Galactic Classifications and AGN

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1 Introduction

Galaxies are extremely important large-scale structures in the Universe, containing millions of stars and planets. We all live in the Milky Way, and helping better understand galaxies provides a crucial basis for understanding the universe as a whole.

2 What is a Galaxy?

A **galaxy** is a large collection of gravitationally bound stars orbiting a central supermassive black hole. Galaxies are extremely far away, and distances to other galaxies are measured in Mpc (megaparsecs, 10^6 pc). When we study galaxies, cosmological effects, like the expansion of the universe, need to be taken into account. Those effects are important for understanding observations such as the fact that almost all galaxies appear redshifted (longer wavelength light, due to the Doppler effect and the expansion of the universe).

Figure 1: The Milky Way Galaxy (Source: Universe Today)

Galaxies at different distances also are visible from different stages in the evolution of the universe, which can be another important factor to take into account. Galaxies are often clustered into **galaxy clusters**, which are then in turn part of larger **superclusters**. Our galaxy, the Milky Way, is part of **the Local Group**, a collection of 30 galaxies, the two largest of which are the Milky Way and Andromeda (M31, the only other galaxy visible to the naked eye), and it is near the larger **Virgo supercluster**.

3 Hubble Sequence and Galaxy Classifications

Galaxies are classified according to the Hubble Tuning-fork diagram.

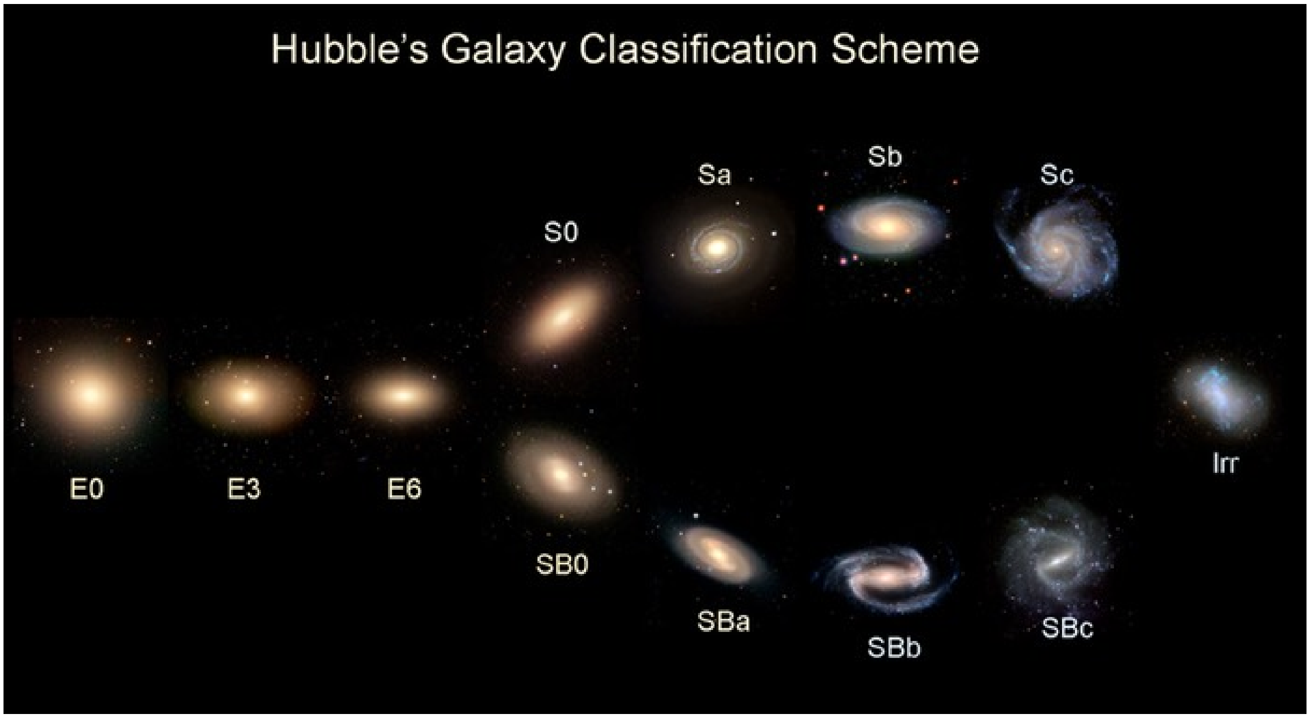

Figure 2: A Hubble tuning-fork diagram (Source: University of Iowa)

