ASTR-3415: Astrophysics
Course Lecture Notes
Section X

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-3415: Astrophysics. This is the Version 1.2 edition of these notes.

X. Galaxies in the Universe

A. Classification of Normal Galaxies

1. The original classification of galaxies was carried out by Hubble in 1926 ⟹ the **Hubble Sequence**. Hubble arranged this sequence into a *tuning-fork* diagram ⟹ the **Hubble Tuning-Fork Diagram** (see Fig. 23.1 in the textbook). There are 5 main classes of galaxies distributed along this tuning fork diagram.

   a) **Ellipticals**:

      i) They appear round or elliptical in shape: E0 (circular), E1, E2, E3, E4, E5, E6, and E7 (most elliptical).

      ii) Have almost no gas or dust.

      iii) Population II stars (no O & B stars).

      iv) Dwarf elliptical are the least massive galaxies in the Universe.

      v) Giant ellipticals are the most massive.

      vi) The *ellipticity* (Eq) of an elliptical galaxy is defined by the ratio of their semimajor 'a' to semiminor 'b' axes:

$$q = 10 \left(1 - \frac{b}{a}\right) . \qquad \text{(X-1)}$$

      vii) Random velocity to rotational velocity ratios for stars in ellipticals is large as compared to spirals.

viii) Smooth distribution of light from the core out to the edge.

ix) This classification is based on the shape of the galaxy *as projected onto the sky.* If we label the axes of a **triaxial spheroid** as a, b, and c (see Figs. 23.2 and 23.3 in the textbook), then we have the following shapes:

- **Sphere** when $a = b = c$.
- **Oblate Spheroid** when $a = b > c$.
- **Prolate Spheroid** when $a > b = c$.

x) B absolute magnitudes range from -8 (dwarf ellipticals) to -23 (giant ellipticals).

xi) Mass ranges from $10^7 M_\odot$ (dwarf ellipticals) to $10^{13} M_\odot$ (giant ellipticals).

xii) Diameters range from $\sim \frac{1}{10}$ kpc (dwarfs) to 300 kpc (giants).

- The smallest dwarf elliptical galaxies are not much bigger than globular star clusters.
- The largest giant elliptical galaxies are among the largest objects in the Universe!

- The largest of the giant elliptical galaxies are classified as cD galaxies.

b) **Normal Spirals**:

i) These galaxies have disks with spiral arms in a disk radiating out from the core.

ii) Subclassified into 3 subdivisions and two intermediate subdivisions: Sa, Sab, Sb, Sbc, and Sc. The characteristics of the 3 subclasses are given below with the $L_{\rm bulge}/L_{\rm disk}$ indicating the ratio of the central bulge brightness to the disk brightness.

- **Sa**: Little dust and gas, large nuclei, tightly wound arms. $L_{\rm bulge}/L_{\rm disk} \sim 0.3$.

- **Sb**: Intermediate in all categories.

- **Sc**: Large clouds of dust and gas, small nuclei, loosely wound arms. $L_{\rm bulge}/L_{\rm disk} \sim 0.05$.

iii) The ratio of random velocities to rotational velocities for stars in spirals is small as compared to ellipticals.

iv) Similar to Milky Way in structure: disk (Population I stars), central bulge (Pop I & Pop II stars), and extended halo (Pop II stars).

v) On average, spirals tend to be the larger galaxies in the Universe:

- Absolute B magnitudes range from -16 to -23.

- Masses range from $10^9 M_\odot$ to $10^{12} M_\odot$.
- Diameters range from 5 to 100 kpc.

c) **Barred Spirals**:

i) 3 subdivisions and 2 intermediate subdivisions exist for the barred spirals as was the case for the normals but these galaxies have bar-like structures going through their nuclei: SBa, SBab, SBb, SBbc, and SBc.

ii) The barred spirals have the same characteristics as the normal spirals except the SBa spirals have a short, thick bar, and the SBc spirals have a long, thin bar.

d) **Lenticulars**:

i) Hubble type S0 (normals) and SB0 (barred).

