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UNIT-III GALAXIES

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UNIT 3

GALAXIES

3.1 What is a Galaxy?

A **galaxy** is a vast, gravitationally bound system of stars, stellar remnants, interstellar gas, dust, and dark matter. Galaxies come in various shapes, sizes, and structures, and they are the fundamental building blocks of the universe. A galaxy can contain anywhere from a few million to trillions of stars, all interacting under the influence of gravity.

The word "galaxy" comes from the Greek word **"galaxias"**, meaning "milky," in reference to the Milky Way galaxy. Galaxies are observed as distinct, often brightly luminous collections of stars and other matter, visible across cosmic distances.

Properties of Galaxies

Galaxies, as vast collections of stars, gas, dust, and dark matter, exhibit a range of physical and observational properties that characterize their structure, behavior, and evolution. Understanding these properties is fundamental to understanding the dynamics of the universe itself, as galaxies are the basic building blocks of cosmic structure. In this detailed explanation, we'll break down the key properties of galaxies, which include their **structure**, **morphology**, **stellar population**, **kinematics**, **luminosity and size**, and **environmental effects**.

1. Structure of Galaxies

The structure of a galaxy refers to the spatial distribution and arrangement of its various components. These components may include stars, gas, dust, dark matter, and other material. The typical structure of a galaxy can be broadly classified into several regions:

- **Core/Bulge**:
  - The bulge is the dense, central region of a galaxy, often containing a large concentration of old stars. In spiral galaxies, the bulge is typically spheroidal or ellipsoidal in shape and is thought to be composed of an older stellar population.
  - Most large galaxies, including the Milky Way, contain a **supermassive black hole** at their center, which can exert significant influence on galaxy evolution.

- **Disk**:
  - The disk is the flat, rotating part of a spiral galaxy, containing most of the galaxy's gas, dust, and younger stars. The disk is often divided into distinct components:
    - **Spiral Arms**: In spiral galaxies, the disk contains arms where active star formation occurs. These spiral arms are sites of higher gas density and active stellar birth.
    - **Interstellar Medium (ISM)**: This is the gas and dust scattered throughout the disk, composed of hydrogen, helium, and heavier elements.
- **Halo**:
  - The halo is a spherical region that extends beyond the visible components of the galaxy. It contains **old stars**, **globular clusters**, and **dark matter**. The halo can extend far beyond the visible edge of the galaxy and is a crucial component for understanding galaxy formation, as the dark matter halo provides the gravitational framework for galaxy formation.
- **Spiral Arms (for Spiral Galaxies)**:
  - Spiral arms are the iconic, winding arms in galaxies like the Milky Way. They are regions of active star formation and dense molecular clouds. The arms themselves are not static; they rotate with the galaxy, but they also act as **density waves**, causing the periodic compression of gas and dust, which triggers new star formation.
- **Bar (for Some Spirals)**:
  - Some spiral galaxies feature a **central bar**, a linear structure of stars that extends from the central bulge and often feeds material into the spiral arms. The formation of bars is still a subject of study in galactic dynamics, but bars are thought to play a key role in the evolution of the galaxy.
- **Dark Matter Halo**:
  - Dark matter, which does not emit, absorb, or reflect light, is believed to exist in large amounts around galaxies, forming an extended halo that accounts for a significant portion of a galaxy's mass. The gravitational influence of dark matter is responsible for maintaining the galaxy's structure and rotational velocity, which cannot be explained by the visible matter alone.

2. Morphology and Classification

Galaxies are often classified based on their **morphological** features, especially the shape of their structure and the arrangement of stars within them.

This classification helps astronomers understand the evolutionary history and dynamics of galaxies.