In the Hubble tuning-fork, there are 4 general classes: **ellipticals (E)**, **normal spirals (S)**, **barred spirals (SB)**, and **Irregulars (Irr)**. The transition between ellipticals and spirals, known as **lenticular** galaxies, are referred to as **S0**. Sometimes, due to incorrect historical reasons, the leftwards galaxies are called early type, and the rightwards ones late type, and although the reasoning for this terminology was incorrect it is still used frequently.

Example 3.1: (USAAAO Round One 2022) Classify the following galaxies according the Hubble galaxies classification:

Figure 1: Galaxy 1

Figure 2: Galaxy 2

Figure 3: Galaxy 3

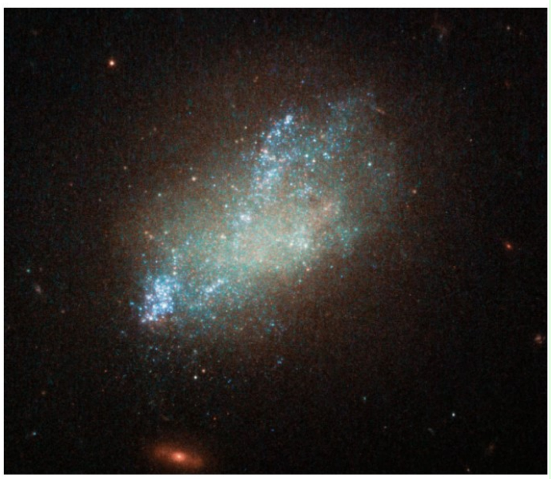

Figure 4: Galaxy 4

Figure 5: Galaxy 5

(a) Sb, Sc, Peculiar, E2, Irregular
(b) Sbc, E4, Irregular, Sb, Peculiar
(c) E3, Sbc, Sa, Peculiar, Irregular
(d) Sc,Sba, Sbc, E2, Peculiar
(e) Sa, Sbb, E3, Irregular, Peculiar

Solution: We can clearly see that the first galaxy is a spiral, with a relatively prominent bulge and well-defined arms, ruling out options c and d. We can clearly see the second galaxy is also a spiral, ruling out b. We can clearly see the third image is an elliptical, ruling out a and leaving us with the **correct answer, E**.

The numbers used in the elliptical galaxy classifications refer to the ellipticity of the galaxy, as defined by

$$\epsilon = 1 - \frac{\beta}{\alpha}$$

and the Hubble type is 10ϵ. The typical range of elliptical galaxies is from E0 to E7. α and β are the apparent semi-minor and semi-major axis respectively. This classification is not physically based, and instead depends on the relative orientation.

For both spiral and barred spiral galaxies, the letters refer to how tightly wound and resolved the arms are and how prominent the bulges are. Sa or SBa are the most tightly wound and resolved arms and most prominent bulges, followed by Sb or SBb, and so on and so forth. Mixed letter categorizations exist, and the Milky way is thought to be an SBbc. Spirals of type Sd and later are called **dwarf spirals**. Some are also designated Sm, which does not refer to an extremely late-type spiral, but instead a **Magellanic type** (has a single spiral arm). Galaxies with a weaker bar can be referred to as SAB. Spiral galaxies can also be classified based on luminosity from I to V, based on how distinct/bright the arms are.

Figure 3: A Magellanic type galaxy (Source: Astronomy Magazine)

Figure 4: A galaxy with a weaker bar, M83 (Source: Wikipedia)

Lenticulars are referred to as S0 or SB0, depending on whether a bar is visible of not, with subscript to indicate the amount of dust visible. $S0_1$ galaxies have no dust, while $S0_2$ have some, and $S0_3$ have significant amounts of dust.