ii) These have a disk but no spiral arms.

iii) Very little dust and gas.

iv) Few O & B stars, mostly Pop II stars.

v) Large central nucleus.

vi) The lenticulars have masses and luminosities comparable to the larger ellipticals. Their diameters are comparable to the larger spirals.

e) **Irregulars**:

- **i)** Hubble classification: Irr.
- **ii)** Small (5% - 25% the diameter of Milky Way).
- **iii)** Large clouds of dust and gas.
- **iv)** Large number of Pop I stars.
- **v)** The Milky Way's satellite galaxies, the **Large** and **Small Magellanic Clouds**, are good examples of irregular galaxies, though the LMC was reclassified as an SBm (*i.e.*, barred spiral, Magellanic type) since it shows a hint of a barred structure).

f) The Milky Way was originally thought to be an Sbc spiral. However, recent observations (*e.g.*, COBE and velocity measures) of the nuclear regions of the Milky Way suggest that our Galaxy is an SBb galaxy (see Fig. 22.5 in the textbook)!

g) Hubble originally thought the tuning-fork diagram was an evolutionary sequence for a galaxy in isolation (E0 → E7 → Sa → Sc → Irr or vise versa) — **it is not!**

- **i)** Ellipticals do not evolve into spirals since ellipticals have little or no gas and dust compared to the spirals hence cannot be younger.
- **ii)** Spirals do not evolve into ellipticals since spirals have many stars with high metal abundance and ellipticals have stars with low metal abundance

hence cannot be younger.

h) As we look deeper into the Universe, we look back in time! Spirals outnumbered ellipticals at earlier epochs in the Universe. Currently, ellipticals outnumber spirals.

  i) As such, it appears that spirals can become ellipticals, but not in the manner that Hubble suggested.

  ii) Galaxy morphology changes occur via galaxy collisions as discussed later in this section. As time progressed from the Big Bang (see §XI), galaxy-galaxy collisions (either spiral-spiral or spiral-elliptical) produced the large elliptical galaxies that reside at the center of galaxy clusters.

  iii) Spiral arms are though to arise from disk galaxy interactions with smaller galaxies (*e.g.*, Milky Way and the LMC/SMC galaxies).

  iv) Ring galaxies (not in the original Hubble sequence) can occur from galaxy collisions.

2. De Vaucouleurs added additional classification IDs to the Hubble types.

a) Renamed normal spiral "S" galaxies to "SA" galaxies.

b) Added suffix "d" for a more chaotic (almost irregular) spirals like the Large Magellanic Cloud.

c) Added suffix "m" to "SA" and "SB" to replace "Irr" classification for "Magellanic" type.

d) Added suffix “r” to disk galaxies to indicate that a ring is present and “s” with the “r” to indicate that their are spiral arms, as well as, a ring.

3. Some astronomers have also suggested that galaxies be classified by the spectrum they emit, though this is not widely used.

4. Van den Bergh developed a luminosity class for galaxies similar to the stellar luminosity classes: I (brightest galaxies), II, III, IV, and V (faintest galaxies). Luminosity type I galaxies are the most massive galaxies. However, these luminosity classes do not necessarily correlate well with the absolute magnitudes of the galaxies.

B. The Distribution of Light and Mass in Normal Galaxies

1. Surface Photometry of Galaxies.

a) The morphology of galaxies is typically studied through **surface photometry**, where one plots the brightness of a galaxy through different filters as a function of distance from the measured center of the galaxy.

b) One can determine star formation locations by then plotting colors versus galactic radii $\Longrightarrow$ **starburst galaxies** were discovered in this manner.

c) De Vaucouleurs found that the surface brightness $\mathcal{L}$ (luminosity per unit area) of an elliptical galaxy as a function of distance r from the center of the system along the major axis could be fit by the power law:

$$\mathcal{L}(r) = \mathcal{L}(0)\, e^{-(r/r_\circ)^{-1/4}} \,, \qquad \text{(X-2)}$$

where the central surface brightness $\mathcal{L}(0)$ and the central scale length $r_\circ$ are adjusted to give the best fit to the observations.

