

COSMIC FRAMEWORK: Unveiling the Dynamics of Galactic Formation and Evolution

¹Baibhab Ghosh, ²Abhijit Dey

¹Undergraduate student, Kokrajhar Government College, Bodoland University, Kokrajhar, 783370, Assam, India., ²Postgraduate student, Gauhati University, Guwahati, 781014, Assam, India

¹Department of Physics

Abstract: This comprehensive article explores the fascinating realm of galaxies, covering their classification, structure, formation, and evolution. We discuss the various types of galaxies, including spiral, elliptical, and irregular galaxies, and examine their composition, such as stars, gas, dust, and dark matter. The paper investigates the role of Supermassive Black holes, Galaxy Clusters and groups, Dwarf Galaxies and the observational techniques used to study these phenomena. We also delve into the cosmological context, discussing the expanding universe, cosmic microwave background, and large-scale galaxy surveys. Finally, we highlight future missions and projects aimed at furthering our understanding of galaxies, including the James Webb Space Telescope and next generation ground-based observatories. This paper provides a thorough understanding of galaxies, their significance in the universe, and the ongoing efforts to unravel their secrets.

Index Terms - Galaxy Clusters and Groups, Supermassive Blackhole, Intergalactic and Interstellar Medium, Dark Matter.

1. INTRODUCTION

1.1 Historical Background:

The study of galaxies has evolved over centuries, from early observations of hazy patches in the sky by Ancient Indian, Greek, and Chinese astrophysics to modern astrophysics exploring their structures, dynamics, formation and evolution.

In Indian text, Surya Siddhanta, which is traditionally dated around 4th-5th century CE, which covered planetary motion, eclipses, timekeeping, celestial distances and Precession of the Equinoxes. It also defines the concept like Yugas (Cosmic cycles), Kalpas (Long cosmic ages), etc.

Another Indian text named Siddhanta Shiromani, whose author was Bhaskaracharya (Bhaskara II), which is traditionally dated around 12th century CE, which introduces Goladhyaya (Spherical Astronomy), Grahaganita (Mathematical Astronomy), Ganitadhyaya (Mathematics), Kuttaka (Indeterminate Equations). This text also predicted planetary positions using mathematical equations, accurately calculated the Earth's rotation time almost the same as modern values, introduced concepts of differential calculus before Newton.

This Indian texts later build interests in Indian Astronomers like Aryabhata, Brahmagupta, and Varahamihira.

In 1610, Galileo Galilei used his telescope to resolve the Milky Way into individual stars, proving it was a collection of stars rather than a single cloud. Charles Messier in the 18th century cataloged many nebulae and star clusters, some of which were later recognized as galaxies. In 1917, Vesto Slipher (USA) measured the redshifts of spiral nebulae. In 1924, Edwin Hubble (USA) confirmed that Andromeda Nebula(M31) was an external galaxy, proving the existence of multiple galaxies beyond the Milky Way. In 1936, Hubble introduced his classification of galaxies. In 1950s-60s, Indian astrophysicist Meghnad Saha contributed to the understanding of stellar and galactic spectra. In 1960s-70s, Quasars and Radio galaxies were discovered, linking galaxies to massive Black Holes.

1.2 What are Galaxies:

Galaxies are the building blocks of the universe, represents vast and complex system comprising billions of stars, gas, dust, and dark matter. Understanding galaxies is crucial to unraveling the mysteries of the cosmos, from their formation and evolution to their role in shaping the universe's large-scale structure. This research paper delves into the multifaceted world of galaxies, exploring their types, structure, formation, and evolution, as well as the techniques used to study them. We examine the significance of Galactic Nuclei, Supermassive Blackholes, and the dynamics of Galaxy Clusters and Groups. By placing galaxies within the broader context of cosmology, we aim to provide a comprehensive understanding of these celestial wonders and their importance in the grand scheme of the universe.

2. TYPES OF GALAXIES AND GALAXY MORPHOLOGY

Galaxies are the primary building blocks of the universe, comprising billions of stars, interstellar gas, dust, and dark matter. Understanding galaxy morphology is crucial in deciphering how galaxies form, evolve, and what their physical properties are in the cosmic past. Morphological classification thus gives a systematic framework through which the structural diversity of galaxies may be analyzed and how they developed their star formation histories and dynamics and how they are interacting with the cosmic web. One of the first and most applied schemes is the Hubble Sequence, proposed by Edwin Hubble in the year 1926, where he classified galaxies according to their shape and form. This section describes the various types of galaxies, their morphological characteristics, and their importance in extragalactic astronomy.

The Hubble Classification Scheme: Edwin Hubble established a morphological classification system called the Hubble Sequence, which groups galaxies into three main classes: elliptical (E), spiral (S), and irregular (Irr). He also developed the class of transitional object, lenticular galaxies (S0), which shares features both of elliptical and spiral galaxies. The Hubble tuning fork diagram illustrates these categories, showing how galaxies could evolve.

2.1 Elliptical galaxies (E-Type):

Elliptical galaxies have a smooth, featureless light distribution with approximately spheroidal or ellipsoidal shape. Classification is further based on their ellipticity, which ranges from E0 (close to spherical) to E7 (highly elongated):

Properties:

1. Stellar Population: Dominated by old, low-mass stars, making it red in color and having minimal star formation.
2. Gas and Dust Content: Low interstellar medium (ISM) content, meaning quiescent star formation.
3. Dark Matter Halo: Inferred to exist from kinematic studies but hard to detect directly.
4. Size Variation: Range from dwarf ellipticals (dE) to giant ellipticals (gE) found in galaxy clusters.
5. Examples: M87 (Virgo Cluster), NGC 4889 (Coma Cluster). Elliptical galaxies are often found in dense environments such as galaxy clusters, where frequent mergers and interactions lead to their formation via hierarchical assembly processes.



Figure 1: Elliptical galaxy NGC 4150
Credit: ESA/Hubble

2.2 Spiral Galaxies(S-Type):

Spiral galaxies have a discoidal shape and well-defined structure with central bulge, flattened disc carrying spiral arms and an extended halo. These are dynamically supported through rotation, accounting for their organized morphology.