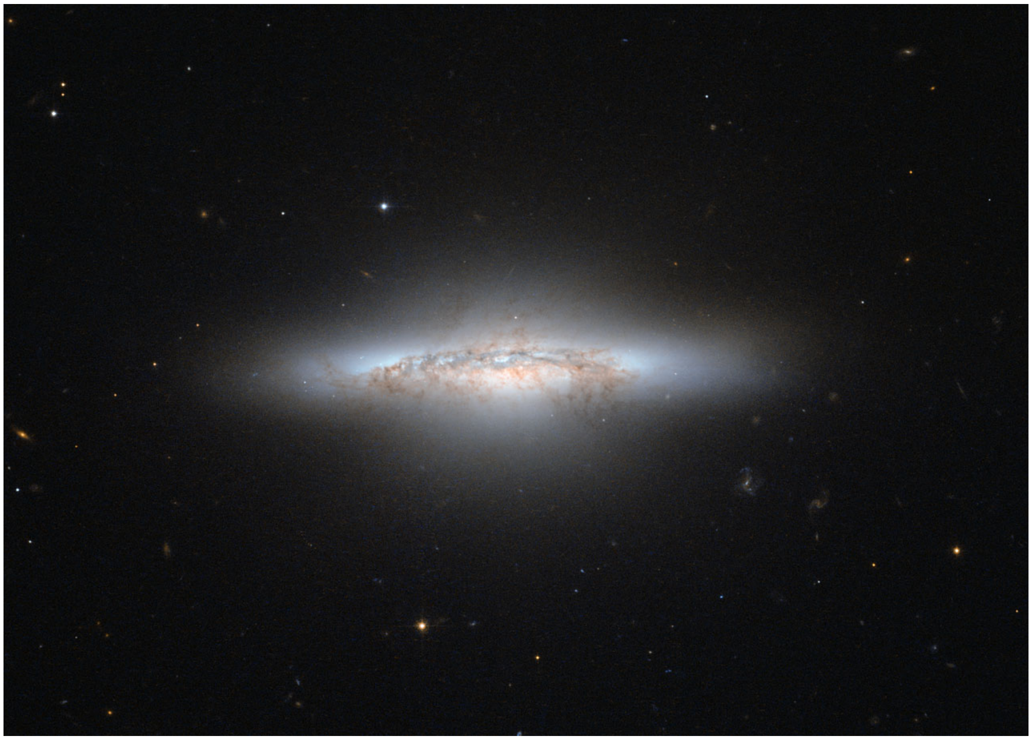

Figure 5: A lenticular galaxy, NGC 5010 (Source: NASA)

Irregulars are split into Irr I and Irr II, with **Irr I** having some form of organized structure, like a spiral arm, and **Irr II** having none whatsoever. Irr II can also be termed Ir or amorphous.

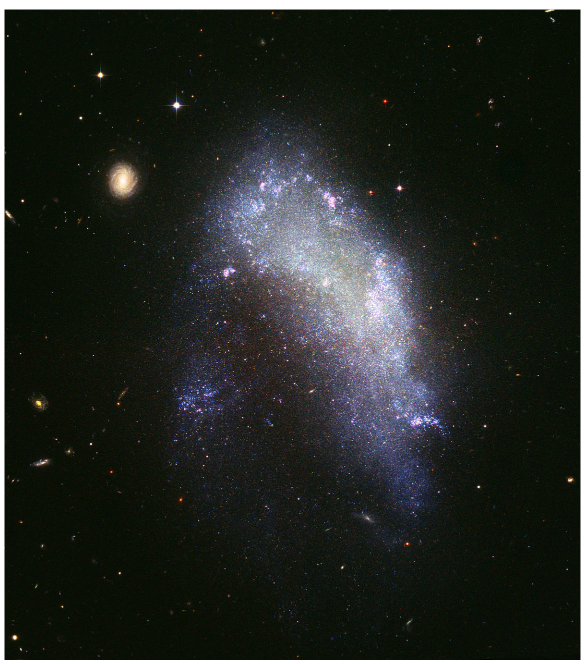

Figure 6: An irregular galaxy, NGC 1427A (Source: Wikipedia)

Designations of (s) for spiral arms that reach the center and (r) for inner bright disk also exist, which go after the Sa/Sb/Sc... designation as Sa(s) or Sa(r) and so on. Large, outer rings are designated with R, as RSa, RSb, and so on. The ring designations can also apply to lenticular galaxies.

