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Research Paper

The Effect of Dark Matter on Structure Formation

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Abstract
One of the greatest mysteries of our time lies in a mass balance problem; all known visible subtances comprise less than 5% of the mass-energy content of the universe. Visibility herein is defined not merely in the the eyes of mankind, but in the eyes of the most advanced detectors of the 21st century. These instruments are primarily designed to capture and investigate particles that interact with the electromagnetic force. However, a series of observations starting with those by Lord Kelvin in the late 19th century suggest that the majority of the universe consists of "dark bodies" that only interact with the gravitional force.
This paper walks through the last one and a half centuries of research looking into the existence of dark matter and the impact it had on the formation of the first large structures in the early universe. Four key pieces of evidence pertaining to the existence of dark matter are presented in this paper: i) bullet clusters, ii) gravitational lensing, iii) galaxy rotation curves, and iv) baryon acoustic oscillations. Finally, key avenues for future work are proposed: i) The notion of hierarchical structure formation; ii) The composition and properties of dark matter, and whether it is essential to stellar formation.
Keywords: *early universe, population III stars, dark matter, structure formation*

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I. Introduction

What is the universe made up of? Billions of humans live on the vast Earth, which is only a minimal portion of the universe. We live in an expanding universe filled with planets and stars, which make up galaxies, and group into clusters that form superclusters. All of these celestial structures can be directly observed from the macroscopic perspective. On the other hand, these structures are composed of microscopic particles, mainly baryons, particles like protons and neutrons that formulate everyday objects. Apart from these particles, there are also other fundamental particles like electrons, neutrinos, and antineutrinos. These particles are part of the Standard Model of particle physics and have been studied extensively in terrestrial experiments and with cosmological data. The expected attribute between these particles is that all of them are observable so that they can be studied by physicists and cosmologists, either of their composition or other characteristics. However, these visible substances only comprise about 4.6% of the universe. The rest are dark matter and dark energy, respectively, taking up about 24% and 71.4% of the universe [1]–[5]. Here is the key question: if only 4.6% of the universe is observable, then what is the composition of the unseen 95.4%?

The rest of the unseen matter is appropriately termed dark matter and dark energy. Since they do not interact with the electromagnetic field, they experience no scattering of light. Thus, they are unseen to most conventional instruments. Dark matter usually refers to nonbaryonic dark matter, especially the cold dark matter on which this paper mainly focuses. For the dark matter discussed in this paper, evidence proves that it is essential to certain phenomena in the universe, without which they could not have existed. Several phenomena would be difficult to explain without the existence of hypothetical dark matter to rationalize them. For example, gravitational lensing provides insights into the existence of dark matter. Assume that dark matter does not exist; light from distant galaxies would have passed in a straight path when passing through the massive galaxy clusters. However, under the influence of dark matter, the light particles, or photons, would be influenced by a gravitational force, thus causing their path to deviate so that the light would bend and distort [6]. As a result, gravitational lensing is one of the famous pieces of evidence proving dark matter's existence and significant properties. Other similar phenomena also appear that visible matter cannot explain, thus leading to the hypothesis of dark matter.

In order to study the matter and/or the particle content of the universe today, we need to consider one of the significant cosmological theories, the Big Bang Theory, which concerns the initial formation of the universe, explaining the large-scale evolution of the universe that continues today. According to the Big Bang Theory, the universe started from a high temperature and density state approximately 13.8 billion years ago [7]. The earliest stage of the Big Bang is known as the Planck epoch, which lasted approximately 10^{-43} seconds [8],[9]. The universe expanded by a factor of 10^{26} over 10^{-36} to 10^{-32} seconds [10]. Then, the universe started to cool, forming baryons from quarks and gluons, followed by mass annihilation. After that, the universe arrived at the dark ages, right after recombination, when electrons and atomic nuclei first combined to form neutral atoms. Eventually, the dark ages ended as the first stars and galaxies began to form. Matter in relatively denser regions exerts a gravitational attraction on each other and groups together into gas clouds, stars, or other cosmological structures.

