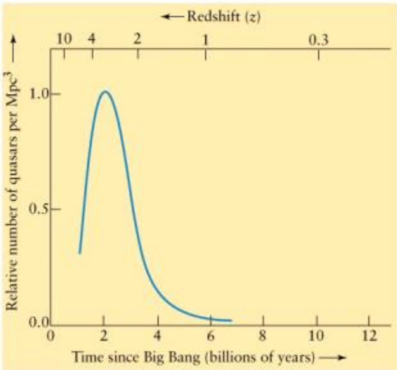
- The black holes which are surrounded by the most material should be brightest.

VII Evolution of Galaxies

- When we look at galaxies, we find that the closest galaxies are more likely to be normal galaxies.
- Active galaxies are more likely to be found further away from us.
- The quasars have large redshifts and are the objects furthest from us.
- If an object is a distance "d" from us, it takes the light an amount of time t = d/c to reach us.



- When we see an object we see it as it looked when the light was emitted, not as it is today.
- For example, when we view a galaxy which is one billion light-years away, the light was emitted one billion years ago.
- For galaxies far away, we are seeing what galaxies looked like when they were much younger.
- there was an early epoch of galaxy formation about 10 billion years ago.
- The most distant objects (quasars) correspond then to very young galaxies.

Aging Quasars

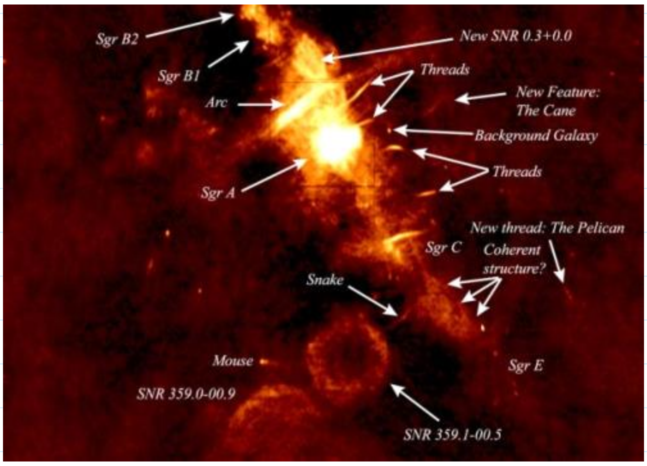
- As the quasars evolve in time, they become less luminous and appear as either Seyfert galaxies or Radio Galaxies.
- Over time, these active galaxies become less bright and appear as regular galaxies.
- In this evolutionary picture, the young galaxies (or quasars) begin with large amounts of gas in their nuclei which spirals onto the black hole's accretion disk, causing it to be very luminous.

- Over time, the black hole consumes gas in the inner regions and less gas is available to accrete onto the disk causing it to be less luminous.
- Observations of nearby galactic centres (such as the Milky Way and Andromeda) have shown evidence that most galaxies have a supermassive black hole at their centre.
- The Milky Way's central black hole is only one million times the mass of the Sun, so it may not have been as bright as a quasar when it was young.

The Centre of the Milky Way

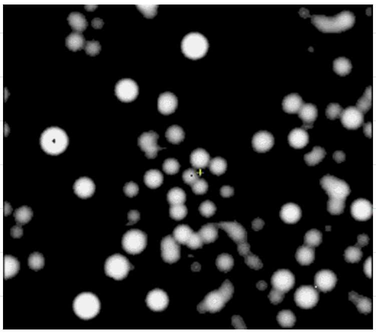
The innermost 1,500 light years of the Galactic Centre (at radio wavelengths)

- The bright radio source called SGR A (Sagitarius A) is the centre of the galaxy.
- The bright region of SGR A seen in this image is about 100 light-years across.



The Central light-year of the Milky Way in Infrared

- Time-lapse photography over 8 years shows motion of stars.
- There are about 100 stars in a region about one light-year cubed in volume.
- A typical velocity of a star 0.3 pc from the the centre is 260 km/s (in a circle around the centre).
- The central region of the Milky Way is smaller than 20 AU in radius. (Too small to be seen in this image.)



- the motion of these stars implies that a mass of 2x 10^6 M_{Sun} lies at the galactic centre.
- We see hundreds of stars in this small region, not millions.
- How such a large mass can be held into a stable configuration of stars or a gas cloud?
- The most likely object is a black hole.

How large is a black hole with such a large mass?

- the event horizon of a black hole has a radius of
  R_{EH} = 3 km M/M_{Sun}
- If the mass of the black hole is 2 x 10^6 M_{Sun}, the event horizon radius is
  R_{EH} = 3 km x 2 x 10^6 = 6 million km = 0.04 AU.
- Since the central source is smaller than 20 AU, and the black hole is smaller than this size, the black hole hypothesis is consistent with the data.

출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect27/lecture27.html>

Summary The Active Galaxy Zoo

Emission line	radio wave	type	nucleus	Luminosity
Blazar	x	sync rad	elliptic	
Quasar	O	O		
Radio Galaxy				
Seyfert Galaxy	O		spiral, unusually bluer, bright;days,weeks	

Most Active Galaxies are related to each other

Radio Loud: powerful radio sources

- Low Power: Radio Galaxies
- High Power: Quasars

Radio Quiet: very weak radio sources

- Low Power: Seyfert Galaxies
- High Power: Quasi-Stellar Objects (QSOs).

All types of AGNs share many characteristics. A problem of modern research is to sift through the similarities and differences to figure out how they might be related to each other.

What powers AGNs?

Properties that need to be explained:

Powerful:

- Luminosities of Billions to Trillions of L_{sun}
- Emit wavelengths from from Radio to Gamma-rays

Compact:

- Visible light can vary on timescales of a few days
- X-rays can vary on timescales of a few hours or less!

The Black Hole Paradigm

The energy source of active galaxies is the steady accretion of matter onto a supermassive Black Hole.

- Supermassive = 10^6 - 10^9 M_{sun}
- Schwarzschild Radii: ~0.01 - 10 AU

Infalling matter releases gravitational binding energy

- Gas settles into an **accretion disk**.
- The hot inner parts of the disk shine brightly, especially at X-rays.

The Central Engine

Black Hole accretion is very efficient:

- up to ~10% efficiency
- ~1 M_{sun}/year of matter needed to power bright active galaxies
- Get their "fuel&fuel; from surrounding gas and stars

Rapidly Spinning Black Hole:

- Acts like a particle accelerator

- Leads to the jets seen in radio-loud AGNs.

Some Nagging Questions:

How do supermassive black holes form?

- We don't really know for sure, but recent work strongly suggests that the formation and growth of supermassive blackholes is tightly coupled to the formation of the bulge of a galaxy.

How are they fueled?

- Galaxy interactions might dump gas into the nuclear regions to feed the Black Hole.
- Stellar bars might be able to funnel gas into the nucleus from the disk of the galaxy.
- Cannibalism of a gas-rich dwarf?

Do most galaxies have supermassive black holes?

- Nearly all spirals show some level of "activity" if perhaps only very faintly.
- There is a growing body of dynamical evidence for the presence of massive black holes in many nearby, but otherwise "inactive" galaxy nuclei (including our own Galaxy, which has a relatively inactive 3 Million M_{sun} black hole at its center).
- There were many more AGNs in the distant past, but few today - where are all the dead quasars?

출처: <http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit4/agns.html>