- **Spiral Galaxies** (S):
  - These galaxies have a well-defined disk with spiral arms, where star formation is ongoing. The spiral arms are areas of increased density of gas and dust, where new stars are formed.
  - **Subtypes** of spiral galaxies are classified by the tightness of their spiral arms (e.g., **Sa**, **Sb**, **Sc**), with **Sa** having tightly wound arms and **Sc** having loosely wound arms.
- **Elliptical Galaxies** (E):
  - Elliptical galaxies are generally round or oval-shaped with smooth light profiles, containing very little gas and dust. They have little ongoing star formation and are primarily composed of older, red stars.
  - They are classified by their **ellipticity**, from **E0** (nearly spherical) to **E7** (elongated).
- **Lenticular Galaxies** (S0):
  - Lenticular galaxies share characteristics of both elliptical and spiral galaxies. They have a central bulge and a disk but lack distinct spiral arms. Star formation in lenticular galaxies is either minimal or absent.
- **Irregular Galaxies** (Irr):
  - Irregular galaxies have no well-defined shape. They tend to have an irregular distribution of stars, gas, and dust, often due to a recent interaction or merger with another galaxy. These galaxies may have higher rates of star formation compared to elliptical galaxies.
- **Peculiar Galaxies** (P):
  - Peculiar galaxies do not fit into the regular classifications and may exhibit irregularities due to galaxy collisions, mergers, or other unusual conditions. For example, **Arp galaxies** are a collection of peculiar galaxies with distinctive features caused by gravitational interactions.

3. Stellar Population and Age

The **stellar population** of a galaxy refers to the collection of stars within it, which vary in terms of age, chemical composition, and evolutionary stage.

- **Population I Stars**:
  - These are younger stars, rich in heavy elements (metals, in astrophysical terms). They are typically found in the **disk** of spiral galaxies and are associated with regions of active star formation.
- **Population II Stars**:

  - These are older stars, typically found in the **bulge** or **halo** of a galaxy. They are poor in heavy elements (metal-poor) and formed in the early stages of the galaxy's life. They include stars like red giants and white dwarfs.
- **Population III Stars**:
  - These stars are theoretical stars that would have been the first generation to form after the Big Bang. They would be composed almost entirely of hydrogen and helium, with almost no heavy elements. No direct observations of Population III stars have been made, but their existence is crucial for understanding the early evolution of the universe.

4. Kinematics and Dynamics

The **kinematics** of a galaxy refer to the motion and velocity of its stars, gas, and other components. Kinematics provides insight into the underlying gravitational structure of a galaxy and how it has evolved.

- **Rotational Curves**:
  - The rotational curve of a galaxy describes the variation of the orbital velocity of stars and gas with distance from the galactic center. In spiral galaxies, stars at the outer regions rotate at similar speeds to those near the center. This is contrary to expectations based on visible matter alone and points to the presence of dark matter.
- **Velocity Dispersion**:
  - In elliptical galaxies, stars tend to move in random directions, with a **high velocity dispersion**. This indicates the dominance of the gravitational potential of the galaxy, which is typically more massive than the visible matter can account for, suggesting a large dark matter component.
- **Galaxy Interactions**:
  - The kinematics of galaxies can also be influenced by gravitational interactions with nearby galaxies. These interactions can result in **tidal forces**, leading to **galaxy mergers**, **tidal tails**, and **disturbed shapes**.

5. Luminosity, Size, and Mass

The **luminosity** of a galaxy refers to the total energy emitted by the galaxy across all wavelengths of electromagnetic radiation, typically measured in terms of **solar luminosities (L_0)**. The **size** refers to the spatial extent of the galaxy, usually defined by the radius where the galaxy's light intensity drops to a certain level. The **mass** of a galaxy includes both visible (stars, gas, dust) and invisible components (dark matter).

- **Luminosity**:
  - The luminosity of a galaxy is determined by the number of stars it contains, their temperature, and their distribution. The total luminosity of a galaxy is related to its **stellar population** and the rate of ongoing star formation. Galaxies can be classified as:
    - **Luminous**: Galaxies with high luminosity.
    - **Dwarf**: Smaller, lower luminosity galaxies, which may contain fewer stars.
- **Size**:
  - The size of a galaxy is often expressed by its **effective radius** (r_e), which is the radius within which half of the galaxy's light is emitted. Spiral galaxies tend to have larger disk sizes compared to elliptical galaxies, which may be more compact or even highly extended.
- **Mass**:
  - The mass of a galaxy is dominated by **dark matter**, which accounts for most of its mass. The mass can be inferred through measurements of its gravitational effects, including its rotational curve (for spiral galaxies) and its velocity dispersion (for elliptical galaxies).

6. Environment and Galactic Groupings

The environment in which a galaxy resides can significantly affect its properties. Galaxies are often found in **groups**, **clusters**, or **voids**, and their interactions with other galaxies can influence their morphology and evolution.