1.1 Structure Formation in the Early Universe

One reason that dark matter is crucial to structure formation, unlike other types of matter, is that it does not interact with the electromagnetic field, so it is unaffected by radiation [8]. Normal matter that is affected by radiation tends to cause density perturbations and compromise structure formation. In particular, the dark matter halo plays a crucial role in consolidating large-scale structures and preventing them from breaking apart. The dark matter halo, a basic unit of cosmological structure, is a hypothetical region of accumulated dark matter particles distributed around visible matter structure. Such dark matter halos exert gravitational attractions on the standard matter, like protons and electrons, pulling them into the halo. When attracted to the dark matter halo, the standard matter would congregate into groups called the standard model particle dust. Subsequently, baryonic acoustic oscillations (BAO), in which baryons are pushed apart while heated with gravity and pulled together when cooled again, and radiation pressure, which is the pressure from electromagnetic radiation on the surface exerted on the standard matter due to their reaction to electromagnetic fields, would cause the standard particles to repel each other. As a result, the photons and other particles inside the dark matter halo would scatter apart under a repelling force without any attraction force. However, with the presence of dark matter halos, a gravitational force is exerted on the repelling particles, pulling them back together, resulting in a balance of attraction and repelling forces, causing the standard particles to approach a freeze-like equilibrium state. Therefore, dark matter would support large-scale structure formation under this process by holding particles with their gravitational influence that would otherwise spread apart.

1.2 Information Gap

These grouping processes must rely on gravitating matter, known as dark matter. Without the presence of dark matter, large-scale structures could not have formed at the speed and scale during the evolution of the universe [8]. Different dark matter candidates have been proposed, and there have been debates regarding dark matter as cold, warm, and hot. Nevertheless, dark matter is essential for forming stars and galaxies since it provides the gravitational force required for elements such as hydrogen and helium to clump together. Although dark matter is hypothesized to explain multiple phenomena in the universe that visible matter cannot account for, there is no clear definition for what a dark matter particle is like due to its lack of interaction with photons. Several dark matter candidates have been proposed, like Weakly Interacting Massive Particles (WIMPs) and Massive Astrophysical Compact Halo Objects (MACHOs) [11]–[16]. WIMPs fit within current dark matter theories because the particles need to be weakly interactive so that they would not react with baryonic matter and radiation, and they need to be massive so their speed would be slow enough for them to exert a gravitational force that fosters structure formation. The WIMP model is the most discussed dark matter candidate since it has a relic density close to that required of dark matter [11]. However, before identifying the structure of dark matter particles and which candidate is the most valid, it is important to understand the critical role of dark matter in structure formation during universe evolution and how the universe would be different without its presence.

Thus, the goal of this project is to explore the role of dark matter in the universe, specifically its contributions to the formation of large-scale structures and the evolution of the universe in general. In Section 0, the paper will briefly introduce key concepts germane to the formation of the universe, and the proposed role of dark matter within it. Then, the paper will outline four pieces of evidence supporting the dark matter hypothesis; i) bullet clusters, ii) gravitational lensing, iii) galaxy rotation curves, and iv) baryon acoustic oscillations.

II. Cosmological Context

To understand the significance of the dark matter in the evolution of the universe, we need contextual background on the evolution of the universe so as to understand the crucial importance of the dark matter in this process, which requires the explanation of the Big Bang Theory, the prominent theory for the evolution of the universe.

2.1 Formation of the Universe

The Big Bang Theory explains how the universe expanded from an initial hot and dense state to a current cool and tenuous state, explaining numerous observable phenomena, including the abundance of light elements, cosmic microwave background, and the formation of large-scale structures. Overall, the Big Bang Theory accounts for the universe's development over the course of 13.8 billion years [7]. The universe's evolution can be divided roughly into eight stages: Singularity, Inflation, Nucleosynthesis, Matter Domination, Recombination, Dark Ages, Reionization, and the Formation of large-scale structures.

The universe was initially in the singularity phase, gravitational singularity, where density, or spacetime curvature, reaches infinity [17]. When the universe exploded, going through the so-called "big bang," the four fundamental forces--the electromagnetic force, the strong nuclear force, the weak nuclear force, and the gravitational force--combined, leading to space conditions of extreme energy density, temperature, and pressure [8]. After this, space started to expand exponentially, going through a phase known as the inflationary epoch [10], in which the universe rapidly expanded in volume, resulting in a sudden increase in density and temperature. It is estimated that the universe expanded by at least a factor of 10^{26} in the three known spatial dimensions (thus, equating to a volumetric increase by a factor of 10^{78} or more). Inflationary models propose that the inflationary epoch began approximately 10^{-36} after the big bang, and lasted about 10^{-32} seconds [8],[10].