d) The light distribution of the central bulges of spiral galaxies also follows this equation.

e) In disk galaxies, with the light averaged in circles surrounding the galaxy's center in order to eliminate the spiral structure, the distribution of light follows:

$$\mathcal{L}(r) = \mathcal{L}(0)\, e^{-(r/r_\circ)} \ . \qquad \text{(X-3)}$$

f) Fish and Freeman found that there is a tremendous variation of $r_\circ$, even when comparing similar galaxy types. However, they also found that $\mathcal{L}(0)$ was remarkably constant for large galaxies. This will prove to be useful in determining the distances to far away galaxies.

2. Velocity Dispersions in Ellipticals and Rotation Curves in Spirals.

a) The only way to get an accurate mass for a galaxy is to deduce this mass from celestial mechanics using velocity information of either stars or gas clouds in the galaxy. However, the mass deduced is only the mass that is interior to the position in the galaxy where the velocities are being deduced. The mass interior to r can be roughly estimated by

$$M(r) = rv^2/G \ . \qquad \text{(X-4)}$$

b) There are 3 difficulties in the actual application of Eq. (X-4):

i) Eq. (X-4) requires a numerical correction, a coefficient of order unity, whose exact value depends on the detailed kinematics and mass distribution within the system. Modeling the mass distribution is usually used to figure out this coefficient.

  ii) The directly measurable quantity is the angular displacement θ from the galactic center, not the linear displacement r. We need to know the distance d in order to convert θ to r.

  iii) The astronomical measurement of v itself is non-trivial.

c) The spectrum of a galaxy is the convolved spectrum of billions of stars moving at different random velocities.

d) The line-of-sight component of these random velocities will broaden such a convolved spectral line due to the Doppler effect.

e) A comparison of the broadened absorption-line spectrum of the galaxy with the intrinsic spectrum of an appropriate chosen star (typically a K giant star) allows an estimate for the velocity dispersion present in the billion of stars seen along the whole line-of-sight through the galaxy.

f) This optical stellar spectrum comparison can be done for both elliptical and spiral galaxies. However, spirals also allow the use of the hyperfine-structure line of H I at 21-cm. Like the Milky Way Galaxy, external spiral galaxies all show a flat (*i.e.*, non-Keplerian) rotation curve in their outer portions $\Longrightarrow$ **all spiral galaxies have massive halos**.

g) The rotation curves of spirals suggest that the surface-mass density $\mu(r)$ falls off as $1/r$. Meanwhile, the surface brightness $\mathcal{L}(r)$ falls off exponentially $\Longrightarrow$ the mass-to-light ratio $\mu(r)/\mathcal{L}(r)$ (observed) or M/L (actual) must increase dramatically at large r in spiral galaxies $\Longrightarrow$ **all spirals are dominated by dark matter**.

3. The **Tully-Fisher Relation**.

a) There are 3 *observable* physical properties of galaxies that one would like to ascertain: radius $R = r_{\rm max}$, luminosity L, and mass M. These can be ascertain through the following observables:

$$\theta = \frac{R}{d} \tag{X-5}$$

$$f = \frac{L}{4\pi\, d^2} \tag{X-6}$$

$$v^2 = \frac{GM}{R}\ , \tag{X-7}$$

where d is the distance to the galaxy of angular size θ, f is the apparent flux, and v is the velocity dispersion of the gas (or stars) in the galaxy.

b) We can eliminate 2 of these equations by deriving an equation for *surface brightness*:

$$\mathcal{L} = \frac{f}{\theta^2} = \frac{L\, v^4}{4\pi\, G^2\, M^2}\ , \tag{X-8}$$

which is independent of distance.

c) Then the luminosity of the galaxy scales as

$$L = \frac{v^4}{\mathcal{L}}\, \frac{1}{4\pi\, G^2\, (M/L)^2}\ , \tag{X-9}$$

where we have introduced the *mass-to-light* ratio (M/L).