- **Galaxy Clusters**:
  - Large collections of galaxies, typically containing hundreds to thousands of galaxies bound together by gravity. The central galaxy in a cluster may be an **elliptical galaxy**. Interaction within clusters can lead to phenomena like **galactic cannibalism**, where smaller galaxies are consumed by larger ones.
- **Galaxy Groups**:
  - Smaller than clusters, galaxy groups contain fewer galaxies (often fewer than 50). In these groups, galaxies may experience tidal interactions or gravitational mergers.

- **Isolated Galaxies**:
    - Some galaxies exist in relative isolation in low-density regions of the universe. These galaxies are less affected by external interactions but may still experience internal evolution and stellar evolution.

Types of Galaxies

Galaxies can be broadly classified based on their **morphological characteristics** (shape and structure) into several types, with the most common being

- **Spiral galaxies**,
- **Elliptical galaxies**,
- **Peculiar galaxies,**
- **Irregular galaxies**, and
- **Lenticular galaxies**

1. Spiral Galaxies

Description:

Spiral galaxies are one of the most common and recognizable types of galaxies in the universe. They are characterized by a **central bulge** surrounded by a flat **disk** with prominent **spiral arms** that wind outward from the center. These galaxies are typically rich in gas and dust, with significant ongoing **star formation** in the spiral arms.

Structure:

- **Central Bulge**: The bulge is a densely packed region of stars at the center of the galaxy, often containing older stars. It may have a roughly spherical shape, and in many spiral galaxies, it hosts a **supermassive black hole** at the core.
- **Spiral Arms**: The spiral arms are regions of active star formation and contain a mix of young, hot stars, as well as large amounts of gas and dust. These arms are wound around the central bulge and can be tightly or loosely wound depending on the galaxy.
- **Disk**: The disk is a flat, rotating region containing stars, gas, and dust. This is where most of the galaxy's stars reside and where ongoing star formation occurs.

- **Halo**: Surrounding the galaxy is a spherical region of older stars and a halo of **dark matter**. The dark matter halo dominates the galaxy's mass but is invisible in optical wavelengths.
- **Stellar Population**: Spiral galaxies typically have a **mixed stellar population** — young stars in the spiral arms and older stars in the bulge and halo.

Examples:

1. **The Milky Way**: Our home galaxy, a classic spiral galaxy with a large disk, well-defined spiral arms, and a prominent central bulge. It is part of the **Local Group** of galaxies.
2. **Andromeda Galaxy (M31)**: The nearest large spiral galaxy to the Milky Way, with a large bulge and two major spiral arms. It is the largest galaxy in the Local Group.
3. **NGC 1300**: A barred spiral galaxy located about 61 million light-years away. It is often cited as a prime example of a **barred spiral** galaxy (a spiral galaxy with a central bar structure).

Types of Spiral Galaxies:

- **Normal Spirals**: Like the Milky Way, these galaxies have well-defined spiral arms and a central bulge. They are classified into different subtypes (Sa, Sb, Sc) based on the size of the bulge and the tightness of the spiral arms.
- **Barred Spirals**: These galaxies have a central **bar-shaped structure** made of stars, which extends out from the central bulge, with spiral arms emerging from the ends of the bar. Example: **NGC 1300**.

2. Elliptical Galaxies

Description:

Elliptical galaxies are often smooth, featureless, and ellipsoid in shape. They lack the distinct spiral structure found in spiral galaxies and have little to no gas and dust. These galaxies are typically composed of older stars and show little to no ongoing star formation. They range from nearly spherical (E0) to more elongated (E7) shapes.

Structure:

- **Shape**: Elliptical galaxies range from nearly spherical (E0) to elongated (E7). The classification depends on the galaxy's **ellipticity** (the degree of elongation).
- **Stars**: These galaxies are predominantly made up of **older stars**, and they contain very little interstellar gas or dust. This leads to a lack of significant star formation, resulting in a **redder** appearance.
- **No Spiral Arms**: Unlike spiral galaxies, elliptical galaxies have no spiral structure or defined arms.
- **Central Bulge**: The central region may be very concentrated, and in many cases, these galaxies contain a **supermassive black hole** at their centers.
- **Halo**: Elliptical galaxies often have a substantial stellar halo that extends beyond the visible part of the galaxy.