In the subsequent period, known as the electroweak epoch, the fundamental forces began to separate, temperature and density began to drop, and the expansion of the universe slowed down, eventually leading to the Nucleosynthesis stage [8]. The high temperature of cosmic inflation led to the formation of quarks and gluons, both of which were elementary particles. At 10^{-6} seconds, with the start of nucleosynthesis, the quarks and gluons combined to form baryons like protons and neutrons. The temperature of the universe began to cool down gradually. Eventually, the rapid collisions of particles declined, leaving only the fastest and strongest reactions that resulted in the formation of hydrogen and helium, the first nuclei in the universe, which signaled a gradual shift of the universe from radiation-dominated to matter-dominated as the energy densities of energy and matter slowly equalized. Matter, in this case, included the still ionized hydrogen and helium particles reacting with photons, and cold dark matter, which will be later discussed. Derived from Friedmann's Equations, the equation for the scale factor of a radiation-dominated universe would be:

$$\alpha(t) \sim t^{1/2} \tag{1}$$

Similarly, the scale factor for a matter-dominated universe would be:

$$\alpha(t) \sim t^{2/3} \tag{2}$$

The scale factor for a dark energy-dominated universe, which will occur later in the evolution of the universe and be discussed later, would be:

$$\alpha(t) \sim exp(H_0 t) \tag{3}$$

The coefficient H_0, the Hubble's constant, is

$$H_0 = 70 \pm 7 \ km \ s^{-1} \ Mpc^{-1} \tag{4}$$

Equations (1)-(4) indicate that the expansion of the universe initially decelerated, and the rate of deceleration declined as matter density surpassed that of energy, and the universe expansion eventually began to accelerate as dark energy dominated [18]. As seen in **Error! Reference source not found.**, the energy density of energy and matter gradually declines. In contrast, dark energy density remains constant over time, thus resulting in the dark energy-dominated universe today.

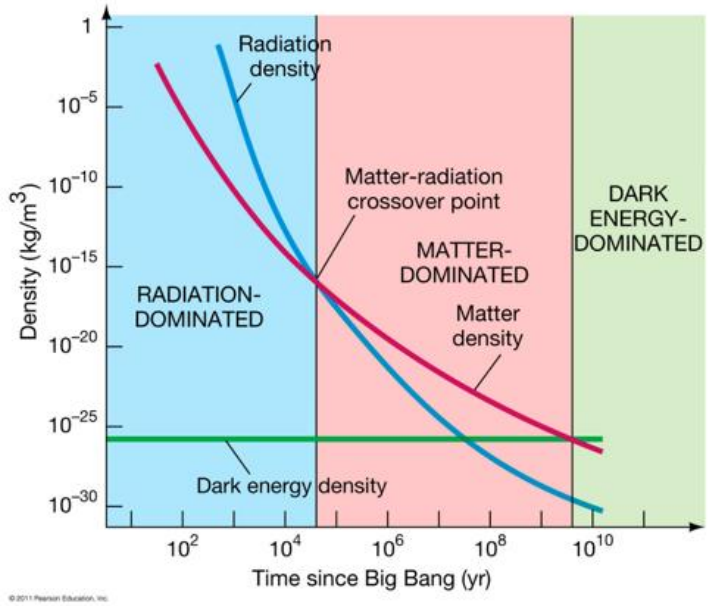

Figure 1: Density vs. Time since Big Bang for radiation density, matter density, and dark energy density [18].

While hydrogen and helium were still ionized during nucleosynthesis and continued to react with photons, during Recombination, neutral atoms of these elements began to form [8]. During the Epoch of Recombination, electrons first combined with protons to form neutral hydrogen atoms. At this time, atoms formed at approximately a redshift of $z \simeq 1100$ and temperature of $T = 3000\ K$. Under these conditions, the plasma could recombine. However, as the temperature further cooled, the cosmic microwave background shifted from red, uniform blackbody radiation to infrared, which is invisible to the human eye, thus leading to the Dark Ages. The Cosmic Microwave Background is the electromagnetic radiation left from the early stages of space evolution, which helps investigate the evolution of the universe.

