ASTR-1020: Astronomy II
Course Lecture Notes
Section X

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Edition 4.0

Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

X. Galaxies in the Universe

A. Normal Galaxies

1. Classification of galaxies $\Longrightarrow$ **Hubble's Tuning Fork Diagram** (see Fig X-1)

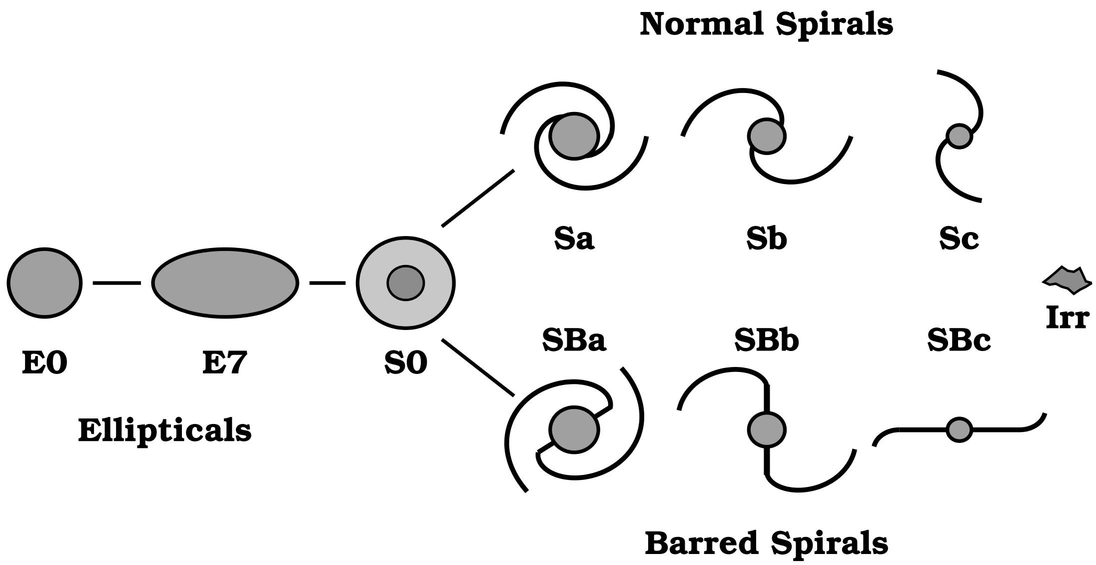

Figure X–1: Hubble Tuning-Fork Diagram

a) There are 3 main classes of galaxies:

i) Ellipticals:

— they appear round or elliptical in shape: E0 (circular), E1, E2, E3, E4, E5, E6, and E7 (most elliptical);

— have almost no gas or dust;

— population II stars (no O & B stars);

— dwarf elliptical are the least massive galaxies in the Universe;

— giant ellipticals are the most massive.

ii) Spirals:

— 3 distinct types: **lenticulars** (S0 & SB0), **normal spirals** (Sa, Sb, Sc), and **barred spirals** (SBa, SBb, SBc);

— Lenticulars (a disk but no spiral arms):

= very little dust and gas;

= few O & B stars;

= large central nucleus;

— Normals (subdivided into 3 categories):

= Sa: little dust and gas;

: large nuclei;

: tightly wound arms;

= Sb: intermediate in all categories;

= Sc: large clouds of dust and gas;

: small nuclei;

: loosely wound arms;

— Barred (3 subdivisions): classified like normals but these galaxies have bar-like structures going through their nuclei.

iii) Irregulars:

— small (5% – 25% the diameter of Milky Way);

— large clouds of dust and gas;

— the Milky Way's satellite galaxies, the Large and Small Magellanic Clouds, are good examples of irregular galaxies.

b) The Milky Way was originally thought to be an Sb spiral. However, recent observations of the nuclear regions of the Milky Way suggest that the Milky Way is an SBb galaxy! (See Page IX-9 of these notes.)

c) The Hubble sequence was originally thought to be an evolutionary sequence (E0 → E7 → Sa → Sc → Irr or vise versa) — **it is not!**

i) Ellipticals cannot <u>on their own</u> evolve into spirals since ellipticals have little or no gas and dust compared to the spirals hence cannot be younger.

ii) Spirals cannot <u>on their own</u> evolve into ellipticals since spirals have many stars with high metal abundance and ellipticals have stars with low metal abundance hence cannot be younger.

iii) However, our current understanding of galaxy dynamics suggests that many, perhaps all, spirals may form as a result of galaxy interactions.

iv) Elliptical galaxies, at least the giant elliptical galaxies may form from galaxy mergers. Indeed, models show that a merging of two spirals could lead to the formation of a giant elliptical galaxy.

d) 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. [Why would you think this is the case?]