Examples:

1. **M87**: One of the largest and most well-known elliptical galaxies, located in the **Virgo Cluster**. It is famous for its **supermassive black hole**, which was imaged by the **Event Horizon Telescope** in 2019.
2. **NGC 5128 (Centaurus A)**: A large elliptical galaxy that shows a characteristic **dust lane** running through its center, indicating some remaining gas and dust. It is located in the **Centaurus Cluster**.
3. **NGC 1399**: Another giant elliptical galaxy in the **Fornax Cluster** with a smooth, elliptical appearance.

Properties of Elliptical Galaxies:

- **Low Star Formation**: Little to no ongoing star formation.
- **Old Stellar Population**: Predominantly made of older stars.
- **Little Gas and Dust**: Most elliptical galaxies lack the gas and dust needed for new stars to form.
- **Large Scale**: Many elliptical galaxies are among the **largest** galaxies in terms of mass and size.

3. Lenticular Galaxies (S0)

Description:

Lenticular galaxies are an intermediate type of galaxy, possessing features of both **spiral galaxies** and **elliptical galaxies**. They have a central bulge and a disk like a spiral galaxy, but their disks lack the prominent spiral arms. They have a

smooth appearance without the extensive star formation seen in spirals. Lenticular galaxies are often found in **galaxy clusters**, and many are considered to be **evolved spiral galaxies** that have exhausted their gas supplies for star formation.

Structure:

- **Bulge**: Like elliptical galaxies, lenticular galaxies have a **central bulge**, but it is typically smaller than those in elliptical galaxies.
- **Disk**: Lenticular galaxies have a disk structure, but unlike spiral galaxies, they **lack spiral arms**. They may have a flat disk, similar to spiral galaxies, but without the distinct star-forming regions.
- **No Ongoing Star Formation**: Lenticular galaxies typically have little to no gas and dust, and thus there is **no significant star formation**.
- **Halo**: Similar to elliptical galaxies, lenticular galaxies may have a stellar halo surrounding the disk, but it is not as prominent.

Examples:

1. **NGC 1023**: A well-known lenticular galaxy in the **Andromeda constellation**, located about 30 million light-years away. It has a central bulge and a disk but lacks spiral arms.
2. **NGC 2748**: Another lenticular galaxy with a prominent central bulge and a flat disk, located in the **Virgo Cluster**.
3. **NGC 1291**: A bright lenticular galaxy in the **Eridanus constellation** with a significant bulge and a smooth disk.

Properties of Lenticular Galaxies:

- **Intermediate Features**: Lenticular galaxies share characteristics with both elliptical and spiral galaxies.
- **Gas-poor**: Like elliptical galaxies, lenticular galaxies have little to no gas and dust, meaning star formation is either absent or minimal.
- **Smooth Disk**: The disk is smooth without the spiral arms that define spiral galaxies.

4. Irregular Galaxies

Description:

Irregular galaxies lack a defined shape or structure, and they do not fit into the well-established categories of spiral, elliptical, or lenticular galaxies. These galaxies are often **disrupted** due to **interactions**, **mergers**, or **gravitational**

forces from nearby galaxies. They can exhibit a variety of features, including regions of intense star formation and unusual gas distribution.

Structure:

- **Shape**: The shape of irregular galaxies is highly **asymmetric** and often appears chaotic. There is no central bulge, no disk, and no spiral arms.
- **Star Formation**: Irregular galaxies often have **active star formation** regions, particularly in the **HII regions** (areas of ionized hydrogen) where new stars are being born.
- **Gas and Dust**: Irregular galaxies may contain large amounts of gas and dust, which can fuel star formation.
- **Internal Kinematics**: The internal dynamics of irregular galaxies can be quite chaotic, and the motion of stars and gas is often **non-ordered**.

Examples:

1. **The Large Magellanic Cloud (LMC)**: A nearby irregular galaxy that is part of the **Local Group** of galaxies and is a satellite of the Milky Way. It has a **distinct starburst region** and is a well-known example of an irregular galaxy.
2. **The Small Magellanic Cloud (SMC)**: Another irregular galaxy in the Local Group, close to the Milky Way. It is much smaller than the LMC and has regions of active star formation.
3. **NGC 4449**: A relatively nearby irregular galaxy known for its **irregular shape** and **star formation activity**.
4. **IC 1613**: A small irregular galaxy located in the **Local Group**. It has a low surface brightness and a large star-forming region.

