Mass-to-Luminosity Ratio and Its Correlation To Dark Matter Distributions Across Different Galaxy Types

By Jaymin Ding, Pradyota Phaneesh, and Abhiram Atluri

Author Bio

Jaymin Ding, Pradyota Phaneesh, and Abhiram Atluri are high schoolers who live in the US. Jaymin, a junior in New York, loves STEM, specifically physics, math, computer science, and astrophysics, and is driven to learn new things. Pradyota, a senior residing in Austin, loves learning about all things science. Abhiram, living in Dallas, loves learning new types of math and computer science. When the three came together to study computational astrophysics at UT Austin, a common interest in researching galaxies and dark matter emerged. Through the High School Research Academy (HSRA) program, the group learned about astrophysics and worked on designing astronomical simulations. Their shared passion for math, science, astronomy, and astrophysics led them to continue their research after the program ended. The group received guidance from Professor Shyamal Mitra from UT Austin.

Abstract

Dark matter is believed to play a pivotal role in the structure and dynamics of galaxies. Unlike ordinary matter, dark matter does not emit light or energy or interact with electromagnetic forces. This study explores dark matter distribution in galaxies and compares various galaxy types. We utilize the Spitzer Photometry & Accurate Rotation Curves database, focusing on late-type and early-type galaxies, including Blue Compact Dwarf, Lenticular, Small Magellanic, Tight Spirals, Loose Spirals, Irregular Spirals, and Elliptical galaxies. Using centripetal acceleration and Newton's Law of Universal Gravitation, we derive a galaxy-mass equation within a certain radius. Luminosity within a given radius is graphed through conversions from the database. Results indicate that the mass-to-luminosity ratio generally increases with radius across all galaxy types, suggesting an intertwined relationship between mass, luminosity, and dark matter distribution. The increasing mass-to-luminosity ratio with radius implies that all galaxies tend to have more mass relative to their luminosity as we move further from the center. This supports the idea that dark matter becomes more prominent in the outer areas of the galaxy, forming a dark matter halo and exerting gravitational forces on visible matter to influence the structure of the galaxy. Our results imply that dark matter is a significant part of galaxies.

Keywords: dark matter, galaxy, distribution, SPARC database, mass, luminosity, mass-to-luminosity, dark-matter halo

History of the Field

Dark Matter has been a focal point of attention since its discovery. This short literature review allows us to explore the initial findings of dark matter and its implications for the future. The concept of dark matter can be traced back to the observations of Fritz Zwicky in the 1930s (Andernach & Zwicky, 2017). Zwicky noticed inconsistencies between the calculated and observed mass of galaxy clusters, hypothesizing the existence of invisible matter, which he referred to as “dunkle Materie” or Dark Matter. However, it was not until the 1970s that the concept of dark matter gained significant attention. Vera Rubin and her colleagues conducted studies on the rotation curves of galaxies. Their observations revealed that stars located at the outer regions of galaxies exhibited velocities higher than expected based solely on visible matter (Rubin, 1983). This behavior suggested the presence of additional mass, dark matter, spread throughout the galaxy. This was confirmed by other investigators as well (Challinor, 2004; de Swart et al., 2017).

Dark matter holds a crucial role in our comprehension of the cosmos, accounting for roughly 27 percent of the total mass of the universe. Its gravitational influence also plays a fundamental part in shaping the formation of galaxies, providing the essential framework that governs the construction of large-scale structures (Bradač et al., 2008). The nature and composition of dark matter are still not well understood (Feng, 2010).

Research Question and Importance

The mystery of dark matter has been puzzling scientists for a long time. Ever since the discovery that the outer parts of galaxies were moving at the same speed or faster than the inner parts of galaxies, scientists have been searching for what dark matter could be made of.

Our study aims to find the distribution of dark matter in a galaxy based on the radius and then compare the distributions for spiral, elliptical, lenticular, and irregular galaxies. Our galaxy classifications were defined by Hubble in his 1926 paper Extragalactic Nebulae (Hubble, 1926). We also want to compare the dark matter distributions in field galaxies to those in a cluster.

Our research is different because we want to investigate the dark matter distributions across different types of galaxies. We are using existing data gathered from the SPARC database, which contains data on the rotation curves and photometric profiles of a large number of galaxies, to do our research. Many researchers also use rotational velocity as their primary indicator of dark matter; however, we will be using the mass-to-luminosity (M/L) ratio, something that is noticeably rarer in the field. The use of the M/L ratio provides some advantages: unlike rotational velocity, it does not have to be compared to observed mass; high M/L ratios will indicate high dark matter concentrations due to dark matter having mass but not luminosity. The M/L ratio is also independent of galaxy orientation to the observer. Investigating the distribution of dark matter within galaxies is crucial for understanding the structure of the universe, the formation of galaxies, and the nature of dark matter. While scientists lack a full understanding of dark matter, there is strong evidence supporting its existence. Because of this evidence, further investigation of dark matter, including its distribution, is warranted. Understanding the distribution of dark matter would also provide an understanding of astrophysical processes, such as galaxy formation and evolution, and allow testing of theoretical models, including cosmological models. Dark matter would also offer a stronger grasp on the formation of galactic halos and gravitational lensing within galaxies (Refregier, 2003).

