How did the conditions and properties of the early universe permit the formation of galaxies?

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Abstract

Understanding galaxies from a cosmological perspective dates back to the 18^{th} century, and has since then majorly evolved. With new telescopes being launched there have been major advancements and theories regarding galaxy formation and evolution. This paper lays out a foundation for the properties which played a key role in developing the first few galaxies as well as explains which aspects of galaxies contain observable evolutionary changes. The review looks at types of galaxies and draws connects between it and galactic evolution. Anisotropies of the CMB, emission spectra of galaxies and other graphs corresponding to aspects such redshift and quantum fluctuations are presented to support arguments made regarding properties of galaxy formation.

1. Introduction

A major aspect of understanding the contents and chronology of our universe are galaxies. Galaxies are large collections of structures such as planets, stars, nebulae, gas and dust, black holes and dark matter. Our universe contains a lower estimate of 176 billion galaxies based on the Hubble eXtreme Deep Field (NASA, 2012), wherein an image ranging across 1/32 millionth a fraction of the sky was taken in 2012 and showed 5500 identifiable galaxies (Siegel, 2018). There could be a predicted 2 billion galaxies due to the fact that gas clouds, distance and other factors prevent galaxies from being imaged (Siegel, 2018). Based on the large number of individually identified galaxies, we have been able to create categories for such galaxies such as elliptical, spiral, irregular, peculiar and even subcategories such as lenticular galaxies, Sb galaxies, etc. Predictions can be made on how new types of galaxies can form and evolve. By studying light from receding galaxies and looking at the Cosmic Microwave

Background (CMB) we are able to look at factors that would have contributed to early galaxy formation (See section 3).

Galaxy formation is reliant on a few theories which will be elaborated upon in section 3. The general thought is that dark matter would have merged together and causes baryonic matter to create structures inside of this dark matter (Benson, 2010). Going further back to the beginning of the universe, matter density perturbations (Benson, 2010) would have created areas with stronger gravitational strength which allowed dark matter to collapse in said regions.

This paper aims to look at galaxy formation and evolution in terms of surrounding properties that allowed for clusters of stars and other objects to form. Understanding galaxy formation and the characteristics that allowed for it to occur need to be looked at from the beginning of the universe, straight from the events of the Big Bang such as the inflationary epoch, era of atoms, recombination, the dark ages and reionization to the birth of new galaxies and predicted ones in the future. This paper explores the key aspects of a galaxy that tend to evolve over time which will be explored in section 4. Based on conditions and properties defined in section 3 and 4, section 5 refers to types of galaxies and how each type may have come into existence.

2. Early Universe

The Early Universe refers to the time from the start of the big bang up to 380,000 years following the big bang. This marks the first time where the universe became transparent as neutral hydrogen formed throughout the universe. During this period the fundamental particles and forces were created and separated, respectively. Theories regarding galaxy formation can be derived from looking at the events of certain eras of the early universe. Understanding temperature anisotropies (Silk, 1968) in the cosmic microwave background (CMB), looking at the changes taking place during the inflationary epoch and interpreting the role of quantum vacuum fluctuations in galaxy formation (Benson, 2010) is essential to theorizing how the first stars and galaxies formed in the universe. This allows us to compare current and early galaxies.

2.1 Quantum Vacuum Fluctuations

Quantum fluctuations refer to random appearances of energized particles in a quantum field, or out of nothing. Given the quantum fields of various virtual particles, due to the uncertainty principle, random points in empty space will never have energy equal to 0. Each field would cause these virtual particles in points in space to oscillate. This creates energy variations across space, scattered randomly. As a result, density and gravity are affected in regions with higher energies. Density will be higher causing gravity to be stronger. Virtual particles, though not real, are created due to real particles such as the collision of matter and antimatter or a photon pair. This means that such energy changes stay temporarily, for a short amount of time and create changes at a subatomic level. However, inflation plays an important role in causing these fluctuations to have cosmic impacts and energy-density imperfections across the universe. If space would have been gravitationally identical in all regions, gas clouds would be unable to collapse and structure formation would not occur.