Properties of Irregular Galaxies:

- **Chaotic Shape**: They lack a distinct structure and are often the result of gravitational interactions.
- **High Star Formation**: Many irregular galaxies are rich in gas and dust, leading to active **star formation**.
- **Low Metallicity**: Some irregular galaxies have a **low metal content** compared to more evolved galaxy types like spirals or ellipticals, indicating they have not undergone as much stellar evolution.

5. Peculiar Galaxies

Peculiar galaxies are a class of galaxies that do not fit easily into the more established categories such as **spiral**, **elliptical**, or **lenticular** galaxies. They often exhibit unusual or irregular features resulting from a variety of phenomena, including **galactic collisions**, **mergers**, **gravitational interactions**, or **active galactic nuclei (AGN)**. These galaxies typically exhibit distortions, asymmetries, or atypical morphological features that make them stand out from more typical, well-structured galaxies.

Structure of Peculiar Galaxies

While peculiar galaxies can have highly varied structures, they often exhibit certain distinctive features depending on the cause of their peculiarity:

- **Distorted Disk**: Many peculiar galaxies show warped or distorted disks. These distortions can arise from gravitational interactions or mergers that disrupt the smooth rotation of the disk.
- **Tidal Debris**: Galaxy interactions, particularly mergers, can create **tidal debris**—streamers of stars, gas, and dust that are pulled out of the main galaxy. These can take the form of **tidal tails**, **bridges**, or **knots** of star formation along the galaxy's outskirts.
- **Active Core**: Some peculiar galaxies may have a highly energetic and active core, indicating the presence of a **supermassive black hole** accreting matter. These galaxies may be classified as **Seyfert galaxies**, **radio galaxies**, or **quasars**, depending on the type of activity.
- **Unusual Color or Brightness Patterns**: Some peculiar galaxies may appear unusually bright or show strange color patterns due to unusual star formation activity or AGN activity at their center.

Examples of Peculiar Galaxies

Some of the most famous and striking examples of peculiar galaxies include:

- **Arp 220**: One of the most well-known **ultra-luminous infrared galaxies** (ULIRGs), formed by the collision of two spiral galaxies. The interaction triggered intense star formation and the emission of a huge amount of infrared radiation.
- **NGC 520**: A **collisional pair** of galaxies that shows significant distortion in the shape of both galaxies, with tidal tails and bright regions of star formation.

- **The Cartwheel Galaxy**: A **ring galaxy** that formed after a collision with a smaller galaxy, creating a prominent ring of stars, gas, and dust, with star formation occurring along the ring.
- **NGC 4038/NGC 4039 (The Antennae Galaxies)**: A pair of interacting spiral galaxies that have been distorted into an unusual shape, with **tidal tails** and **intense star formation** occurring as a result of the gravitational interaction.

Properties and Characteristics of Peculiar Galaxies

Unusual Morphology:

- Peculiar galaxies typically show **distorted** or **irregular** shapes due to interactions, mergers, or tidal forces.
- They often lack the **well-defined structure** of normal galaxies, exhibiting asymmetries or displaced components.

High Star Formation Rates:

- Many peculiar galaxies show **increased star formation**, either due to gravitational interactions or the presence of a **supermassive black hole** in the center (as in **Seyfert galaxies**).

Enhanced Activity:

- Some peculiar galaxies, especially **Seyfert galaxies** and **radio galaxies**, are characterized by heightened activity at their centers, where energy is emitted by an active galactic nucleus (AGN).

Presence of Tidal Features:

- Interaction or merger between galaxies often results in the formation of **tidal tails**, **bridges**, or **plumes**—long structures of gas and stars pulled from one or both interacting galaxies.

3.2 Evolution and Origin of Galaxies

The **origin and evolution** of galaxies is a central topic in cosmology and astrophysics, and our understanding is continually refined by both observational data and theoretical models.