d) If we assume the surface brightness $\mathcal{L}$ for a galaxy is roughly constant (and it is for each galaxy type) and that the mass-to-light ratio is constant (again, this is typically true for each galaxy type), then we can write

$$L \propto v^4, \tag{X-10}$$

which is the basis of some of the most useful distance indicators in cosmology (see below).

e) For instance, if we are observing spiral galaxies, the appropriate velocity to use is the maximum velocity in the rotation curve which can be determined from H I 21-cm spectra. Then, we have

$$L \propto v_{\rm max}^4, \tag{X-11}$$

which is known as the **Tully-Fisher relation**.

f) On the other hand, if we were interested in elliptical galaxies, the appropriate velocity is the central *velocity dispersion*

$$L \propto \sigma_v^4, \tag{X-12}$$

which is known as the **Faber-Jackson relation**.

g) Both of these relations were discovered empirically and are justified through the arguments given above. In summary, velocities are deduced from spectral line widths of a galaxy, which is then converted to a luminosity based on the laws above. This luminosity is then compared to the observed or apparent luminosity and the galaxy's distance is deduced from the distance modulus formula.

4. With these velocity laws, we can also estimate the mass of the galaxies using Kepler's 3rd law. Galaxies range in mass from $10^{-6}\ M_{\rm MW}$ to $50\ M_{\rm MW}$ ($1\ M_{\rm MW} = 2 \times 10^{11}\ M_\odot$).

C. The Distances to Galaxies

1. We determine the distances to galaxies by using **distance indicators**:

   a) Galaxies with $d < 6$ Mpc (1 Mpc $= 10^6$ pc):

      i) Classical Cepheids and W Virginis pulsating stars ($P \rightarrow m - M_V \rightarrow d$).

      ii) O & B main sequence stars.

      iii) Novae.

      iv) RR Lyrae stars (all have the same approximate luminosity).

   b) Galaxies with $4 < d < 40$ Mpc:

      i) Diameter of giant H II regions (all have the same approximate size).

      ii) Brightness of largest globular star clusters (all have the same approximate brightness).

   c) Galaxies with $40 < d < 600$ Mpc:

      i) Tully-Fisher or Faber-Jackson relations.

      ii) Brightest of Sc I galaxies.

      iii) Supernovae.

      iv) The 3 brightest galaxies in a cluster.

      v) Diameters of bright galaxies.

d) Galaxies with $d > 600$ Mpc: use Hubble's Law.

e) Each of these distance indicators is calibrated on the previous ones!

2. Hubble's Observations and Hubble's Law.

a) Hubble compared magnitudes of galaxies to their redshifts and found that the fainter the galaxy, the bigger the redshift $\Longrightarrow$ **Hubble's Law**.

b) The more distant a galaxy (*i.e.*, fainter galaxies), the larger the redshift hence recession velocity (see Figure 25.6 in the textbook)

$$\Longrightarrow \boxed{\textbf{The Universe is Expanding.}}$$

c) Hubble's Law mathematically:

$$v_r = H_\circ \, d \ , \qquad \text{(X-13)}$$

where v_r is the recession velocity, d is the distance to the galaxy, and $H_\circ$ is Hubble's constant.

i) Prior to the launch of the Hubble Space Telescope (HST), $H_\circ$ was not accurately known $\Longrightarrow$ values ranged between 50 to 90 km/sec/Mpc.

ii) The primary reason the HST was built was to determine an accurate value for $H_\circ$. This is one of the so-called *Key* Projects of HST.

iii) This HST Key Project has ascertained the following value for Hubble's constant (see Freedman *et al.* 2001, *Astrophysical Journal*, **553**, 47):

$$H_\circ = 72 \pm 8 \text{ km/sec/Mpc} \qquad \text{(HST Result).} \qquad \text{(X-14)}$$

iv) The WMAP mission to map the cosmic microwave background (see §XI of the notes) has determined an even higher precision to Hubble's constant:

$$H_\circ = 71 \pm 4 \text{ km/sec/Mpc} \qquad \text{(WMAP Result)} \tag{X-15}$$

(see the WMAP website at http://map.gsfc.nasa.gov/).