Sub-classification by Hubble: Spiral galaxies are distinguished by the nature of their central bulge, as well as the tightness of their spiral arms:

1. Sa: High bulge, tightly wound arms, very little star formation.
2. Sb: Intermediate bulge, moderately wound arms.
3. Sc: Low bulge, loosely wound arms, actively forming stars. Examples: The Milky Way (Sb/c), Andromeda Galaxy (M31, Sb).

A large proportion of spiral galaxies have a central bar structure, which plays a role in gas dynamics and star formation. The bar directs gas to the nucleus, which may feed supermassive black holes (SMBHs) and starbursts. Like ordinary spirals, they are subclassified as SBa, SBb, SBc according to arm tightness. Examples: NGC 1300(SBb), the Milky Way (SBbc)



Figure 2: Milky way galaxy

Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

2.3 Lenticular Galaxies (S0-Type):

Lenticular galaxies serve as a transition between ellipticals and spirals. They possess a disk-like structure but lack prominent spiral arms, suggesting a decline in star formation due to gas depletion.

Properties:

1. Bulge-dominated structure, like ellipticals.
2. Disk component with minimal or no active star formation.
3. Common in galaxy clusters, likely due to environmental effects like ram pressure stripping. Examples: NGC 2787, NGC 1023.



Figure 3: Lenticular Galaxy

Credit: NASA, ESA, P. Erwin (Max-Planck-Institute für extraterrestrische Physik), L. Ho (Peking University), and S. Kaviraj (University of Hertfordshire); Processing: Gladys Kober (NASA/Catholic University of America)

2.4 Irregular Galaxies (Irr-Type):

Irregular galaxies lack a well-defined shape due to gravitational interactions, mergers, or internal turbulence. They are often rich in gas and dust, making them sites of intense star formation.

Subcategories:

1. Irr I: Some structure but lacks symmetry (e.g., Large Magellanic Cloud).
2. Irr II: Completely chaotic morphology with no discernible structure.

Irregular galaxies play a crucial role in understanding early galaxy formation since they share similarities with high-redshift star-forming galaxies.

Examples: Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC).



Figure 4: Irregular galaxy NGC 1427A

Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

2.5 Galaxy Morphology in Evolutionary Studies:

Galaxy morphology is a key source of information about the **evolutionary paths** of galaxies. The main factors that determine morphology are:

1. Mergers and Interactions: They drive the spirals to ellipticals.
2. Star Formation History: It is regulated by gas accretion, feedback mechanisms, and environment.
3. Dark Matter and Halo Dynamics: They affect galaxy stability and structural evolution.
4. Supermassive Black Holes (SMBHs): Influence morphological changes via Active Galactic Nuclei (AGN) feedback.

The Hubble classification system provides the basis for classification, but newer observational techniques have led to further refinement. The on-going development of high-resolution telescopes and simulations will progressively add strength to our comprehension of the processes by which galaxies acquire their shapes, evolve, and interact within the cosmic web. Future missions, including the Vera C. Rubin Observatory and James Webb Space Telescope (JWST), will further develop the knowledge of how the morphological type of galaxies evolves over cosmic time.

3. STRUCTURE AND COMPOSITION OF GALAXIES

3.1 Galactic Structure and Arrangement of Star System:

Galaxies are huge framework or systems of stars, gas, dust, and dark matter bound together forming a network under the influence of gravity. Depending on their distributions in space and the effect of gravity, galaxies are found in various sizes and shapes. But their structure can be generalized based on three components: the central bulge, the disk, and the halo.

Central Bulge: The central bulge is highly dense, spheroidal structure located at the core of the galaxy enclosed by the disk (most probably in spiral and some elliptical galaxies). It is the most important attribution of the galactic Centre. The bulge is basically composed of a ring of older red stars and comparatively less amount of gas and dust relative to the galactic disk. The galactic Centre of Milky Way galaxy is enclosed by massive central bulge with five spiral arms coiled around it. Also, the galactic Centre of Andromeda galaxy (M31, NGC224) is made up of dense and compact red stars, clusters in ring shaped, more diffused, enclosed by disk and a newly discovered disk of young blue stars.

The shape of the central bulge varies accordingly. It can be spherical, boxy and even in peanut-shaped depending on the historical background of the galaxies and galaxy dynamics.

Spherical bulges are predominantly found in early-type spiral galaxies (Sa, Sb), where 'Sa' signifies 'spirals without bar' and 'Sb' signifies 'spiral, barred'. They are generally formed through activities such as rapid mergers and accretions that occurs in the early age of the galaxy's history. These explosive events cause a collapse and successive star formation which leads to the dense spheroidal distribution of stars like elliptical galaxies with a smooth, centrally polarized light contour and an old stellar population.

Boxy or peanut-shaped bulges are more prominently observed in late-type spiral galaxies (Sc, Sb), where 'Sc' signifies 'spiral galaxies having small central bulge as well as narrow and well-defined central arms'. Their formation is usually associated with the secular evolution of the galaxy, specifically the presence and extension of a bar structure within the galactic disk. As the bar evolves, it can warp and stiffen, forming a boxy or peanut-shaped bulge. This transformation is operated by dynamical instabilities within the bar, which redistribute gas and stars, originating the distinct bulge shape. This variations in bulge morphology are further discussed in galaxy morphology and Hubble classification scheme.

The central bulge often forms a spheroidal shape which contains a high concentration of older, evolved stars. These stars are naturally older than those in the galactic disk and have low metal content, indicating they formed early in the galaxy's history. The central bulge contains a significant amount of intergalactic gas and dust. This matter plays significant role in star formation, although the rate of formation of new stars in the bulge is usually lower than in the galactic disk.

Supermassive Black Holes (SMBH): Colossal black holes, usually positioned at the center of galaxies, are crucial in shaping galaxy formation and development. Their impact is diverse, affecting both the structural characteristics and stellar birth rates of their associated galaxies. Supermassive Black Holes (SMBHs) can emit vast amounts of energy via Active Galactic Nuclei (AGN) activity. This energy can warm or drive out the gas inside galaxies, thus diminishing star formation. This mechanism, referred to as AGN feedback, is essential in understanding the observed link between the masses of supermassive black holes and the

characteristics of their parent galaxies. The energy output from Supermassive black holes (SMBHs) can drive powerful jets and winds that interact with the interstellar medium (ISM). These interactions can result in the suppression of star formation in large galaxies, facilitating their shift from active star production to a dormant state.