During the Dark Ages, the universe experienced a relatively little amount of change, and the first compounds were formed: small amounts of H_2, HD, and LiH_2. The Dark Ages ended when the first stars began to form due to the collapse of dark matter halos. As the first stars formed, objects that could emit energy and light emerged in the universe, thus making everything visible to the human eye today.

During the formation of the first stars and the first galaxies, there is this period called the Reionization period[19],[20]. Similar to the Recombination period, the Reionization period was the second major gas phase transition during the formation of the universe. Reionization refers to separating protons from electrons in hydrogen, thus transitioning the phase from a gas to a plasma, which is an energized gas that would emit a glow. As usually believed, the first stars and galaxies that formed in the universe assisted with the process of Reionization, with a few types of galactic structures contributing the energy source required to ionize the gas--quasars, dwarf galaxies, or population III stars, especially the last one. The population III stars, highly related to what will be discussed later in dark matter, possibly contributed great energy through supernovae forms. After the Reionization period, early stars and galaxies were pulled together by gravitational forces to form galaxies or superclusters. However, such processes would be unlikely without dark matter, which will be discussed in the following sections. Until now, we offer a clear view of the background in which dark matter is discussed.

2.2 **Evidence for the Big Bang Theory**

2.2.1 Redshift

The most prominent source evidence for the Big Bang Theory is a phenomena known as redshift, wherein light from a source appears to have a different wavelength (or color) depending on the relative depending on the relative velocity between the observer and the source [21]. The light approaching us from galaxies (as determined via spectroscopy), appears redder than it truly is (that is, has an increased apparent wavelength). This indicates that distant stars and galaxies are moving farther away from Earth. With stars and galaxies moving away, people on Earth would perceive an increase in wavelength that causes light to shift to the red end of the color spectrum, thus "red-shifted." On the contrary, the blueshift would be observed due to decreasing wavelengths if the galaxies were moving toward the Earth. Therefore, the redshift observed from galaxies supports the assertion of the Big Bang Theory that the universe is expanding from the point of singularity and coming to the present accelerating expansion. The Doppler Effect is another phenomenon with the same core principle, applied to sound waves. Instead of wavelengths of light, the Doppler effect concerns wavelengths (apparent pitches) of sound, wherein sound waves in front of a moving object are closer to each other than those behind it, causing different pitches of sound depending on the relative position of the receiver with respect to the moving source.

2.2.2 Cosmic Microwave Background

Another important piece of evidence for the Big Bang is the Cosmic Microwave Background (CMB), the term given to electromagnetic radiation emitted during one of the early stages of universe evolution, specifically the Recombination Period [19],[20]. The space between stars and galaxies is usually not seen with visible telescopes. However, with radio telescopes, an emission mainly in the microwave range can be detected, which is the cosmic microwave background. The cosmic microwave background was the leftover of the big bang explosion that shifted gravitational singularity into the inflation period. As the Big Bang Theory presumes, the universe was initially at extreme temperatures and density, but as time proceeded, it eventually cooled down, and mass spread out. While the decrease in density could be explained by the expansion of the universe, along with Inflation theory (which was developed by several theoretical physicists including Alexei Starobinsky and Alan Guth, and Andrei Linde) [22],[23], the gradual decrease in temperature could be explained by observed patterns of the cosmic microwave background. Right after the Big Bang, the universe was a dense, hot body of plasma. Since the photons could not scatter far due to interactions with electrons, the universe was opaque. However, as it later cooled down (in the Recombination period), electrons combined with protons to form neutral atoms; this allowed photons to linearly scatter in the universe, thus causing the universe to become transparent. At this stage, radiation with wavelength on the order of microns consisting of these photons was emitted (a.k.a. CMB). Therefore, the presence of cosmic microwave background radiation provides sufficient evidence for the component of the Big Bang Theory that postulates that the universe experiences a gradual decrease in temperature over time.