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

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

i) Cepheids ($P \rightarrow m - M_V \rightarrow d$).

ii) O & B main sequence stars (*i.e.*, spectroscopic parallax).

b) Galaxies with $d < 40$ Mpc:

i) Giant H II regions.

ii) Globular star clusters.

iii) Both of these are typically the brightest objects in a galaxy.

c) Galaxies with $d < 600$ Mpc:

i) Brightest galaxy in a cluster.

ii) Supernovae.

iii) 21-cm H line width: $v_{rot} \propto M \propto L \Longrightarrow$ this is the **Tully-Fisher relation**.

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

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

3. 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

$\Longrightarrow$ **The Universe is Expanding.**

c) Hubble's Law mathematically:

$$\boxed{v_r = H_\circ \, d \ ,} \qquad \text{(X-1)}$$

$v_r \equiv$ recession velocity
$d \equiv$ distance
$H_\circ \equiv$ Hubble's constant
$= 71$ km/sec/Mpc (based on current measurements).

i) Prior to the launch of the *Hubble Space Telescope* (HST), $H_\circ$ was not accurately known (values ranged from 50 to 90 km/sec/Mpc) $\Longrightarrow$ its actual value is of the utmost importance!

ii) The primary reason the HST was built was to determine an accurate value for $H_\circ$. Based on measurements by HST, $H_\circ = 72 \pm 8$ km/sec/Mpc (where the ± 8 is the uncertainty of the measurements).

iii) In 2001, the Wilkinson Microwave Anisotropy Probe (WMAP) was launched to study the cosmic microwave background of the Big Bang (see §XI of these notes). One of the results of this mission was a determination of Hubble's constant, which has determined the most accurate value to date: $H_\circ = 71 \pm 4$ km/sec/Mpc (where the ± 4 is the uncertainty of the measurements).

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?

$$\begin{aligned} v_r &= \frac{\Delta\lambda}{\lambda_\circ}\, c = \frac{4800 \text{ Å} - 4000 \text{ Å}}{4000 \text{ Å}} \,(3.00 \times 10^5 \text{ km/s}) \\ &= \frac{800 \text{ Å}}{4000 \text{ Å}} \,(3.00 \times 10^5 \text{ km/s}) \\ &= 0.2\,(3.00 \times 10^5 \text{ km/s}) = 6.00 \times 10^4 \text{ km/s} \\ d &= \frac{v_r}{H_\circ} = \frac{6.00 \times 10^4 \text{ km/s}}{71 \text{ km/s/Mpc}} = 8.50 \times 10^2 \text{ Mpc} \end{aligned}$$

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

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d) The redshift z is defined as

$$z = \frac{\Delta\lambda}{\lambda_\circ} = \frac{v_r}{c}, \qquad \text{(X-2)}$$

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

$$z = \frac{\Delta\lambda}{\lambda_\circ} = \frac{\sqrt{1 + v_r/c}}{\sqrt{1 - v_r/c}} - 1, \qquad \text{(X-3)}$$

for the *relativistic* (*i.e.*, $v_r \lesssim c$) version.

4. Galaxies range in mass from $10^{-6}\ M_{\rm MW}$ to $50\ M_{\rm MW}$ ($1\ M_{\rm MW} = 6 \times 10^{11}\ M_\odot$ is the mass of the Milky Way Galaxy).

a) Note that this mass of the Milky Way included material out to 40 kpc from the galactic center.

b) The mass of the Milky Way within 15 kpc of the galactic center is $2 \times 10^{11}\ M_\odot$.

c) Finally the mass of the Milky Way inside the Sun's position (8 kpc from the galactic center) is $9 \times 10^{10}\ M_\odot$.