The radius of the Supermassive Black Holes (SMBHs) can be determined by Schwarzschild radius. It is the radius of the event horizon of a black hole, calculated as $R_s = 2GM/c^2$, where G is the gravitational constant, M is the mass of the black hole, and c is the speed of light.

Supermassive blackhole	Galaxy	Mass (Solar Masses)	Schwarzschild Radius (Km)
Sagittarius A*	Milky Way	-4.3 million	-12.7 million
M87*	Messier 87	-5.4 billion	-16 billion
Holmberg 15A	Holmberg 15A	-40 billion	-118 billion
NGC1600	NGC 1600	-17 billion	-50 billion
Centaurus A	Centaurus A	-55 billion	-162 million

* The mass and size estimates are based on current astronomical observations and may be refined with future research.



Figure 4: The image was released in 2019 by the Event Horizon Telescope Collaboration. SMBH from the galactic core of Messier 87. Credit: Wikipedia

Huge massive galaxies like Alcyoneus galaxy, Andromeda galaxy, including Milky Way galaxy have a supermassive black hole (SMBH) at their galactic centers. Generally, masses of these black holes' ranges from 10^5 solar masses to several billion solar masses. Some observations of distant stars by NASA shows that some supermassive black holes (SMBH's) formed in the first billion years after the birth of the universe which may began with the collapse of supermassive stars in the early universe. Supermassive black holes (SMBH's) play a significant role in the galaxy dynamics and their evolution.

Galactic Disk: Galactic disk is usually flat and extends horizontally, encircles the central bulge and keeps spinning. The galactic disk is primarily composed of stars, gas and dust arranged in a relatively thin plane, disklike structure. The stars, gas and dust all of which entirely orbits around the core of the galaxy, but the distribution of these elements is not uniform. Galactic disk includes both old and young stars, with younger stars and star formation typically takes place in regions found in the spiral arms and older stars are found in more diffused areas of the disk. Spiral galaxies like Milky Way noticeably feature a disk with Spiral arms. On the other hand, elliptical galaxies are more influenced by their central bulge and have less defined or unclear disks.

The estimation of diameter of our Milky Way's galactic disk is approximately about 100,000 light years(ly) and 1000 light-years(ly) thick, according to Las Cumbres Observatory. The diameter of Andromeda galaxy's disk is approximately about 152,000 light-years(ly) and a giant Alcyoneus galaxy has diameter of approximately about 242,700 light-years(ly).

Galactic Halo: The Galactic Halo encompasses the entire galaxy, diversifying far beyond the Galactic disk and central bulge. The halo has a very less Steller density contrasted to the bulge and disk. It contains a dense collection of ancient stars called globular clusters, old stars, and a large proportion of dark matter. Globular clusters are amongst the oldest objects in the universe, contributing as key examiner for understanding and get a perspective of the early stages of galaxy foundation. By proper observation of these objects, one can understand the original mass function, development of star formation history and chemical enrichment of the galaxy.

One of the most crucial arrangements in the formation and evolution of galaxies are Dark Matter Halo. The overall masses and gravitational potential of the galaxy are governed by the dark matter, and they are immensely massive than the observable parts of the galaxies. Generally, Dark matter halos originate through gravitational collapse and manipulates the interaction, energy, movement and distribution of Baryonic matter (Ordinary matter).



Figure 4: Galactic Halo

Credit: NASA/ESA/A. Field, STScI

Gaseous halos are composed of hot gases enveloping galaxies and reach beyond the galaxy's observable limits. As the gas within these halos' cools, it can eventually lead to creation of stars within the galaxy. Phenomena like cooling streams, galactic winds, and interactions with the Intergalactic Medium (IGM) are vital in shaping the development of these gaseous halos. The intergalactic Medium (IGM) refers to the gas that exists in the regions outside galaxies yet within the confines of Dark Matter halos. This medium interacts with the Interstellar Medium (ISM) within galaxies, with phenomena like gas accretion and outflows (Example- Galactic winds) have considerable impacts on the development of galaxies. The Intergalactic Medium (IGM) encompasses a substantial amount of the Universe's Baryonic matter and is fundamental in elucidating the cosmic gas cycle.

3.2 What are Galaxies Composed of?

Galaxies are primarily composed of a few elementary components such as Stars, Interstellar Medium (ISM), Dark Matter, Planets and Other Objects interact through Gravitational forces, Electromagnetic radiation, and diverse physical phenomena, structuring the composition and advancement of galaxies.

Stars: Within the galaxy, Stars composed from clouds of gases and dust, experiencing a life cycle that affects their host galaxy. Stars are the main visible constituents of galaxies, extending from small, dim Red Dwarfs to massive, luminous Supergiant.

There are several unique types of stars available in numerous galaxies such as Red Giants, White Dwarfs, Neutron Stars, Binary Stars, Blue Giants, Variable Stars, Pulsars, Protostars. Each type of stars has diverse characteristics and emissions and provides extraordinary perception into the life cycle of stars. The spatial distribution of stars, their ages, and their chemical compositions offers valuable information about the history and evolution of their host galaxies.

Due to the vastness of the Universe and the limitations of current observational technology, it is difficult to estimate the number of stars in different galaxies. However, NASA and other astronomical organizations has provided overall statistical estimates based on observations and simulations. Here's the general overview of the estimated number of stars in various types of galaxies:

Milky Way Galaxy: There are approximately about 100 to 400 billion stars in our Milky way galaxy.

Andromeda Galaxy: There are approximately about 1 trillion stars in Andromeda galaxy(M31).

Large Magellanic Cloud: The Large Magellanic Cloud (LMC) is a satellite galaxy of the Milky way. There are approximately about 10 billion stars in Large Magellanic Cloud (LMC).

Small Magellanic Cloud: The Small Magellanic Cloud (SMC) is another satellite galaxy of the Milky way. There are approximately about 3 to 5 billion stars in Small Magellanic Cloud (SMC).