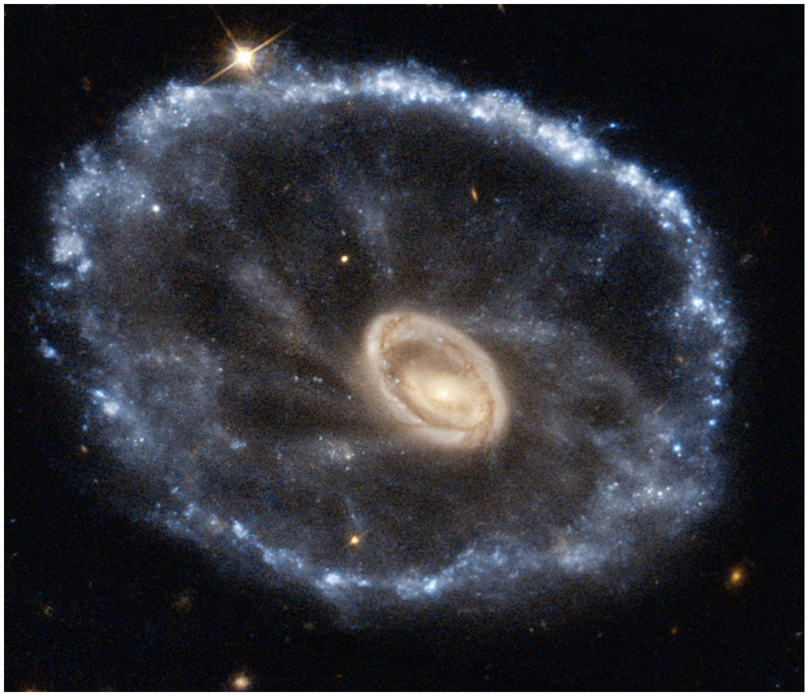

Figure 7: A galaxy with a ring, the cartwheel galaxy (Source: Arizona State University)

4 Spirals

Figure 8: A spiral galaxy, galaxy m101 (Source: Wikipedia)

Spiral galaxies have large and majestic arms. The largest and most majestic arms are called **grand-design** spirals, while the least well-defined ones are called **flocculent**. Very few spiral galaxies are grand design. Earlier spirals are more massive, rotate faster, have less gas and dust, and have more old, red stars. However, in all spiral galaxies, the arms tend to have more bright, young, blue stars, as well as large HII regions.

Most spiral arms are trailing, with the tips appearing to "bend back" opposite the direction of rotation (in the manner most people would expect). However, some galaxies do have arms that point in the other direction.

The origin of these arms is debated, but it is thought to have been caused by a series of density fluctuations in star density, which can be described by **Lin-Shu density wave theory**. While it may seem initially like the arms can be explained by differential rotation, this leads to arm over-winding relatively quickly. Lin-Shu density wave theory accounts for this by suggesting an overdensity quasi-static wave that stars can move independently of, but tend to follow and trigger star formation enough to lead to bright prominences.

This theory explains the central and inwards nature of many dust bands (differential rotation and less tight binding to the arms), the young, bright, blue stars and HII regions (triggered by the motion and density waves), and the large amount of old, red stars (which have fallen out of the arms).

5 Ellipticals

Figure 9: An elliptical galaxy, galaxy NGC 4150 (Source: Wikipedia)

There appear to be, separate from the Hubble classifications, five classes of elliptical galaxies.

cD galaxies are large, rare, bright elliptical galaxies almost 1 Mpc in size (compared to 0.1 for the largest spirals like the Milky Way), and are usually near galactic cluster centers. They are extremely massive, with very bright central regions and large diffuse envelopes, and many globular clusters, and very large amounts of dark matter.