5. Galaxies are not isolated but are located in groups called *clusters of galaxies.*

a) Galaxies form in clusters just as stars do.

b) The Milky Way and Andromeda (M31) galaxies are the 2 most massive galaxies in our galaxy cluster called the **Local Group**. It is a small cluster containing nearly 50 members (see Fig. 24.13 in text).

c) Over 2700 clusters have been cataloged within 4 billion light years of the Milky Way.

d) There are rich clusters (see Fig. 24.15 in the text) which contain 1000 galaxies or more in a spherical volume about 3 Mpc in diameter with typically a **giant elliptical galaxy** (GEG) at the center.

i) The density of galaxies is so high near the center that galaxy collisions can occur.

ii) The GEG can cannibalize smaller galaxies $\Longrightarrow$ **galactic cannibalism**.

iii) As earlier mentioned, galaxies of similar size also can collide which induces either spiral arms, tails, or rings to form (see Figs. 25.6, 25.7, and 25.8 in the text).

iv) The **Virgo cluster** is the nearest rich cluster to us. M87 (a GEG) is at its center. The Local Group is actually part of the Virgo cluster lying on its outer regions.

e) There are poor clusters which contain less than a few hundred galaxies.

i) No central condensation of galaxies.

ii) The Local Group is a good example of a poor cluster.

6. Clusters of galaxies conglomerate into groups called **superclusters**. They are from 50 to 75 Mpc in extent.

7. Superclusters are linked together in a filamentary structure with giant voids (bigger than the superclusters) in between the superclusters (see Fig. 25.24).

B. Active Galaxies

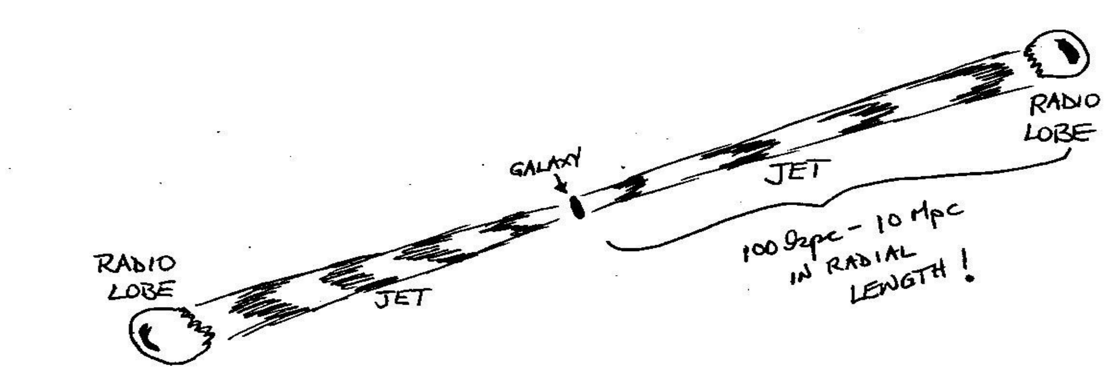
1. Radio Galaxies.

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

b) They are usually elliptical galaxies.

c) Two types: *Double-lobed* and *Active-core.*

i) Double-lobed:



— they radiate synchrotron radiation: e^- spiraling in a strong magnetic field;

— most intense radio light from the back side of the lobes away from the optical galaxy;

— much energy in the lobes $\Longrightarrow$ 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.

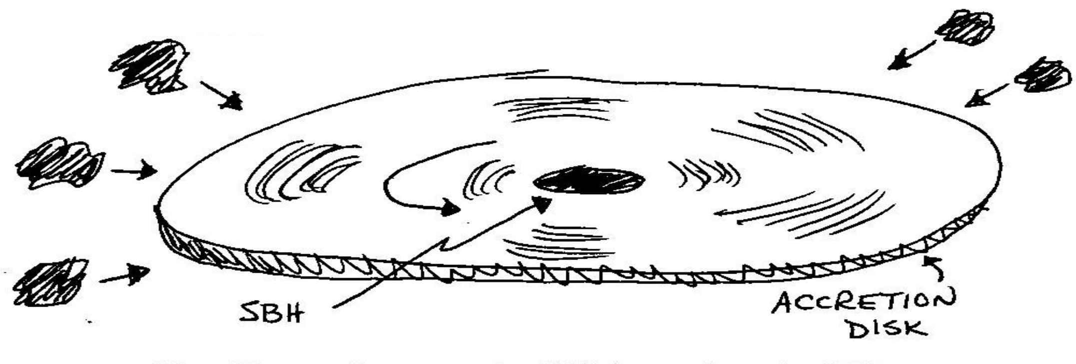
ii) Active-core:

— strong radio emission from the core (*i.e.*, the periodic eruptions).