Dwarf Galaxies: Dwarf galaxies can contain anywhere from a few million to a few billion stars.

Elliptical Galaxies: Elliptical galaxies contain stars in the range from a few billion to over 10 trillion stars.

Total number of stars in the universe: The estimated number of stars in the observable universe to be around 1 to 2 trillion trillion stars (or 10^{24} stars).

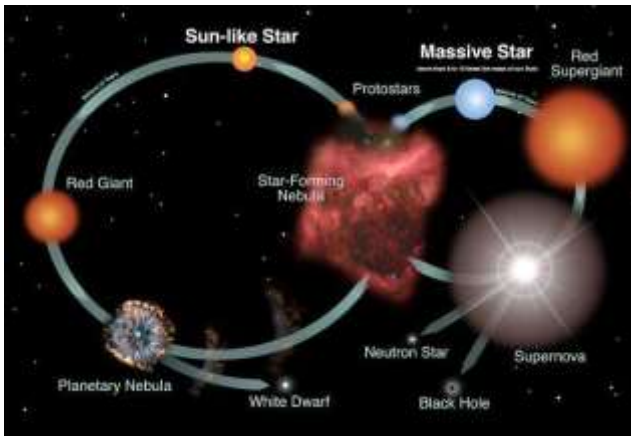


Figure 5: Special stars (evolution of stars)
Credit: NASA and the Night sky network

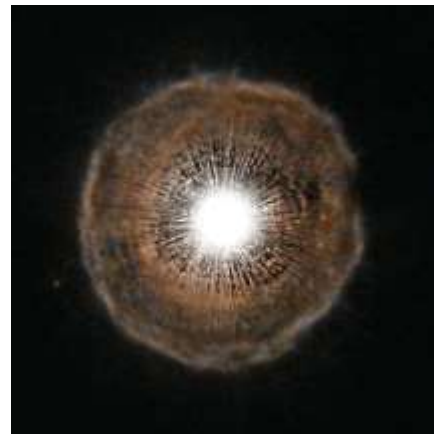


Figure 6: Red Giant
Credit: ESA/NASA



Figure 7: Sirius-B
Credit: NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester)

Interstellar Medium (ISM): The Interstellar Medium (ISM) is characterized as the matter occupying the regions among the stars within a galaxy. This medium consists of gas (in its ionic, atomic, and molecular states), dust particles, and cosmic rays, which extends throughout the space between stars.

The interstellar Medium (ISM) is a complicated and dynamic feature of galaxies, interacting with and being modified by the processes of star formation and stellar evolution. It is responsible for numerous Nebulae visible in galaxies and it is a key factor in the physical processes of galaxies, including development of stars (It operates as the reserves of matter for new stars and Astronomical Systems), transmission of electromagnetic waves and the dynamics of the galactic structure. Interstellar Medium is also affected by the energy and matter emitted by dying stars and is crucial for understanding wider mechanisms involving the lifecycle of matter and cosmic evolution.

Interstellar Dust: Interstellar Dust is mainly composed of tiny solid particles found in the Interstellar Medium (ISM) of galaxies. These particles are predominantly formed from Silicates, Carbon, Ice, and Metallic substances. Dust grains typically range from a few nanometers to roughly a micrometer. Studying and understanding dust is crucial for interpreting celestial observations accurately. It delivers knowledge about the star life cycle and the growth trajectories of galaxies.

The sources of Interstellar dust are:

Evolved Stars: The production of dust is significantly influenced by Asymptotic Giant Branch (AGB) stars and Supernovae, which release elements into the Interstellar Medium (ISM).

Supernovae: The cataclysmic end of massive stars that adds to the creation of dust and heavy elements.

Grain Growth: In dense molecular clouds of the Interstellar Medium (ISM), dust grains can expand by accreting atoms and molecules.

Destruction and Reformation: Through processes such as Supernovae and similar processes lead to the ongoing destruction and reformation of dust grains.

The role of Interstellar Dust in Galaxies encompasses star formation, the absorption and scattering of radiation, and chemical evolution.

Composition of Interstellar Dust in various types of Galaxies:

- I. Spiral Galaxies: The dust percentage of spiral galaxies are approximately about 0.5% to 1% of the total mass of the Interstellar Medium (ISM).
- II. Elliptical Galaxies: Elliptical galaxies generally have a lower dust percentage compared to spiral galaxies.
- III. Irregular Galaxies: The dust percentage of irregular galaxies are approximately about 0.1% to 0.5% of the total mass of the Interstellar Medium (ISM).
- IV. Starburst Galaxies: The dust percentage of starburst galaxies can be significantly higher, often around 1% to 5% of the total mass of the Interstellar Medium (ISM).
- V. Lenticular Galaxies: The dust percentage of lenticular galaxies are approximately about 0.1% to 0.5% of the total mass of the Interstellar Medium (ISM).
- VI. Dwarf Galaxies: The dust percentage of dwarf galaxies are typically less than 0.1% of the total mass of the Interstellar Medium (ISM).

Dark Matter: What is Dark Matter? How it is different from regular matter? Dark matter is a form of matter thought to account for approximately 27% of the universe's total mass energy content. Unlike regular matter, dark matter does not emit, absorb, or reflect light, making it invisible and it is detectable only through its gravitational effects up to now. Its presence is inferred from various astrophysical observations, particularly in galaxies. One of the primary indicators of dark matter in galaxies comes from the study of galactic rotation curves. In a typical spiral galaxy, visible mass (stars, gas, and dust) is concentrated near the Centre. according to Newtonian mechanics, we would estimate the rotational velocities of stars to decrease with distance ($r^{1/2}$) from the galactic Centre. However, observations show that the rotational velocities of stars in the outer regions of galaxies remain constant or even increase with distance. This discrepancy suggests the presence of additional, unseen mass extending well beyond the visible components of the galaxy. This unseen mass is attributed to a dark matter halo wrapping the galaxy. The density of a dark matter halo typically decreases with distance from the galactic Centre. The exact density profile of these halos has been a focal point of substantial research and argumentation. One commonly known model is the Navarro-Frenk White (NFW) profile, which describes a specific mathematical form for the density distribution of dark matter within halos.