Example X–1. If we see an Fe line at 4800 Å, which at rest is at 4000 Å, how far away is the galaxy?

$$\begin{aligned} v_r &= \frac{\Delta\lambda}{\lambda_\circ}\, c = \frac{4800 \text{ Å} - 4000 \text{ Å}}{4000 \text{ Å}} (3.00 \times 10^5 \text{ km/s}) \\ &= \frac{800 \text{ Å}}{4000 \text{ Å}} (3.00 \times 10^5 \text{ km/s}) \\ &= 0.2\,(3.00 \times 10^5 \text{ km/s}) = 6.00 \times 10^4 \text{ km/s} \\ d &= \frac{v_r}{H_\circ} = \frac{6.00 \times 10^4 \text{ km/s}}{71 \text{ km/s/Mpc}} = 8.49 \times 10^2 \text{ Mpc} \end{aligned}$$

$$\boxed{d = 850 \text{ Mpc.}}$$

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d) Recalling our discussion of redshift in §IX of these notes, the redshift z is defined as

$$z = \frac{\Delta\lambda}{\lambda_\circ} = \frac{v_r}{c}, \tag{X-16}$$

for the *nonrelativistic* (*i.e.*, $v_r \ll c$) version, and

$$z = \frac{\Delta\lambda}{\lambda_\circ} = \frac{\sqrt{1 + v_r/c}}{\sqrt{1 - v_r/c}} - 1, \tag{X-17}$$

for the *relativistic* (*i.e.*, $v_r \lesssim c$). Rewriting this relativistic formula, we can express velocity as a function of redshift:

$$\frac{v_r}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}. \qquad \text{(X-18)}$$

You will note that there is no way for a galaxy's velocity to exceed that of light when using the relativistic form of the Doppler effect.

3. Velocity in Hubble's Law represents the expansion velocity of the Universe as a whole (see §XI). This Hubble velocity is referred to as the **Hubble Flow**.

4. A galaxy's recession velocity will not exactly match the velocity as predicted by Hubble's Law since this law is based on the velocity distribution as a function of distance of numerous galaxies. Any excess velocity that a galaxy retains when the Hubble Flow is subtracted out is called a galaxy's **peculiar velocity**.

D. Groups and Clusters of Galaxies

1. Galaxies are typically not found in isolation. Instead, nearly all galaxies are found in *associations* $\Longrightarrow$ either "groups" or "clusters."

   a) **Groups** generally have less than 50 members.

      i) They are about 2.0 Mpc across.

      ii) The galaxies of the group have velocity dispersions of about 150 km/s.

      iii) The average mass of a group is $2.8 \times 10^{13} M_\odot$ as obtained from the virial theorem.

      iv) The mass-to-light ratio for galaxy groups is approximately 370 $M_\odot/L_\odot \Longrightarrow$ a lot of dark matter is present.

v) The Milky Way and Andromeda (M31) galaxies are the 2 most massive galaxies (by far) in our group called the **Local Group**.

- Our group contains about 30 members.
- In terms of luminosity, the Milky Way, M31, and Triangulum (M33) galaxies (all spirals) dominate the light output of the local group.
- The next 3 most massive members are M33, the Large Magellanic Cloud (LMC), and the Small Magellanic Cloud (SMC), respectively. The LMC and SMC are satellites of the Milky Way.
- The Milky Way and Andromeda galaxies are on a collision course with each other! The relative velocity between both galaxies is 119 km/s. Assuming this velocity will stay somewhat constant for the next 6 or 7 billion years, the collision will take place some 6.3 billion years in the future. At this point, the Sun will be in its AGB stage, possibly as a Mira variable.
- The collision of the Milky Way and M31 may result in the creation of a giant elliptical galaxy.
- The mass-to-light ratio for the Local Group is about 60 $M_\odot/L_\odot$ which is similar to the mass-to-light ratios for both the Milky Way and An-

dromeda.

b) Larger associations (> 50 members) are called **clusters**.