2.1.1 The Inflationary Epoch

The inflationary epoch refers to the period from 10^{-36} seconds and 10^{-33} seconds after the big bang. This period signifies the rapid expansion of space from the size of around 10^{-50} meters to 1 meter in radius (Inglis, 2007). The volume would have increased by a factor of 10^{78} and its distance by a factor of 10^{26} along all 3 axes. This rapid expansion could have been caused due to the strong nuclear force separating from the weak nuclear and electromagnetic forces. As mentioned above, quantum fluctuations occurred during the very early universe, fractions of seconds after the big bang. As inflation took place, the sizes of quantum fields would have grown as much as the universe did in the short period of time. This allowed subatomic energy and density imbalances to be comparable to the entire size of the observable universe. These perturbations acted as seeds for structures (Benson, 2010).

2.2 The Cosmic Microwave Background

The Cosmic Microwave Background (CMB) refers to the first light in the universe and the period in which atoms formed and light was not absorbed anymore which created a transparent universe. The CMB can be seen at redshift of 1100. The CMB plays an important role in understanding galaxy formation by observing its temperature fluctuations.

2.2.1 CMB anisotropies and density fluctuations

From a broader perspective, the CMB appears isotropic in all directions and flat. However, due to quantum fluctuations that expanded from micro to macroscopic sizes, tiny density irregularities were created which are observed in the CMB. With an average temperature of 2.725K (Fixsen, 2009) according to data from the Far-InfraRed Absolute Spectrophotometer (FIRAS). Anisotropies are produced by photon scattering, primarily through Compton scattering. Density fluctuations can be inferred by the fact that Compton scattering is isotropic, so it should have flattened the CMB’s anisotropy. By observing temperature differences, where blue regions are the hottest and red the colder regions, temperature fluctuations within a range of -3.35mK to +3.35mK from

2.725K are used to signify which areas contain disruptions. While this appears tiny, these areas were large enough to instigate gas collapse and galaxy formation.

3. Galaxy Formation

In the aforementioned section, understanding and predicting initial galactic formations plays a vital role in laying out the timeline of our universe and what might the future of the universe appear to be. As explained above, the energy changes that oscillate across quantum fields known as quantum vacuum fluctuations would have rapidly expanded to cosmological sizes during the inflationary period, allowing the gravitational strength in certain regions to exceed those in others where energy variations would not have taken place. As a result, hydrogen would have clumped to begin nuclear fusion. These stars would come to be known as Population III stars due to no metallicity, as the universe was too young to have an abundance of heavier, metallic elements. This primordial gas mixture of hydrogen and helium would hold responsible for the formation of initial stars, 30 million years post the big bang, within the gravitationally dense regions, present with dark matter halos (Barkana, 2006). This section aims to look at proposed theories for galaxy formation, observations regarding initial formations of spiral arms, halos and inner-galactic structures.

3.1. Initial formations

Taking a general view from the ΛCDM model of the universe, firstly we understand that the universe contains the cosmological constant denoting the acceleration and force responsible for the expansion of the universe, secondly, the presumed existence of cold dark matter as observed in CDM halos and finally, the presence of baryonic matter.

Understanding that dark matter, primarily cold, is accountable for 21% of the universe and 4% is baryonic (Mo et al., 2010) which permits the creation of galaxies. In this paper we assume that the universe is homogenous and isotropic throughout, but does contain slight perturbations which appear almost negligible on a broader scale. Explained in section 2.2, we understand that the cosmic microwave background, while appearing uniform and smooth, does contain minute and near negligible temperature differences in certain regions. While such a change is small, it is responsible for the presence of galaxies. Before understanding the formation of galactic properties such as bulges, arms and discs, looking at the role of gravitational collapse of dark and baryonic matter, halo formation and gas cooling and assembly and energy/mass exchanges is imperative.