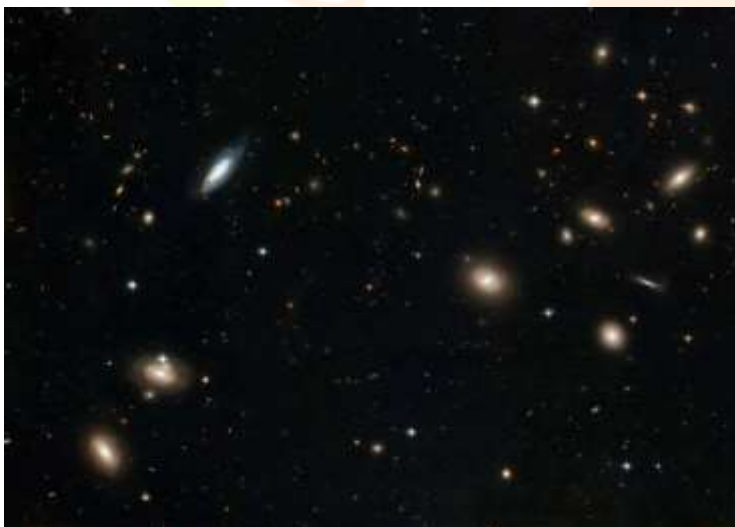


Figure 8: Dark matter
Credit: NASA Science

Observational Evidence of Dark Matter research:

1. Beyond individual galaxies, dark matter's presence is also inferred from observations of galaxy clusters. For example, the Bullet Cluster provides compelling evidence for dark matter. Within this structure, two galaxy clusters have interacted, and analysis indicate a divergence between the detectable matter (mainly as hot gas producing X-rays) and the inferred gravitational mass (determined through gravitational lensing).
2. Detailed maps of the Cosmic Microwave Background (CMB), such as those produced by NASA's Wilkinson Microwave Anisotropy Probe (WMAP), reveal minute temperature fluctuations that correspond to regions of varying density in the early universe. The pattern observed in the CMB align with the models that require dark matter to explain the formation and distribution of galaxies.

4. GALAXY CLUSTERS AND GROUPS

4.1 What are Galaxy Clusters and Groups?

Galaxies are not randomly distributed in the universe but tend to cluster together due to gravity. These clusters vary in size and configuration.

I. Galaxy Groups: Galaxy groups are smaller associations of galaxies which are gravitationally bounded, typically containing up to about 100 or fewer members. These groups are the building blocks of larger cosmic structures and play a significant role in the large-scale organization of the universe. A classic example is the Local Group, which includes our Milky Way galaxy, the Andromeda Galaxy(M31), The Triangulum Galaxy(M33), and over 50 other smaller galaxies.

The dynamics of the Local Group are changing and after speculation, it came out that one day may be the two large spirals in it (M31 and the Milky Way) may collide and merge to form a giant elliptical galaxy. It is also possible that the Local Group may one day merge with the next nearest big galaxy cluster, the Virgo Cluster.

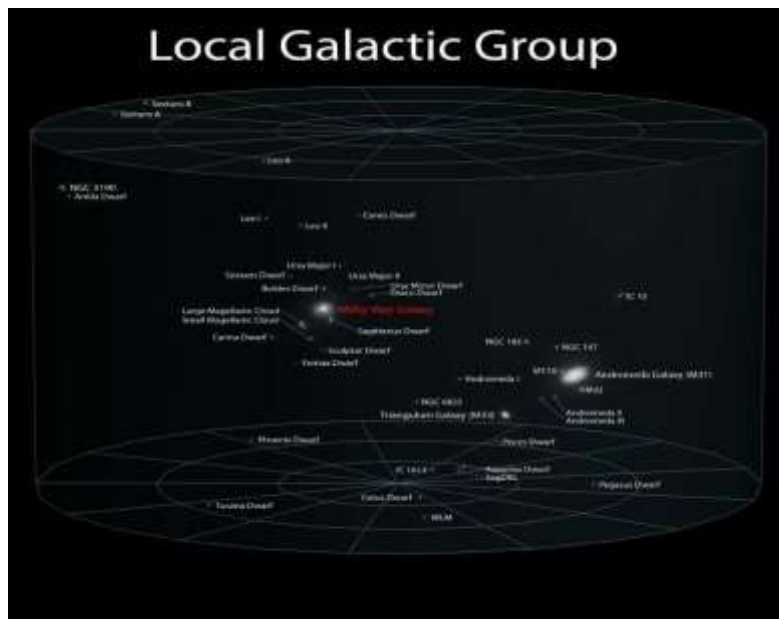


Figure 8: Local Galactic Group

Credit: Azcolvin429, via Wikimedia Commons, Sun.org

II. Galaxy Clusters: Galaxy Clusters are among the universe's most massive structures, comprising hundreds to thousands of galaxies bound together by gravity. Galaxy Clusters form over billions of years through the merging of smaller groups and clusters, driven by gravitational attraction. A classic example is Virgo Cluster, which is situated about 60 million light-years away. It is the nearest large galaxy cluster to the Milky Way. It contains over 2,000 galaxies, with a mix of spiral and elliptical types.



Figure 9: Virgo Cluster

Credit: Rogelio Bernal Andreu (deepskycolors.com)

Another example is Coma Cluster (Abell 1656), located approximately 320 million light- years from Earth. It is one of the densest known clusters, containing over 1,000 individual galaxies. Most of these are elliptical galaxies, though spiral galaxies are also present.

III. Galaxy Superclusters: Galaxy superclusters are the largest known structures in the universe, comprising multiple galaxy clusters and groups bound together by gravity. These vast cosmic structures can extend across hundreds of millions of light-years and contain tens of thousands of galaxies. For instance, the Laniakea Supercluster, which includes the Milky Way, encompasses approximately 100,000 galaxies over a region spanning about 520 million light-years in diameter.

Superclusters are not isolated structures; they are interlinked, forming an immense cosmic web of filaments and voids. These filaments are enormous, thread-like structures that can extend upto 500 million light-years, delineating the Large-Scale Structure (LSS) of the universe. Observations of these immense structures help astronomers understand the gravitational effects over vast distances and the role of dark matter in shaping the cosmos.