I. The Formation of Galaxies

The formation of galaxies is believed to have occurred during the **early universe**, shortly after the **Big Bang**. The process can be broken down into several stages:

1. **Primordial Fluctuations**:
   - After the **Big Bang**, the universe was in a hot, dense state. Small fluctuations in the density of matter and energy in the early universe (observed as **cosmic microwave background radiation**) created regions of higher and lower density. Over time, these fluctuations began to collapse under the influence of gravity, forming the **first clumps** of matter.
2. **Formation of Proto-Galaxies**:
   - As matter continued to collapse, it formed **proto-galaxies**, which were collections of gas and dark matter. The first stars began to form inside these proto-galaxies, initiating the process of **galactic assembly**.
3. **Merging and Growth**:
   - The first galaxies were relatively small, but as time passed, they began to **merge** with other proto-galaxies. This process, known as **galactic mergers**, led to the growth of larger galaxies. During these mergers, gas clouds would collide and trigger bursts of star formation. Mergers also led to the formation of **supermassive black holes** at the centers of galaxies.
4. **Dark Matter and Galaxy Formation**:
   - **Dark matter** played a crucial role in galaxy formation. The invisible dark matter halos that surround galaxies provided the gravitational framework needed for galaxies to form and evolve. Dark matter is thought to have clumped together in large halos, acting as gravitational wells into which normal matter (gas and stars) collapsed, forming galaxies.
5. **Star Formation and Evolution**:
   - As gas clouds in these proto-galaxies cooled and collapsed, stars began to form. These stars formed in clusters and were often short-lived, particularly in the early stages of galaxy formation. Over billions of years, the galaxy continued to evolve, with star formation occurring in waves, governed by the availability of gas and the interactions between galaxies.

II. Galaxy Evolution: From Early to Present Day

1. **Early Star Formation**:
   - During the **epoch of reionization** (about 400 million years after the Big Bang), the first stars formed and began to ionize the surrounding gas. These stars likely formed in small groups, and the intense radiation from these early stars influenced the gas in galaxies, leading to the formation of new generations of stars.
2. **The Role of Supermassive Black Holes**:
   - **Supermassive black holes (SMBHs)**, which reside at the centers of many galaxies, are believed to have played a significant role in galaxy evolution. These black holes can grow by accreting matter, and their growth may be tied to the growth and evolution of their host galaxies. Active galactic nuclei (AGN), which are powered by the accretion of matter onto supermassive black holes, can influence the surrounding galaxy, triggering or quenching star formation.
3. **The Cosmic Star Formation Rate**:
   - The star formation rate of a galaxy is influenced by factors like gas content, interactions with other galaxies, and feedback from active galactic nuclei (AGN) or supernovae. In the **early universe**, star formation was much more intense than today. As galaxies evolved, star formation began to slow down, with many galaxies transitioning into **quiescent phases**, where star formation is nearly halted.
4. **Galaxy Mergers and Interactions**:
   - **Galaxy mergers** are a key driver of galaxy evolution. Large galaxies like the **Milky Way** are believed to have formed through a series of mergers over billions of years. When galaxies collide, their gas clouds can trigger **intense bursts of star formation**, while the galaxies themselves may undergo a transformation in structure. Mergers can turn spiral galaxies into elliptical galaxies or trigger the formation of **lenticular galaxies**.
5. **Environmental Effects on Galaxy Evolution**:
   - The **environment** in which a galaxy resides can have significant effects on its evolution. For instance, galaxies in **dense clusters** are subject to a phenomenon known as **galactic harassment**, where interactions with other galaxies can strip gas and halt star formation. Galaxies in **voids** (regions with fewer galaxies) may evolve differently, with lower rates of interactions and mergers.
6. **Cosmological Feedback Mechanisms**:
   - Feedback processes, such as **supernova explosions**, **AGN activity**, and **winds from young stars**, play a crucial role in regulating the

rate of star formation within galaxies. These processes can heat up and expel gas, preventing further star formation or triggering new cycles of star birth.