3.1.1. Gravitational instability and dark matter halos

Gravitational instability is one of the rather modern theories explaining galaxy formation. The density perturbations are given by:

$$\Delta\rho = \rho/\rho_m.$$

Here, ρ is the matter density in a volume and ρ_m is the mean matter density of the universe (Gramman et al., 2015). Given the expansion of the universe, this density instability occurs in regions in space comparable to an order of 1 to a trillionth. Gas present in such regions would provide pressure to overcome the force of gravity and continue said region to continue expanding. However, whenever the density instabilities become over-dense (Mo et al., 2010), the gas cloud will stop expanding and rather collapse. This refers to a gas cloud's critical mass, where the material is no longer able to expand and oppose gravity. According to the Jeans mass, the denser and cooler a gas cloud is, the more unstable it becomes against gravitational collapse, and will eventually permit the formation of galactic halos (Dayal and Ferrara, 2018).

Cold dark matter (CDM) halos are described as non-linear dark matter structures. Through accretion or collisions with other halos, the CDM halos would grow in size. CDM halos nullify the effects of thermal radiation and pressure that prevented baryonic collapse, further allowing for the possibility of stellar formations and eventually the presence of galaxies within said halos. Given the dark matter halo's growth, sub-halos are formed through possible dark matter halo mergers. CDM halos have an undefined boundary, which refers to the region where dark matter remains in equilibrium to the infalling dark matter present at the edge of a halo (Zavala and Frenk, 2019). When this boundary is crossed the sub-halos are formed. Smaller halos, may enter a larger halo's boundary and become a sub-halo. This creates the general structure of a galaxy before the occurrence of the collapse of baryonic matter. Certain theories believe that post the creation of a halo, dark matter does not play a role in the evolution of galaxies aside from gravitational influence.

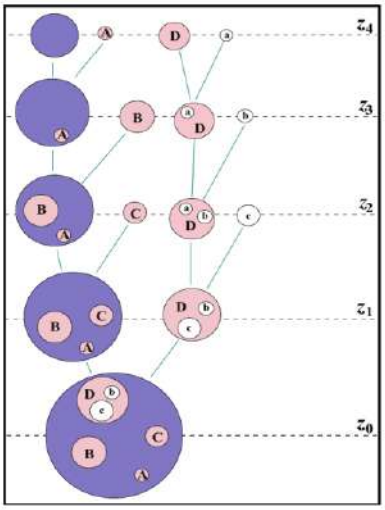

Figure 1: Tree diagram of dark matter sub-halos forming. The large halo at redshift Z_4 grows in size until neighboring halos enter and grow into its virial radius, making it a sub-halo. This repeats and might allow sub-halos to contain halos. Figure from Zavala, J. & Frenk, C.S. 2019.

3.1.2. Gas cooling

The virial theorem relates the average over time of kinetic energy of a stable system to the potential energy of the same system. In a galactic context, the theorem relates the kinetic energy of a gravitating set of particles to the body's gravitational potential energy which is derived by:

$$M = \frac{v^2 R}{G}$$

M is the galaxy's mass, v is the velocity of stars in the galactic system, G is the gravitational constant and R is the galaxy's radius. Within gas cooling, gas diffused within a halo is shock heated due unstable supersonic flow (Barkana, 2006) in the halo, to the virial temperature (T_{vir}) of the system (Cole et al., 2000), which refers to the mean temperature of the system that satisfies the virial theorem. The unstable supersonic shockwaves would create abnormally high pressures for the gas for a short period of time. Gas cooling is important as it lays out the conditions for the gas present inside of a halo, to create galaxies. The primary purpose of cooling is to reduce the pressure that opposes gravity by radiating energy (Barkana, 2006). Once gravity dominates, the gas collapses to the centre of the halo and begins the formation of stars and the galactic disc. For the first few galaxies that formed, gas had low metallicity (Primordial gas), which would mean that the temperature range of the halo would have to be specific to allow star formation to occur. Where $T_{vir} \leq 10^4 K$, the gas is neutral. Since primordial gas is void of heavy metals, there is close to no cooling of the gases due to radiation, causing the pressure of the gas to remain high and oppose gravitational collapse. However, the H_2 present in primordial gas provides the required cooling (Dayal and Ferrara, 2018) to permit the gas' gravitational collapse. Whenever $T_{vir} \geq 10^4 K$, the Lyman-alpha transition present in the gas is able to cool. Electrons are excited and radiate, permitting gas cooling. Larger halos often rely on Ly-α for cooling (Dayal and Ferrara, 2018), as it is a more efficient radiator than molecular hydrogen.

3.1.3. Star formation

Due to the hydrogen and helium-rich gas present at the beginning of star and galaxy

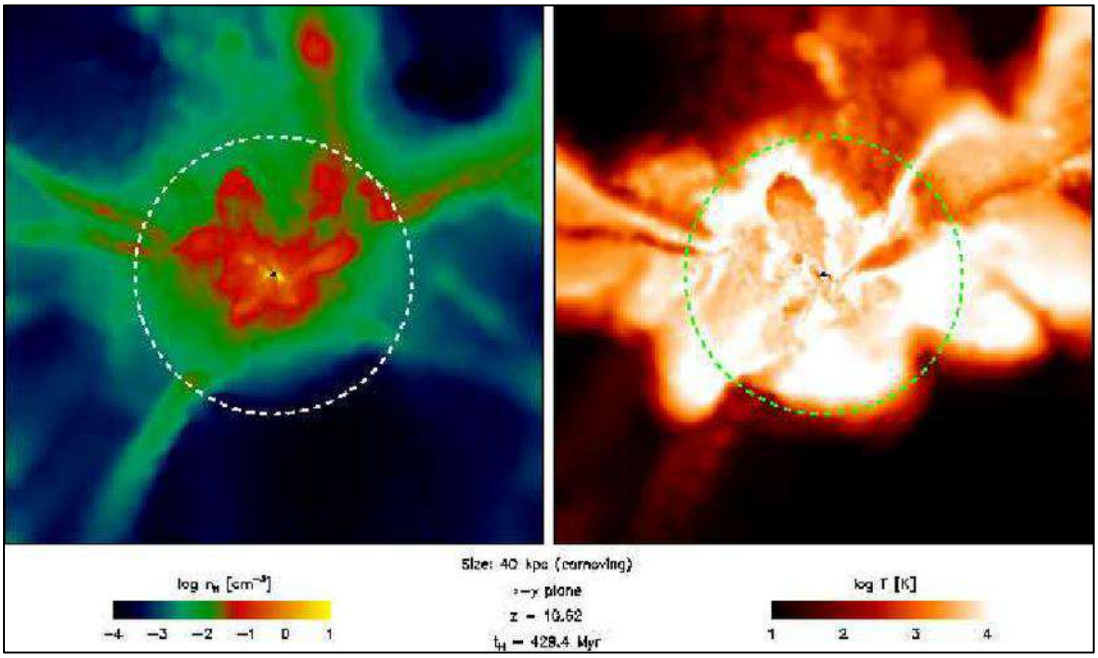

Figure 2: A depiction of gas collapse inside of a halo at redshift $z \approx 10$, using number density (left image) and temperature (right image). The circle denotes the virial radius of the halo. In the number density diagram, you can observe hydrogen gas collapsing and creating a disc-like shape. Figure from Johnson, J.L. 2011.