Figure 10: Laniakea Supercluster

Credit: SDvision interactive visualization software by DP at CEA/Saclay, France

4.2 Formation and Evolution of Galaxy Clusters:

The development of these structures is dictated by hierarchical clustering, wherein smaller entities merge progressively over time to give rise to large formations.

What is the role of Dark Matter? Dark Matter functions as the gravitational framework that enables galaxies and gas to cluster. In the primordial cosmos, subtle perturbations in the dark matter density functioned as the initial instigators of Large-Scale Structure (LSS) formation. Over time, these perturbations amplified under gravitational instability, leading to the hierarchical coalescence of dark matter halos. Baryonic matter was subsequently drawn into these gravitational potential wells, undergoing radiative cooling and condensation to form galaxies. Through successive mergers and continuous mass accretion, these dark matter halos evolved into massive galaxy clusters observed in the present epoch. The intricate evolution of galaxy clusters is significantly governed by dark matter. During cluster collisions, dark matter halos traverse one another with negligible interaction, whereas the Intracluster Gas (ICG), constituting most of the baryonic matter undergoes ram pressure effects, giving rise to detectable phenomena such as shock fronts. A notable example is the Bullet Cluster, where observations reveal a distinct spatial displacement between dark matter and the Intracluster Gas (ICG) following such an impact. The dissociation serves as compelling empirical evidence for dark matter's existence and provides crucial insights into its properties and behavior in high-energy astrophysical processes. Furthermore, the distribution and concentration of dark matter within clusters affect their internal structure and stability. Studies have shown that the dark matter density profiles of massive galaxy clusters exhibit a consistent form across different redshifts, suggesting that these profiles are established early in the cluster's history and remain stable over time.

Hot Gas and X-Ray Emission Clusters: Clusters contain hot gas at millions of kelvins, emitting X rays. The Intracluster Medium (ICM) is studied using telescopes like Chandra X-ray Observatory and X-ray Multi-Mirror Mission (XMM-Newton).

4.3 Dynamics Within Galaxy Clusters:

Clusters exhibit complex internal dynamics:

4.3.1. Velocity Dispersion: In galaxy clusters, member galaxies exhibit high velocities, ranging from hundreds to thousands of kilometers per second. This phenomenon, known as velocity dispersion, arises due to the cluster's substantial gravitational potential well. Understanding velocity dispersion is crucial for insights into the mass distribution and dynamical state of galaxy clusters. Accurate measurements of velocity dispersion can be challenging due to factors such as the presence of interlopers (foreground or background galaxies not bound to the cluster) and the selection of cluster members. Studies have investigated biases in velocity dispersion and mass estimates, especially in regimes with a small number of observed galaxies, to improve the reliability of these measurements.

4.3.2. Galaxy Mergers: Cosmic Mergers are crucial occurrences in the cosmos, deeply shaping the development of galaxies. When two galaxies interact and unite, their gravitational forces can trigger remarkable astronomical events, particularly intense star formation and the ignition of galactic cores, leading to Active Galactic Nuclei (AGN).



Figure 11: Galaxy merger

Credit: International Gemini Observatory / NOIRLab / NSF / AURA

A starburst is a phase of vigorous stellar production, where the rate of star birth is considerably higher than in an ordinary galaxy. During a collision, gravitational interactions disrupt the gas and dust within the merging galaxies, causing these materials to condense and collapse under their own gravity. This collapse results in accelerated star formation. Observations indicate that such starburst activity frequently occurs in interacting galaxies. For example, research utilizing the Atacama Large Millimeter/Submillimeter Array (ALMA) has demonstrated that intermediate stage mergers like VV 114 display both concentrated core and widespread star-forming regions, signifying extensive stellar production throughout the merging system. Beyond initiating starbursts, galaxy mergers can channel vast quantities of gas and dust into the central regions of the interacting galaxies. This inward flow of material can fuel the Supermassive Black Holes (SMBH) at their cores, activating them as Active Galactic Nuclei (AGN). AGN are distinguished by their immense energy output, often surpassing the total luminosity of all the stars in the host galaxy. Studies suggest that AGN occur more frequently in merging galaxies than in isolated ones. For instance, an analysis of Sloan Digital Sky Survey (SDSS) data revealed a higher prevalence of AGN in post-merger systems, indicating that mergers play a crucial role in triggering AGN activity.

Case Studies of Galaxy Mergers:

I. NGC 3256: This galaxy, located approximately 100 million light-years away, resulted from a cosmic collision and displays distinct tidal tails and dual cores. NGC 3256 is experiencing intense stellar formation, as indicated by abundant H II regions, and exhibits evidence of AGN activity, emphasizing the combined influence of mergers in driving both starbursts and AGN.



Figure 12: NGC 3256

Credit: Hubble space telescope

II. Arp 220: Situated around 250 million light-years from Earth, Arp 220 emerged from the merger of two galaxies. It exhibits a powerful starburst, with its brightness primarily driven by infrared radiation from dust-obscured stellar formation. Observations also point to the existence of an AGN, suggesting that both starburst activity and AGN processes are unfolding concurrently in this interacting system.



Figure 13: Arp 220

Credit: Combination of James Webb space telescope and Hubble space telescope (STScI, NASA/ESA/CSA)

4.3.3. Tidal Interactions: Gravitational encounters between galaxies, known as tidal interactions, are essential in molding their structures and guiding their evolutionary trajectories. These interactions can cause substantial shape alterations, initiate star formation, and impact the internal motion and organization of the affected galaxies. When galaxies come into proximity, their mutual gravitational pull can deform their structures, creating features like tidal tails, bridges, and distortions. For instance, the Antennae Galaxies (NGC 4038/ NGC 4039) display prominent tidal tails, formed as their stellar and gaseous components stretch due to their interaction. These extended formations serve as clear evidence of the intense gravitational forces acting during galactic encounters. Likewise, simulations have shown that tidal interactions can generate one-armed spiral patterns in galaxies, like those seen in certain Magellanic-type spirals.