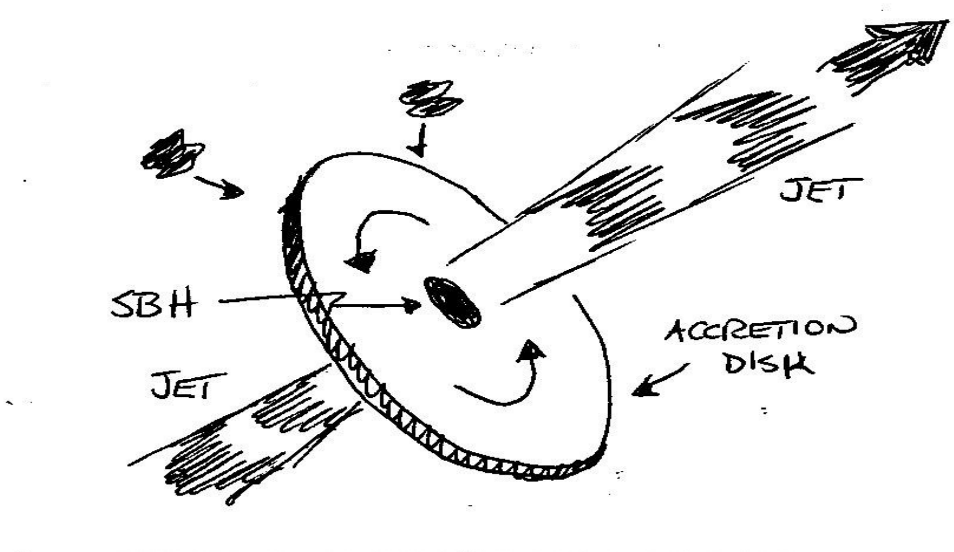
d) The model:

i) A supermassive black hole (SBH) at the center of a giant elliptical galaxy (GEG) gobbles up gas from a low mass galaxy that has ventured too close to the GEG.

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

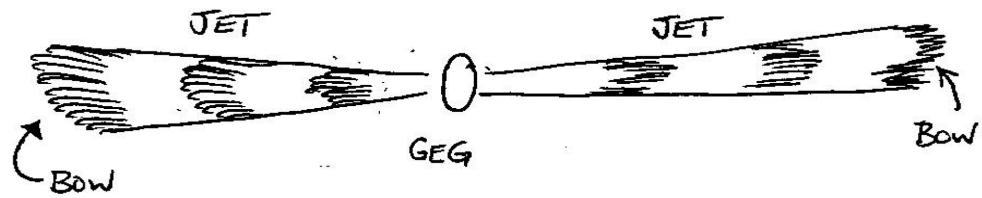


iii) The gas flows into the SBH faster than the SBH can *eat* it $\Longrightarrow$ jets form above and below the disk (they *turn on*).

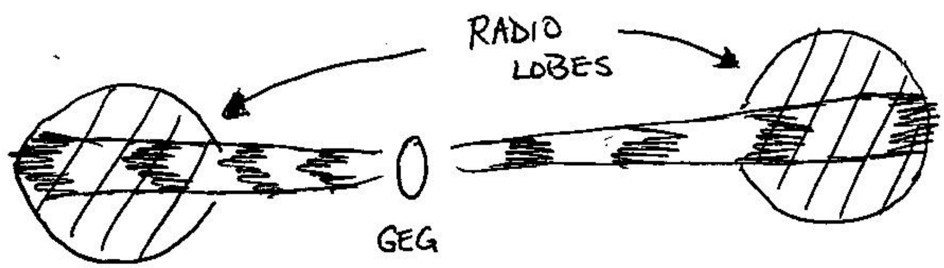


iv) The jets remain on as long as matter flows into the SBH. Temperatures are high in the jets, ionizing the gas. The flow of these charged particles produces a magnetic field. Electrons spiral around the strong magnetic field lines producing synchrotron radiation.

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.



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**.



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.

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

2. **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 (spiral galaxy analogy to GEG radio galaxy).

d) The core emits synchrotron radiation $\Longrightarrow$ strong magnetic field.

e) Emission lines are seen on a continuum spectrum.

3. Quasars (QSOs).

a) 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 $z = 6.43$ ($d = 4.1$ Gpc $= 13.3$ billion light years, note that 1 Gpc $= 10^9$ pc, where the 'G' is the metric system unit prefix for 'giga').

b) About 10% of them are strong radio sources.

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) Emission lines are typically seen on a continuous spectrum.

f) Where is all of this energy coming from?

i) Perhaps 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 (see Fig. 25.29 in the text) $\Longrightarrow$ quasars must be *cosmologically* distant for this to happen!

— A model where quasars are not cosmological distant (*i.e.*, not far away) is called the **Local Hypothesis** — it is no longer supported by 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.