Normal ellipticals are condensed galaxies largely comparable to spirals in their parameters, and include the **giant ellipticals (gE)** which are the same size as large spirals; **intermediate luminosity ellipticals (E)** which are average; and **compact ellipticals (cE)** which are slightly tighter in size.

dE or **dwarf ellipticals** have relatively low surface brightnesses, and are small in size and mass, as well as having relatively low metallicities.

dSph or **dwarf spheriodals** have even lower surface brightnesses and are even smaller than dE.

BCD or **blue compact dwarf galaxies** are small very blue galaxies, which indicates strong star formation. They are relatively small, have large amounts of gas, and low mass-to light ratios.

Overall, most ellipticals have less gas than comparably sized spirals do, but a significant amount of dust, including dust that is often rotating in the opposite direction of the galaxy. The rotation scheme of most ellipticals is not clear.

6 Irregulars

Irregular galaxies are highly varied in nature. Most ellipticals are thought to be undergoing or have recently undergone tidal interactions with another galaxy, or are undergoing a galaxy merger of some form that has disturbed the galaxy from its normal morphology and led to its irregular shape.

7 Galactic HR Diagrams

Galactic distances, and a sense of galactic evolution, can also be determined via cluster HR diagrams and main sequence fitting. This involves creating an HR diagram, and analyzing the type of star past which stars start leaving the main sequence, known as the **turn-off point**, which can reveal a lot of information.

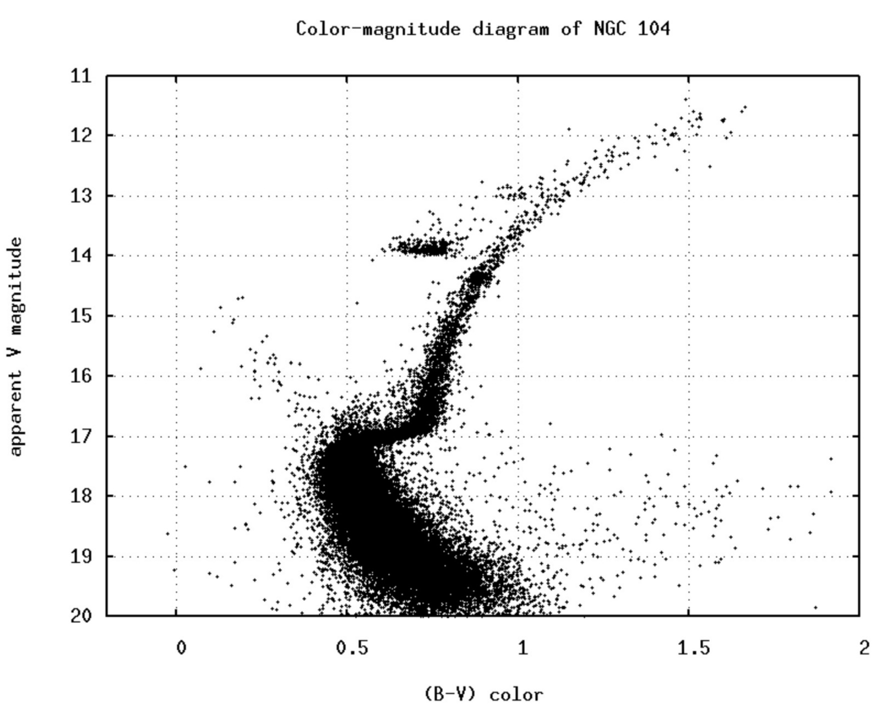

Figure 10: An HR diagram for a cluster (Source: RIT)

8 What is an AGN?

AGN, or **active galactic nuclei**, are galactic centers that are actively accreting large amounts of matter. They are extremely bright, and very energetic. There are a large number of classes of AGN; here is a brief overview of them:

Seyfert I galaxies appear to be star-like, with narrow lines and broad lines. **Seyfert II galaxies** are similar but only have narrow lines. **Seyfert 1.5s** are intermediate. Most are spirals.

Radio galaxies have extremely bright radio lobes that are moving away from the center. These can also be classified into broad and narrow, as **BLRGs** and **NLRGs**.

Quasars are higher redshift active galaxies, and include **radio-quiet** and **radio-loud** types. These are often also designated as QSOs (quasi-stellar objects) which are radio quiet, as well as QSRs (which stands for quasars, but in an old designation that only applies to radio-loud galaxies) which are radio loud.