Figure 14: Galactic Tide

Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA

5. OBSERVATIONAL TECHNIQUE

Advancements in observational techniques are crucial to deepen our understanding of galaxies, their structures, and the cosmos. Modern astrophysics utilizes a range of wavelengths and methodologies, from optical to radio, infrared, and high-energy observations. These techniques enable astronomers to map diverse galactic components, revealing the evolution and large-scale structure of the universe. Each method contributes unique insights, highlighting different aspects of galactic morphology, composition, and dynamics.

5.1 Optical Astronomy:

Optical astronomy is basic in galaxy research as it presents observations through visible light that portray the structural and compositional features of galaxies. Through ground-based and space-based telescopes, optical surveys record the spatial distribution of stars, the morphology of spiral arms, and central bulges to provide a basis for classification along the Hubble sequence. Optical wavelength observations allow photometry and spectroscopy, which give valuable information regarding the populations of stars, abundances of elements, and redshifts for calculating distances in galaxies. New telescopes employing adaptive optics technologies (such as the Very Large Telescope) significantly minimize distortion introduced by the atmosphere, thereby offering high resolution images for detailed investigation of distant structures of galaxies.

5.2 Radio Astronomy:

Radio astronomy examines the cold, diffuse constituents of galaxies, such as interstellar gas, molecular clouds, and magnetic fields. The Atacama Large Millimeter Array (ALMA) and the Square Kilometer Array (SKA) are now able to survey galaxies at radio wavelengths to give tremendous high-resolution imaging of neutral hydrogen (H I) gas and molecular lines like CO, tracing cold molecular clouds where star formation occurs. This is important for observing the Large-Scale Structure (LSS) and dynamics within galaxies since H I emissions outline extended galactic disks and halos, even in dust obscured regions. Furthermore, radio observations observe non thermal synchrotron emissions linked to cosmic magnetic fields, tracing interactions between cosmic rays and thus furthering our knowledge of energy processes in galaxies

5.3 Infrared Astronomy:

Infrared astronomy is crucial for peering through the dust-obscured regions of galaxies, which provides a window of knowledge into the obscured processes of star formation and the growth of Supermassive Black Holes (SMBHs). The near to mid-infrared views of the James Webb Space Telescope (JWST) and Spitzer Space Telescope (SST) reveal young stellar populations and properties of dust that absorbs and re-emits stellar light at longer wavelengths. In the far-infrared, Herschel traces cool dust emission, enabling us to calculate star formation rates and Interstellar Medium (ISM) properties. Infrared wavelengths therefore capture galactic phenomena which otherwise would be unavailable to be seen in detail, hence providing a better look at star formation history and stellar feedback mechanisms effecting galactic evolution.

5.4 High-Energy Observations: X-ray and Gamma-Ray:

High-energy astronomy explores the most extreme processes in galaxies, such as accretion onto supermassive black holes (SMBHs), supernova remnants, and interactions within galaxy clusters. Emissions of hot, ionized gas from the cores of galaxies are observed by x-ray telescopes such as Chandra and XMM-Newton, showing signatures of active galactic nuclei (AGN) and supernova heated interstellar gas. Gamma-ray observatories such as Fermi detect emissions from cosmic ray interactions and the annihilation of particles, providing insight into the high-energy astrophysical processes that shape the evolution of galaxies. Observations of these energetic processes help explain the role of feedback from AGN and massive stars in driving outflows and redistributing gas, which is a crucial ingredient in models of galaxy formation.

5.5 Cosmic Microwave Background (CMB) Observations:

While primarily associated with early universe studies, CMB observations provide a cosmic backdrop that helps elucidate the Large-Scale Structure (LSS) of the universe and the gravitational influence of massive galaxy clusters. Experiments like the Planck satellite measure subtle temperature fluctuations in the CMB, which arise from gravitational interactions with galaxy clusters through the Sunyaev Zel'dovich effect. This phenomenon allows astronomers to measure cluster masses, study dark matter distribution, and understand the evolution of large-scale structures, linking galaxy clusters with broader cosmological models.

5.6 Simulations and Synthetic Observations:

Advances in computational power have made simulations indispensable in the interpretation of observational data and in testing theoretical models of galaxy formation and evolution. Tools like Illustris, EAGLE, and Millennium Simulation model galaxy evolution over cosmic time, including physics of dark matter, star formation, and feedback. Simulations produce synthetic observations that mimic telescope data, allowing astronomers to compare real observations with theoretical models. By reconciling simulation outputs with observational data, researchers refine our understanding of galactic dynamics, dark matter distribution, and the interaction of galaxies with their cosmic environment.

5.7 Role of Multi-Wavelength and Multi-Messenger Astronomy:

No observational technique captures the complete complexity of galaxies. Multi-wavelength studies that combine data from across the electromagnetic spectrum are critical in constructing a comprehensive picture of galaxy properties and behaviors. The inclusion of gravitational wave detections and neutrino observations in multi-messenger astronomy opens dimensions toward studying phenomena such as black hole mergers and supernovae that could not have been detected before. Such methods complement traditional astronomical observations and are changing our understanding of galaxy evolution and the fundamental forces of the universe.

6. GALACTIC QUASARS

Quasars are quasi-stellar objects, some of the most luminous and energetic phenomena in the universe. These distant galactic nuclei are powered by massive supermassive black holes, which are surrounded by accretion disks that produce radiant emission over the entire electromagnetic spectrum. Research on quasars could provide very important information related to galactic formation and evolution, distances within space, and Large-Scale Structure (LSS) of the universe.

With unprecedented luminosity, quasars are capable of outshining entire galaxies. Their high redshifts signal their existence in the distant universe, offering a glimpse into its early development. The short-term variability of their brightness implies compact emission regions, and their spectra show broad emission lines from ionized gas at high velocities. These features make quasars useful probes of astrophysical processes on both galactic and cosmic scales.

At the core of each quasar lies a Supermassive Black Hole (SMBH) with a mass ranging from millions to billions of solar masses. Matter spiraling into these black holes forms a luminous accretion disk, generating immense energy as gravitational forces, which is used to heat the surrounding gas. Surrounding black holes, there are broad-line and narrow-line regions, where ionized gas orbits at varying distances, producing distinct emission lines. Some quasars also exhibit relativistic jet streams of particles traveling at nearly the speed of light that can be detected through radio and X-ray observations.