- **i)** **Poor clusters** contain anywhere from 50 to a few hundred galaxies.

- **ii)** **Rich clusters** can contain nearly a thousand galaxies.

- **iii)** Rich clusters are about 8.5 Mpc across.

- **iv)** The galaxies of a rich cluster have velocity dispersions that range between 800 km/s and 1000 km/s.

- **v)** The average mass of a rich cluster is $1.4 \times 10^{15} M_\odot$ as obtained from the virial theorem.

- **vi)** If a cluster has a spherical distribution of galaxies with a central concentration (typically with a giant elliptical galaxy at the center) it is called **regular**.

- **vii)** If the cluster is not spherically symmetric it is called **irregular**.

- **viii)** The mass-to-light ratio for galaxy clusters is approximately 560 $M_\odot / L_\odot \Longrightarrow$ clusters contain even a larger percentage of dark matter with respect to luminous matter as compared to smaller groups.

ix) The nearest cluster to the Milky Way is the **Virgo cluster** some 16 Mpc distant.

- It is an irregular cluster containing 205 members.

- It contains 3 giant elliptical galaxies (M84, M86, and M87), with M87 as the largest near the center of this cluster.

- M87 alone is as big (in size) as the entire Local Group of galaxies and is approximately $3 \times 10^{13} M_\odot$!

- M87 as a mass-to-light ratio of 750 $M_\odot/L_\odot$ — 250 times the mass-to-light ratio of the Milky Way $\Longrightarrow$ M87 is made up of 99% dark matter!

- The Local Group has a peculiar velocity of 168 ± 50 km/s in the direction of the Virgo cluster $\Longrightarrow$ we are falling in towards the center of the Virgo cluster. This peculiar velocity of the Local Group is called the **Virgocentric peculiar velocity**.

x) The nearest rich cluster is the **Coma cluster** at a distance of 90 Mpc and 6 Mpc in diameter. This rich cluster contains on the order of 10,000 galaxies!

2. Clusters of galaxies conglomerate into groups called **superclusters**.

- **a)** Superclusters typically have an elongated (*i.e.*, cigar) shape that are between 50 to 75 Mpc long.

- **b)** The Virgo cluster is near the center of the **Local Supercluster** in which the Local Group is a member. The Local Supercluster has a mass of approximately $10^{15} M_\odot$ and a mass-to-light ratio of 560 $M_\odot / L_\odot$.

- **c)** Two superclusters lie to either side of our supercluster, the Perseus-Pisces supercluster at a distance of 70 Mpc and the Hydra-Centaurus supercluster at a distance of 42 Mpc.

- **d)** There is a large-scale streaming motion (relative to the Hubble Flow) of the Virgo cluster, Local Group, and a thousand other galaxies through space at $\sim$ 600 km/s towards the constellation of Centaurus.

    - **i)** This riverlike motion extends at least 56 Mpc both upstream and downstream of us.

    - **ii)** The Hydra-Centaurus supercluster is not the cause of this motion since it too is following the "river." This implies that the source of this motion lies beyond this supercluster.

    - **iii)** The source of this riverlike motion is referred to as the **Great Attractor** (GA) and is thought to lie some 65 Mpc away. There is a diffuse collection of galaxies at that location, but their masses are insufficient to account for the motion. The GA may be composed of 90% dark matter!

Figure X–1: Cartoon of a double-lobed radio galaxy.

3. Superclusters are linked together in a filamentary structure with giant voids (bigger than the superclusters) in between the superclusters (see Fig. 25.21 in the textbook).

E. Active Galaxies

1. Radio Galaxies.

a) They are strong radio sources (10^7 times more radio energy than normal galaxies).

b) They are usually associated with giant elliptical galaxies (see Figure X-1).

c) Two basic types have been observed: **double-lobed** and **active-core**.

i) Double-lobed:

- They radiate synchrotron radiation: e^- spiraling in a strong magnetic field.

- The most intense portion of the radio light is from the back side of the lobes away from the optical galaxy.