2.3 Large Scale Structure Formation

Structure Formation refers to the formation of large-scale structures like stars, galaxies, and clusters. It will be one of the most critical concepts investigated for dark matter. The formation of structures remains one crucial stage of the universe's evolution, which completely altered the universe from independent scattering ions to a hierarchical system of structures. While the factors influencing structure formation will be discussed later with the incorporation of dark matter ideas, it is first important to understand the large-scale structures. Stars, formed with plasma being attracted together by gravitational forces, are combined into galaxies, a combination of stars, interstellar gas, dust, and more substances. Galaxies, in turn, combine into galaxy groups, most of which with less than fifty galaxies. The larger combination of galaxies would be galaxy clusters, consisting of hundreds and thousands of galaxies. Several of these minor clusters would then combine to form superclusters, which are the largest known structures in the universe. With knowledge of the basic large-scale structures, we can then discuss dark matter’s effects on the formation of the structures.

i. The First Stars (Population III)

Another subject to be investigated is Population III stars, which is the name given to the first stars formed in the universe [8]. Population III stars are the most unfamiliar to scientists compared to Population I and Population II stars that subsequently formed. Categorized according to formation conditions, the metallicity of the stars decreases from Pop I to Pop III, with the Pop III stars consisting of only the lightest elements in the universe – hydrogen and helium for most, with a negligible amount of Lithium and Beryllium. The Sun, for example, is an example of a Pop I star with a metallicity of about 2%, which is considered to be relatively high for stars [24]. The Pop III stars are significant to the evolution of the universe in that they contribute to the formation of the first 26 elements heavier than hydrogen and helium – including the early metals – which contributed to the subsequent formation of planets and life. Therefore, the Pop III stars are critical to the evolution of the universe to its present state. While Pop I and Pop II stars are both observable, and examples can be found in the universe, Pop III stars have yet to be observed. One explanation of this would be the pair-instability supernovae, an explosion that emits metals, leading to the formation of later generations of stars, the Pop II stars, with slightly greater metallicity [25]. While most Pop III stars fit this phenomenon, some experienced photodisintegration, in which stars collapse into black holes, regions of extreme gravitation that consume all matter in close proximity.

As previously mentioned, Pop III stars are only hypothetical since none are directly observed despite indirect evidence indicating their existence. Assuming that Pop III stars exist, possible reasons for their lack of direct observation would be that they might be mistaken as Pop II stars. This could occur either due to the convection of metals inside the core of the stars coming to and contaminating the surface, which would cause them to be confused with Pop II stars of poor metallicity. Such confusion could also be possible due to the gas of the interstellar medium contaminating the surface of Pop III stars, which also causes them to be observed as Pop II stars. Apart from their confusion with Pop II stars, the Pop III stars are also unobservable due to their extremely high masses, which leads to greater contracting gravitational force ($F_g = \frac{GM_1m_2}{r^2}$), increasing the temperature of the core, leading to a higher rate of nuclear reaction, thus causing the hydrogen to be exhausted faster, leading to supernovae exploding the stars, leaving no observable remnants. Though possible observations could be made for remnants such as white dwarfs, neutron stars, or black holes, they do not provide definite support for the existence of Pop III stars since their origins could not be determined. However, possible evidence confirming the existence of Pop III stars includes gravitational lensing and the discovery of heavy elements in quasar emission spectra, though further investigation is required.

2.4 Dark Matter & Evidence for its Existence

According to its name, dark matter is a hypothetical matter that exerts a gravitational influence on structures in the universe but is not observable. Contrary to the common expectation, visible matter only takes up about 4.6% of the universe, with the remaining dark matter at 24% and dark energy at 71.4% [1]–[5] .