formation, stars would be formed without heavy metals. These stars are called Population III stars. Given that H_2 was an inefficient radiator, much more gas had to be cooled in order to allow gravity to overcome pressure, as opposed to present-day star formation wherein more efficient radiators permit quicker formation of smaller stars. Initial protostars are theorized to have masses up to 100M⊙, but would eventually become stars of 40M⊙ due to its low metallicity, encouraging ionization radiation (Silk et al., 2013). Initial star formation would have begun with the rapid collapse of the primordial gas and the gas’ increase in temperature and density. Primordial gas in a halo is separated into regions with giant molecular clouds (GMC’s), gas clumps and cores with masses of 10^6 M⊙, 10^3 M⊙, and 0.1 – 10M⊙ respectively. The cooling process during collapse tends to reduce, and create areas with high densities, which eventually become stars that begin nuclear fusion. The initial rate of star formation when collapse first occurs is high, and can create small, thin galactic discs. In spiral galaxies, spiral arms are often responsible for star formation due to the abundance of GMCs (Mo et al., 2010), however initial star formation would begin out of irregular gas presence, and not through existing galaxies. Protostar formation occurs after 2 gas collapses. In collapsing cores, the gas becomes adiabatic from being isothermal due to increasing opacity (Dayal and Ferrara, 2018). As temperature increases with pressure, H_2 is dissociated and creates the protostar.

Star formation continues in galaxies by colliding or interacting with each other and collecting gases near the galaxy's arms. Modern day stars form within galaxies through the intersections of strands in the cosmic web. Mass and energy can also be received through supernova explosions at the edges of the web's filaments and release high-metallicity mixtures into the intergalactic medium.

3.2. Galactic Disks

Galactic disks are a vital aspect of disk galaxies, containing gas required to continue star formation, which makes the disk the region containing most of the stars in a galaxy. Stars in the disc tend to rotate with specific motion with respect to the galaxy's centre of mass. Gas in discs contain warm and cool gas, primarily hydrogen, which while not well-defined, should be evenly distributed across the disc. The rotational characteristic of discs is given responsibility to the maintenance of angular momentum. The angular momentum provides rotational support (Benson, 2010) by overcoming the gravitational collapse of gas within the system. Discs in general are thin and would be formed by monolithic collapse of gas clouds present and create an orbit around a common centre. Spiral arms are predominant features in galactic disks, primarily observed in spiral galaxies, which are considered regions of a higher density of stars. Stars in these areas aren't always part of that arm, and might enter and leave the arms based on its distance from the galactic centre. Spiral arms move based on a set angular frequency, whereas stars move at independent speeds, unaffected by the arms. The movement of spiral arms can be defined by the density wave theory, which states that the movement of the density wave (The spiral arm) moves slower than surrounding objects. Additionally, galactic discs have been observed to grow in mass and size when observed between redshift of z=2 and the present (Renzini, 2020). Due to gas entering arms and creating shocks with other high-velocity gas clouds, star formation occurs.

3.3. Bulge

Galactic bulges refer to the central regions in a galaxy, where there is a greater concentration of stars, clouds and dust. Stars follow random orbits in the bulge and are associated with velocity dispersion. The random orbits, indicate that an equal number of stars move in opposite directions around the galactic centre. The stability of the system is maintained by the lowered rotation of the central stars. The formation of bulges has been theorized by monolithic collapse and dissipative collapse (Prugniel, et al., 2001) and starburst.

Bulges follow the process of dissipative or monolithic collapse to create highly concentrated regions of stars with greater gravitational attraction. Due to angular momentum, mass creates an inward path and a common centre of mass or centre of rotation, leading to starburst in this region, further promoting the formation of the bulge. This supports the creation of the central supermassive black hole as well due to stellar collapse.

4. Evolution of Galaxies

Chapter 3 looks at the basics of galaxy formation during the initial stages of the universe as well as the formation of specific parts of the galaxies such as discs and arms. Over 13.4 billion years, the universe has evolved and along with that so has structure development. This chapter explores how early galaxies would have evolved to develop into larger and more complex galaxies, such as spirals, lenticular and disc. The section refers to four types of evolution; Secular, Mergers and Interactions, Passive, and Chemical.