- The lobes store large amounts of energy $\Longrightarrow$ energy emitted = energy produced by 1 million stars.

- Periodic eruptions from the core of the galaxy produce *jets* which takes material out to the lobes.

ii) Active-core:

- These radio galaxies have strong radio emission from the core with no apparent lobes associated with the galaxy.

- These active-core radio galaxies may represent the initial stages of the formation of a double-lobed source.

d) Spectroscopically, radio galaxies also can be classified as:

i) **Broad-Line Radio Galaxies** (BLRG) which have broad emission lines. These galaxies are associated optically with **N galaxies**, which have a bright, starlike nucleus surrounded by a very faint, hazy envelope.

ii) **Narrow-Line Radio Galaxies** (NLRG) which have narrow emission lines. These galaxies are associated optically with giant elliptical galaxies (typically of the **cD** class).

e) The model of the evolution of a radio galaxy:

i) A supermassive black hole (SBH) at the center of a giant elliptical galaxy (GEG) gobbles up gas

Figure X–2: Galactic cannibalism as the cause of radio galaxies.

from a low mass galaxy that has ventured too close to the GEG (see Figure X-2).

ii) Gas from the low mass galaxy falls towards the SBH and forms an accretion disk surrounding the SBH.

iii) The gas flows into the SBH faster than the SBH can *eat* it $\Longrightarrow$ jets form above and below the disk (they *turn on* — see Figure X-3).

iv) The jets remain on as long as matter flows into the SBH. Temps are high in the jets, ionizing the gas. The flow of these charged particles produces a magnetic field. Electrons spiral around the strong magnetic field lines producing synchrotron radiation.

Figure X–3: Accretion disk and jet formation.

v) Millions of years pass so that the jets have expanded from up to 100's to 1000's of kpcs from the core and SBH as shown in Figure X-4.

vi) As the jets expand, the pressure in the bow of the jets decrease until they come into pressure equilibrium with the surrounding intergalactic medium. This acts like a dam and the free electrons start forming a reservoir behind it $\Longrightarrow$ the **radio lobes** (see Figure X-5).

vii) As time passes, the SBH consumes all of the gas from the collision with the small galaxy and the jets turn off, just leaving the radio lobes behind (see Figure X-6).

viii) Even later, the lobes dissipate leaving the GEG alone, ready for another galaxy encounter!

Figure X–4: Jets pushing outward from the GEG.

Figure X–5: Formation of radio lobes.

Figure X–6: Jets turn off in the radio galaxy.

2. **N Galaxies**.

   a) Elliptical galaxies with a bright nucleus. Often appear with jets originating from the core.

   b) Some are radio sources. Broad emission lines are seen in their nucleus.

   c) Probably related to a very early stage of the GEG radio galaxies.

   d) **BL Lac Objects** are probably related to N galaxies except they show no emission lines $\Longrightarrow$ featureless continuum.

      i) Their extragalactic nature was demonstrated when spectra was obtained from *fuzz* that appears around these objects.

      ii) Their redshifts showed them at extragalactic distances.

      iii) The fact that we don't see emission lines probably has to do with the orientation that these galaxies are being observed (see below).

3. **Seyfert Galaxies**.

   a) Spiral galaxies with unusually bright tiny cores that fluctuate in brightness (10% of the most luminous spirals are Seyferts).

   b) Very bright in the IR.

   c) About 100 out of the known 700 emit X-rays, a few have been seen to emit gamma rays $\Longrightarrow$ SBH are thought to be responsible for the large energy output.

d) Nuclear region shows emission lines and some synchrotron radiation $\Longrightarrow$ strong magnetic field.

e) These are probably the spiral analogy to the elliptical N galaxies.

f) This galaxy class comes in two flavors:

  i) **Seyfert 1** galaxies have very broad emission lines that include both allowed line (H I, He I, He II) and narrower forbidden lines (such as [O III]).

  ii) **Seyfert 2** galaxies have only narrow lines (both permitted and forbidden).