LIRG (Luminous Infrared Galaxies), and **ULIRG** (Ultraluminous Infrared Galaxies), are two more designations which are bright at infrafed wavelengths.

Blazars are a sub-class of highly variable and highly linearly polarized in the visible range active galaxies. Two common blazar sub-designations are **BL Lac objects**, which are variable on very small timescales, as well as much more luminous and broad-line containing **OVV**s, or Optically violently variable quasars.

LINERs are Low Ionization Nuclear Emission-line Regions that are not especially bright in the nuclear region, but have strong emission lines relatively.

9 The Unified Model

The unified model of AGN describes a single process and regime to generate all of the above galactic types. Since their discovery, AGN have been classified into two types, type I and type II, based on whether broad lines were visible or not. Broad lines have more thermal Doppler broadening. A relatively recent and still not fully proven theory seeks to unify these two types by describing them as the same thing, just being viewed from different angles (like viewing a frisbee from the top versus from the side). This theory is called the **unified model**, and countless versions of it exist in the literature.

A confirmation or disproval of various forms of the unified model has the potential to revolutionize our understanding of galactic centers, and all that comes with it. The most common formulation of the unified model proposes that AGN have a hot disk-shaped broad-line region around a central black hole, with a cooler dusty *toroidal* (donut shaped) region around that, and a collection of warm scattered gas clouds dispersed in general. It also includes two conically shaped **relativistic jets**. This torus is inflated by radiation, and the jets are thought to expel tremendous amounts of relativistic gas and dust, and can lead to extremely large outflow structures.

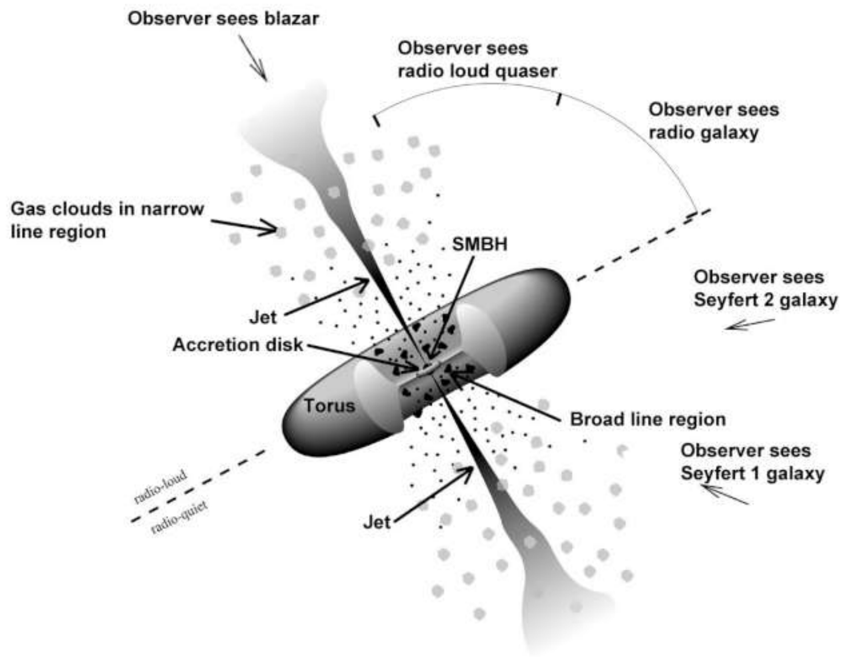

Figure 11: The unified model of AGN (Source: Fermi Gamma-Ray Space Telescope)

While fundamentally the energy for this extreme emission and ejection comes from the accretion, the exact processes through which it is converted into the energy to generate the observed effects is unknown. The leading theory to explain it is the **Blandford-Znajek mechanism**, in which the rotation of a black hole in a magnetic field produces a potential difference with an extremely low resistance, and leads to power being extracted from the rotation of a black hole.

10 Conclusion

Despite being extremely far away and removed from the conditions we experience here on Earth, understanding galaxies and AGNs is crucial to our understanding of the many complexities of the universe, our own galaxy, and our place in the universe.