4.1 Structural Classification

Galaxy classification branches out into lenticular, elliptical, spiral and irregular galaxies. According to Hubble's classification model each of the types are divided into subcategories. Observations based on luminosity, bulge size, shape of arms or presence of arms and discs are used to decide the category of a galaxy. Elliptical galaxies are the result of the collision of spiral galaxies creating elliptical isophotes (Mo et al., 2010). Spiral galaxies contain a disc and arms and a prominent bulge. Isophotes of spirals are thinner and contain oval-shaped contours with 4 extrusions in each direction. Lenticular galaxies are considered to be between elliptical and spiral galaxies due to the presence of thin disks, but a larger bulge. Barred lenticulars are a subcategory of lenticulars. Irregular galaxies are the result of mergers and are not symmetrical and lack a prominent bulge.

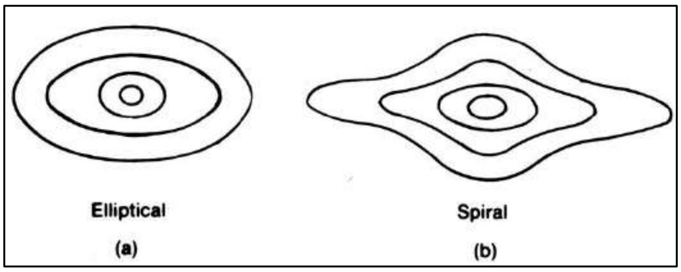

Figure 3: The comparison between light contours of isophotes of elliptical and spiral galaxies. The evident difference is high useful in classifying galaxies and viewing the effects of evolution. Figure from Cambridge University Press, 19

4.1.1 Forms of evolution

Galaxy evolution is guided predominantly guided by mergers and interactions. Luminosity, morphology, star formation rate and the presence of structures allow galaxies to be classified. Mergers and interactions change all these factors and promote the creation of new classifications, such as elliptical and irregular which are the result of mergers. Similar mass galaxies merge over long period of time ranging from 10 to 100 million years (Giavalisco, 2001). The altering gravitational potential of a system promotes violent relaxation wherein stars change orbit and displacement of stars may occur. The end result of mergers are elliptical structures which are classified based on flatness and indicated by either E0, E1, E2, E3, E4, E5, E6 and E7, where E0 is round and E7 is flat. Mergers between elliptical galaxies can give rise to spiral galaxies (Sa) or barred spirals (SBa). Between elliptical and spiral galaxies lie lenticulars (S0) as mentioned above and contain compositions similar to elliptical galaxies, but a thin structure similar to spirals. While merger theories on the formation of lenticulars yet vary, it is possible that they are the result of two spiral mergers which opposed Hubble's tuning fork model (Millis, 2020).

Passive evolution follows isolated evolution wherein time is the only affecting factor. The usage of resources and fuel in cores eventually lead to the dimming of galaxies from blue hues to red ones. Stars begin to expand into red giants and then collapse. Observations of older galaxies show them as red in colour indicating passive evolution. Secular evolution relies on surrounding changes such as increased surrounding luminosity from galaxy clusters in order to instigate evolution. Increased star formation in spiral arms are also examples of secular evolution as they lead to changes in luminosity.

5. Conclusion

Galaxy formation follows numerous physical processes focused on gravitational collapse further leading to increased pressure and temperature. A culmination of resistive forces such as expansion and gravitational forces are the primary origination of galaxies. Initial stages of the universe's development are tied to galaxy formation, primarily due to the expansion of density perturbations and inflation. This paper has defined the key processes regarding models for halo formation and baryonic collapse. Variables such as luminosity, temperature, gravity and intergalactic interactions have permitted the evolution of galaxies as seen in different shapes.

Future prospects for galactic studies span out to how might galaxies evolve differently over the next few billion years and how might we precisely understand how galaxies developed such unique shapes.

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