4. Quasars and Quasi-Stellar Objects (QSOs).

a) The difference between *quasars* and *QSOs* is that quasars are strong radio sources whereas QSOs are not. Both probably represent the same type of object however.

b) These are objects that appear stellar (*i.e.*, point sources) at visible wavelengths. They show very high redshifts:

  i) Most have *relativistic* redshifts (*i.e.*, $z \geq 0.2$).

  ii) Largest redshift observed for a quasar is PC 1247+3406 with $z = 4.897$ (which corresponds to $v_r = 0.94c$ and $d = 4.0$ Gpc from Hubble's Law with $H_\circ = 71$ km/s/Mpc — note that 1 Gpc = 10^9 pc).

c) For their great distances, they should be too faint to be seen if they were normal galaxies $\Longrightarrow$ they must emit tremendous amounts of energy (1000 times the luminosity of a GEG)!

d) Fluctuations in light occur over a period of just a few weeks $\Longrightarrow$ the light emitting region must be smaller than a few light weeks in diameter (*i.e.*, size of the solar system).

e) Deep exposures of QSOs with the Keck 10-m telescope and HST have shown *fuzz* around the starlike nucleus of the QSO which demonstrates that these object are indeed galaxies with active nuclei.

f) Emission lines are typically seen similar to Seyferts.

g) Usually strong emitters of X-rays and IR light.

h) Where is all of this energy coming from?

  i) Maybe quasars are not as far away as their redshifts indicate.

  - Arp has taken photos of quasars near galaxies of lower redshifts and they appear to be connected with a bridge of gas.

  - Then we have a new problem — what causes the severe redshifts?

  - We now have evidence for quasar images caused by gravitational lensing $\Longrightarrow$ quasars must be *cosmologically* distant for this to happen (see Figure X-7)!

Figure X–7: Gravitational lensing of quasar due to an intervening galaxy.

- A model where quasars are not cosmological distant (*i.e.*, not far away) is called the **Local Hypothesis** — it is no longer supported by observations (nor the astronomical community).

ii) More likely, gas falling into a SBH causes this tremendous energy output. Many quasars are seen with jets which supports this model.

i) **Blazars** are probably related to quasars, except like the BL Lac objects, they have no emission lines. Blazars and BL Lac objects result from the outward moving jets pointing in our direction, whereas quasars and N galaxies have jets that are being viewed at an angle to the line-of-sight.

5. Jets that are seen in these active galaxies often show **superluminal** motion $\Longrightarrow$ blobs in the jets appear to move faster than light! In reality, the blobs are not moving faster than light but are traveling *close* to the speed of light. Relativistic effect cause the apparent larger than light velocities. See §26.3 on pages 1194 to 1202 in the textbook for details of superluminal jets.

6. There are various observations and theoretical studies that suggest that supermassive black holes are responsible for all of this activity. Please see §26.2 on pages 1178 to 1194 in the Carroll and Ostlie textbook for details.

7. Since QSO's are so bright and so distant, we can use them as probes to investigate the **intergalactic medium** (IGM) via the **Lyman-$\boldsymbol{\alpha}$ forest**. These are Lyman-α hydrogen absorption lines from intergalactic clouds at various redshifts that lie between us and a QSO (see Figure 25.40 in the textbook).

8. The gravitational potential well of clusters that lie between us and a QSO can be probed by the distortion in the QSO's image. The cluster acts like a **gravitational lens** (see Figure 26.39).

F. Galactic Evolution.

1. Even though the Hubble sequence does not define an evolutionary sequence, galaxies do change in time from a variety of processes.
   - a) Stellar evolution within the galaxy causes a chemical evolution of the ISM of a galaxy.
   - b) Internal dynamic evolution in the form of disruption of star clusters from *differential galactic rotation* and *tidal stripping* for clusters that get to close to the center of a galaxy.
   - c) External dynamic evolution from galaxy collisions.

2. We will save a discussion of the formation of galaxies until the next section (§XI). We don't have time to cover the details of galactic evolution in lecture. Instead, read Chapter 24 in the Carroll and Ostlie textbook carefully for a full description of this material.