While dark matter remains a hypothetical construct since it is largely unobservable (almost by definition), there are various pieces of evidence indirectly proving its existence, some of which are outlined in the following sections.

ii. Bullet Clusters

Bullet clusters, referring to the two colliding galaxies, provide substantial evidence for the existence of dark matter [26],[27]. During the collision of the two galaxies, the visible matter, or hot gas, would presumably exert a drag effect between the two clusters. However, the mass of clusters is not affected, and the galaxies continue to move past each other, which implies the effects of some invisible matter that does not interact with each other, accounting for the continuous movement of the galaxies. Therefore, dark matter particles would explain this phenomenon in that they do not exert dragging effects on each other and thus causing the galaxies to pass over each other. Moreover, the fact that the observed center of mass differs from the baryonic center of mass also indicates the dark matter altering the center of mass, thus indicating the possibility of dark matter constituting a portion of the universe.

iii. Gravitational Lensing

Another phenomenon accounting for the existence of dark matter is gravitational lensing [28]–[30]. For observers, far galaxies can appear distorted since light is affected by the gravitational effects of distant matter, causing gravitational lensing. The distant matter is hypothesized to be dark matter. Notably, it does not directly bend light; instead, dark matter distorts spacetime, which affects the path of photons that follow the curvature of spacetime, resulting in the distortion of distant galaxies. Therefore, the gravitational lensing phenomenon is hard to explain without dark matter.

iv. Galaxy Rotation Curves

A spiral galaxy is usually a flat disk with the bulge in the center, which is the central stars, surrounded by a fainter halo of stars, which is then surrounded by gas, dust, and stars. According to Kepler's Second Law, if the luminous mass constitutes all the matter, the greater the distance from the center, the less the velocity. However, unlike the expected trend, the velocity of the matter far from the center of the galaxies does not experience a decrease in velocity [31]. In fact, the velocity is kept relatively constant despite the change in distance, as shown in **Error! Reference source not found.**.

The curve for the observed trend in velocity is flat instead of downward sloping, which implies the influence of some unobserved matter.

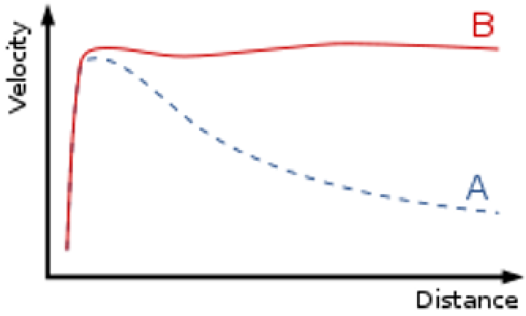

Figure 2: Rotational Curve of a Typical Spiral Galaxy. Curve A shows the predicted trend, and curve B shows the observed trend [31].

v. Baryon Acoustic Oscillations

Baryon Acoustic Oscillations (BAOs) are sound waves caused by fluctuations in the density of visible matter, and they provide by far the most compelling evidence for dark matter [32],[33]. Baryon acoustic oscillations are crucial in investigating the distribution of stars and the expansion history in the universe. One significant factor of baryon acoustic oscillations is density fluctuations, the different densities in different regions of the universe. Denser regions would exert gravitational attractions on their surroundings, causing matter, including dark matter, to flow inward. Photons would then exert outward pressure to equalize with the inward force, causing radiation to push outward, resulting in the detected acoustic waves. Initially, the shells of the regions were expanding fast since the sound waves were traveling at half the speed of light. Therefore, BAOs provide important evidence for the existence of dark matter.

III. Conclusions

A brief overview of the formation of the early universe, as predicted by the Big Bang theory has been presented. According to mathematical analysis, there is a substantial mass defect (95%) between the mass-energy of observable particles (5%) and that which should exist to bring our universe to its current condition. Thus, it is clear that some mysterious form of matter must exist to explain the mass defect. The terms given to the unknown mass and energy that would fix the discrepancy are dark matter (26%), and dark energy (68%), respectively. Various pieces of evidence for the existence of dark matter as we know it have been outlined, namely: i) bullet clusters, ii) gravitational lensing, iii) galaxy rotation curves, and iv) baryon acoustic oscillations.

a. Future Work

Given the compelling body of research surrounding the existence of dark matter, it would be appropriate to investigate further to discover what the true composition of dark matter is, and the implications it has on the past, present and future of the universe. We suggest the following avenues for future work: i) The notion of hierarchical structure formation, and the assumptions required therein; ii) The composition of dark matter and how it may change the Standard Model; iii) the properties of dark matter, whether is relatively cold (according to the popular Lambda-CDM model) or not; and iv) Whether dark matter is essential to stellar formation, and what the universe may have looked like without it.

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