III. The Future of Galaxies

The future of galaxies is closely tied to the fate of the universe itself. In the far future:

- **Merging of Galaxies**: The **Milky Way** and the **Andromeda Galaxy** are on a collision course, and they will likely merge in about **4.5 billion years** to form a larger elliptical galaxy.
- **Star Formation Slowdown**: As galaxies exhaust their supply of gas, star formation will gradually decline. In the distant future, most galaxies will be composed mostly of **old stars** and will have little to no new star formation.
- **The End of the Universe**: The ultimate fate of galaxies is uncertain, depending on whether the expansion of the universe accelerates forever (driven by dark energy) or if it eventually slows down and reverses (leading to a "Big Crunch"). If the universe continues to expand indefinitely, galaxies will drift apart, becoming increasingly isolated.

3.3 Active Galaxies and Quasars

The study of **active galaxies** and **quasars** is a cornerstone of modern astrophysics. These objects, driven by the intense energetic processes occurring at their centers, offer crucial insights into the physics of supermassive black holes, galaxy evolution, and the large-scale structure of the universe. They not only showcase some of the most extreme and energetic phenomena observed but also act as powerful probes to study distant parts of the universe.

1. Active Galaxies

Definition and Overview

An **active galaxy** is a galaxy with an unusually energetic core, emitting significantly more radiation than a normal, non-active galaxy. This excess energy is primarily due to the activity in the galaxy's **Active Galactic Nucleus (AGN)**, which is often powered by a **supermassive black hole (SMBH)**. The AGN can emit vast amounts of radiation across the electromagnetic spectrum, from radio waves to gamma rays, often outshining the rest of the galaxy.

The Structure of an Active Galactic Nucleus (AGN)

At the heart of an active galaxy is the **Active Galactic Nucleus (AGN)**, which houses a supermassive black hole. The AGN is a complex system consisting of various components:

1. **Supermassive Black Hole (SMBH)**:
    - Supermassive black holes at the centers of active galaxies can have masses ranging from **10^6** to **10^10 solar masses**. These black holes have gravitational fields so strong that not even light can escape from them once it crosses the event horizon.
    - The intense gravity of the black hole pulls in surrounding gas, dust, and other material, feeding the AGN. This material forms an **accretion disk** that spirals inward, heating up due to friction and gravitational forces, emitting radiation across the spectrum.
2. **Accretion Disk**:
    - The **accretion disk** is made of gas, dust, and other matter that is spiraling toward the black hole. As matter falls inward, friction between particles in the disk generates heat, causing the disk to glow brightly. This is the primary source of the radiation observed from the AGN.
    - The innermost parts of the disk, closest to the black hole, are heated to extremely high temperatures, often millions of degrees Kelvin, and emit large amounts of **X-rays** and **ultraviolet radiation**.
3. **Broad-Line Region (BLR)**:
    - Surrounding the accretion disk is the **broad-line region (BLR)**, where gas clouds move at high velocities due to the gravitational influence of the black hole. These gas clouds are ionized by the intense radiation from the accretion disk.
    - The ionized gas emits **broad emission lines**, which are key to identifying AGNs. These lines are broadened due to the Doppler shifts of the rapidly moving gas clouds. Spectroscopic observations of AGNs reveal broad hydrogen and other spectral lines, such as the **H-alpha** line.
4. **Narrow-Line Region (NLR)**:
    - Further out from the black hole, beyond the BLR, lies the **narrow-line region (NLR)**. The gas in this region moves at lower velocities compared to the BLR, producing **narrow emission lines** in the spectrum of the galaxy.
    - The NLR is generally located a few thousand light-years from the nucleus, and it is much cooler compared to the BLR.
5. **Relativistic Jets**:

- Many active galaxies are also characterized by **relativistic jets**: narrow beams of ionized gas and particles that are ejected from the black hole's poles at speeds close to the speed of light. These jets are typically visible in radio wavelengths, and their presence can sometimes dominate the total energy output of the galaxy.
- These jets can extend over millions of light-years, and their study helps astronomers probe the physics of black holes, high-energy particle acceleration, and the interaction of these jets with the intergalactic medium.