The formation of quasars is closely linked with the growth of Supermassive Black Holes (SMBH), often triggered by galaxy mergers or the inflow of gas into Galactic Nuclei. Their peak activity occurred during the universe's first few billion years, aligning with the era of galactic assembly. Over time, as black holes consume surrounding matters, Quasars evolve into less Active Galactic Nuclei (AGN).

Quasars play a pivotal role in modern astronomy. Their high redshifts allow astronomers to study the young universe, the epoch of Cosmic Reionization, and the Intergalactic Medium (IGM). Their predictable luminosity enables measurements of cosmic distances, contributing to our understanding of the universe's expansion. Furthermore, the distribution of Quasars reveals the large-scale cosmic web, providing clues about dark matter and galaxy formation.

Observing Quasars requires advanced techniques across various wavelengths. Optical and Ultraviolet telescopes, such as the Hubble Space Telescope (HST), capture their spectra and measures redshifts. Radio telescopes like the Very Large Array (VLA) detect relativistic jets, while X-ray observatories such as Chandra and XMM-Newton study high-energy emissions from accretion disks. Future missions, including the James Webb Space Telescope (JWST) and the Extremely Large Telescope (ELT), are expected to revolutionize our understanding of Quasars by revealing unprecedented details about their host galaxies, formation environments, and role in cosmic evolution.

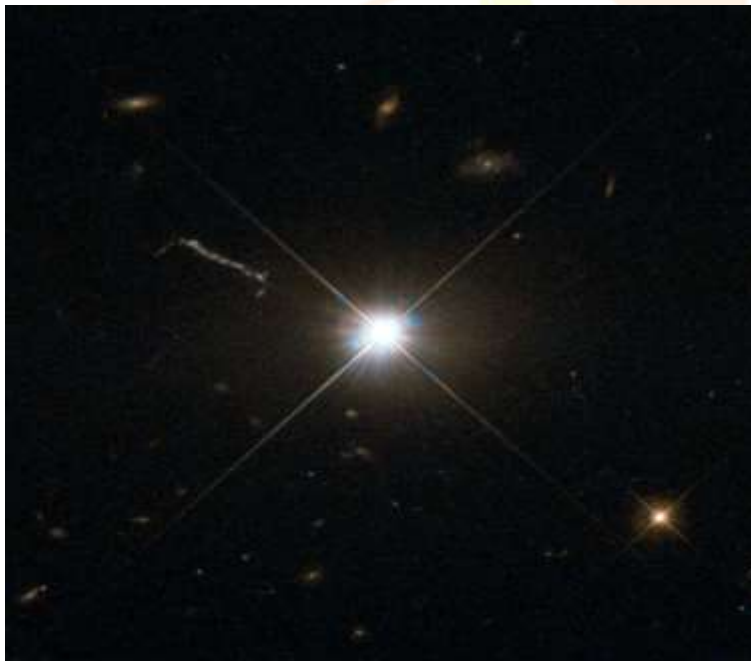


Figure 13: Quasar 3C 273

Credit: ESA/Hubble

In conclusion, Quasars serve as cosmic beacons illuminating the distant past and fundamental astrophysical processes. Their study continues to enhance our comprehension of Black Hole Physics, Galactic Evolution, and the Large-Scale Structure (LSS) of the cosmos, reinforcing their significance in contemporary astrophysics.

7. FUTURE MISSIONS AND DISCOVERIES

7.1 High-Resolution Imaging and Interferometry by NASA:

A significant advancement in astrophysics in the development of large-scale interferometers for stellar and galactic observations. NASA recently completed a nine-month study on the Artemis enabled Stellar Imager (AeSI), proposed a 1-km ultraviolet/optical interferometer on the Moon. With 15–30 telescopes, AeSI aims to image stars such as Sirius A and Alpha Centauri, study Active Galactic Nuclei (AGN) winds, accretion disks, and Supernovae, leveraging the Moon's stable environment for unprecedented resolution.

7.2 Electric Propulsion Systems of ISRO:

The Indian Space Research Organization (ISRO) successfully completed a 1,000-hour life test of its 300mN Stationary Plasma Thruster on March 27, 2025. This technology is designed for future satellites and enables all-electric propulsion for orbit-raising and station-keeping. This advancement reduces reliance on chemical propellants and enhances mission longevity, which is crucial for deep space astrophysics missions.

7.3 Europa Clipper Mission by NASA:

Set for launch in October 2024, this mission will study Jupiter's moon Europa. By conducting flybys to analyze its icy shell, subsurface ocean, and geology, it seeks to assess its habitability, contributing to astrobiology and planetary astrophysics.

7.4 Nancy Grace Roman Space Telescope:

Planned for launch in 2026 or 2027, this observatory will image Earth-sized exoplanets and study the universe's earliest galaxies, building on the Hubble and James Webb Space Telescopes' legacies. It also aims to investigate dark energy and create a 3D map of Dark Matter. The telescope will have a field of view 100 times larger than the Hubble Space Telescope, enabling expansive imaging of the Universe.

7.5 Exoplanet and Solar System Missions by ESA:

ESA's CHEOPS (launched in 2019) and upcoming PLATO (2026) missions target exoplanet characterization, while BepiColombo (launched in 2018, arriving at Mercury in 2025) studies planetary magnetospheres—key to comparative astrophysics.

7.6 SPHEREx Mission by NASA:

SPHEREx Mission is Launched in March 2025, NASA's SPHEREx(Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer) aims to map millions of galaxies across the entire sky. This mission seeks to investigate the early moments following the Big Bang and search for water within the Milky Way, enhancing our understanding of Galaxy Formation and Evolution.

7.7 Athena and Euclid Mission by ESA:

Athena (Advanced Telescope for High-Energy Astrophysics) planned for launch in the late 2020s, Athena will observe X-ray emissions to study the formation and evolution of galaxies, as well as the growth of Supermassive Black Holes(SMBH). Euclid Mission launched in 2024, Euclid aims to map billions of galaxies to study the geometry and nature of the dark universe, contributing to our understanding of Galaxy distribution and Evolution.

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