Types of Active Galaxies

Active galaxies can be classified into several types based on the nature of their activity and their observed characteristics. This classification is heavily influenced by the orientation of the galaxy relative to the observer, which determines the visibility of certain features of the AGN:

1. **Seyfert Galaxies**:
   - Seyfert galaxies are one of the most well-known classes of active galaxies. They are characterized by a bright, compact nucleus and are classified into two main types:
     - **Seyfert 1 Galaxies**: These galaxies show broad emission lines in their spectra, indicating the presence of a fast-moving, ionized gas in the BLR. Seyfert 1 galaxies are viewed face-on, allowing us to see the broad emission lines.
     - **Seyfert 2 Galaxies**: These galaxies show only narrow emission lines in their spectra, suggesting that we are observing them edge-on. The orientation prevents us from seeing the broad-line region.
2. **Radio Galaxies**:
   - These galaxies are primarily identified by their intense emission in the radio part of the spectrum. Radio galaxies often have powerful relativistic jets that emit in the radio wavelengths. These jets can extend across vast distances, sometimes even beyond the host galaxy itself, creating **radio lobes**.
   - **Example**: **Cygnus A**, one of the brightest and most well-known radio galaxies.
3. **LINERs (Low-Ionization Nuclear Emission-line Regions)**:
   - LINERs are a subset of AGNs characterized by weaker, low-ionization emission lines. The central engine is still a supermassive black hole,

but the material surrounding it is not ionized as strongly as in Seyfert galaxies.

4. **Blazars**:
   - Blazars are a type of active galaxy that is observed to have an unusually powerful jet pointing directly toward Earth. They are characterized by extreme luminosity across the entire electromagnetic spectrum, especially in X-rays and gamma rays, and their emissions can vary dramatically over short timescales.
   - **Example**: **Markarian 421**, one of the brightest and most studied blazars.

2. Quasars: Definition, Structure, and Properties

What is a Quasar?

A **quasar** (short for "quasi-stellar object") is an extremely energetic and luminous form of active galactic nucleus, located at the center of a distant galaxy. Quasars are powered by the accretion of matter onto a supermassive black hole and emit tremendous amounts of radiation across the entire electromagnetic spectrum. Quasars are typically observed at extremely high redshifts, meaning they are located very far away, often billions of light-years from Earth.

Characteristics of Quasars

1. **Extreme Luminosity**:
   - Quasars are among the most luminous objects in the universe. They can emit more energy than an entire galaxy, sometimes more than **1,000 times the luminosity of the Milky Way**.
   - This emission occurs across the spectrum, from radio waves to X-rays, and even into gamma rays. The energy is primarily due to the material in the accretion disk being heated to very high temperatures as it spirals into the black hole.
2. **Redshift and Distance**:
   - Quasars are typically located at **high redshifts**, meaning they are incredibly distant. High redshift corresponds to the fact that the universe has been expanding since the quasar emitted its radiation. This means that many quasars we observe are from a time when the universe was much younger (and more active), often only a few billion years after the Big Bang.

   - Some quasars are located more than **12 billion light-years** away, giving us a glimpse into the early universe, when galaxies and supermassive black holes were in their infancy.
3. **Emission Across the Spectrum**:
   - Quasars are extraordinary emitters of radiation in **X-ray** and **ultraviolet** wavelengths, and they can also emit strong **radio waves**. The quasar's **accretion disk** and **relativistic jets** contribute to this broad spectrum of emissions.
   - Rapid variability is often observed in their radiation, particularly in their **optical and ultraviolet** light. This variability on timescales of **days to months** suggests that the emitting region is very compact, on the order of a light-day across.
4. **Relativistic Jets**:
   - Quasars often exhibit **relativistic jets —** narrow beams of ionized gas moving at speeds close to the speed of light, directed along the axis of the black hole's spin. These jets can extend for vast distances from the quasar, sometimes **over a million light-years**. The jets are observed primarily in **radio** wavelengths, but they can also emit at optical, infrared, and X-ray wavelengths.

Structure of a Quasar

Quasars have a very similar structure to other AGNs but at an enhanced and extreme level:

- **Supermassive Black Hole (SMBH)**: At the core of the quasar is a supermassive black hole that is the engine driving the activity.
- **Accretion Disk**: The accretion disk surrounding the black hole emits radiation due to the heating of gas as it spirals inward.
- **Broad-Line Region (BLR)**: Surrounding the accretion disk, where gas is ionized by the intense radiation from the central black hole, producing broad spectral lines.
- **Narrow-Line Region (NLR)**: Further away, where slower-moving gas clouds emit narrower lines in the spectrum.
- **Relativistic Jets**: Powerful jets are launched perpendicular to the accretion disk. These jets are highly collimated and move at relativistic speeds.