Data Sources

SPARC Database

We are using the Spitzer Photometry & Accurate Rotation Curves (SPARC) database of galaxies (Lelli et al., 2016). We specifically focus on the Basic SPARC Data, which is for Late-Type Galaxies, and the Early-Type Galaxies Data (Lelli et al., 2017) for our analysis. Our sample encompasses various galaxy types, including Blue Compact Dwarf (BCD), Lenticular (S0), Small Magellanic (Im), Tight Spirals (Sa), Loose Spirals (Sc), Irregular Spirals (Sm), and Elliptical (E0-E7). By including galaxies across different classifications, the goal was to capture a wide range of dark matter distribution patterns. The database includes data on 175 late-type galaxies, such as spirals and irregulars (Starkman et al., 2018). It also includes a limited sample of early-type galaxies, such as ellipticals and lenticulars. Its measurements are from Spitzer photometry at 3.6 µm (which traces the stellar mass distribution) and high-quality H-I, H-α rotation curves (which trace the gravitational potential to large radii).

Highlighted Galaxies

We have chosen the specific galaxies shown in Figure 1 based on their classification and characteristics in order to capture a diverse range of dark matter distribution patterns.

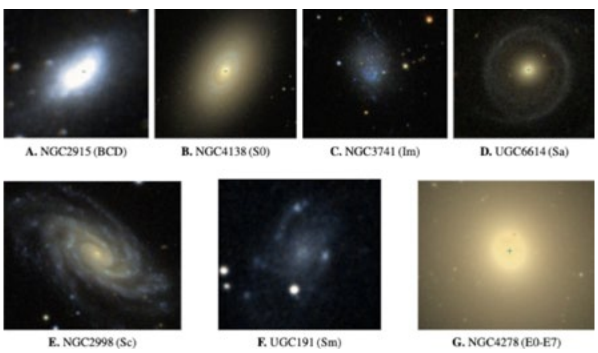

Figure 1. Chosen representative galaxies from the sample population.

Methods

Our first step was to calculate the mass of the galaxies given their rotational velocities. We assumed each galaxy to be circular, simplifying the mathematical modeling and analysis of the data. In reality, different galaxies can vary in shape, so while this assumption is useful, in the future, more complex models may be needed to obtain more accurate data. To gather the data we needed, we followed several steps: downloading, compiling, sorting, and formatting data from the SPARC database, which includes the Basic SPARC Data on Late-Type Galaxies, Early-Type Galaxy Data, Galaxy Samples, Newtonian Mass Models, and Photometric Profiles. We then filter the dataset to 7 specific galaxies of interest, each galaxy representing one galaxy type. We then obtained the rotation curve of each galaxy, found in the Newtonian Mass Models provided in the SPARC database, and used equation (1) to calculate mass:

$$M = \frac{v_{rot}^2 r}{G}$$

where M is the mass in kilograms contained within the radius r in meters, vrot is the rotational velocity in km/s of the galaxy within that radius, and G is the universal gravitational constant, we can find the mass of the galaxy within that radius. We get Figure 2 with the seven galaxies chosen.

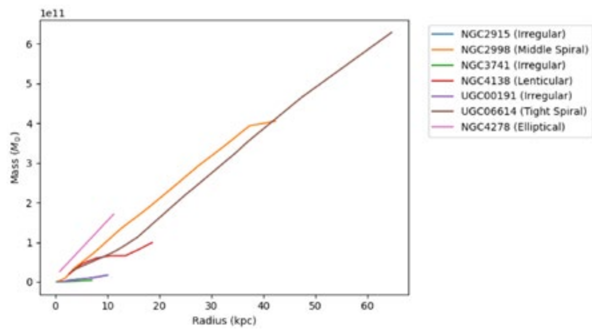

Figure 2. Mass within a Radius vs. Given Radius

As part of the process of finding the dark matter mass distributions, we also found the luminosity of the galaxy to be approximately represented by

$$L = \sum_i \left[\left(206265^2\right) \pi \left(1000 R_i\right)^2 \left(10^{0.4(M_\odot - S_i - 5)}\right) \right]$$

where L is the luminosity contained within the radius Ri, Si is the surface brightness within the radius, and M is the absolute magnitude of the sun at the measured wavelength, in this case, 3.26 at 3.6 m. Both Ri and Si are measured. In simple terms, the formula works by adding up the amount of brightness (luminosity) of the galaxy at different levels of distance from its center. This summing process is similar to how you would calculate the area under a curve using small rectangles, which is known as a Riemann Sum. Utilizing equation (2), Figure 3 is obtained.

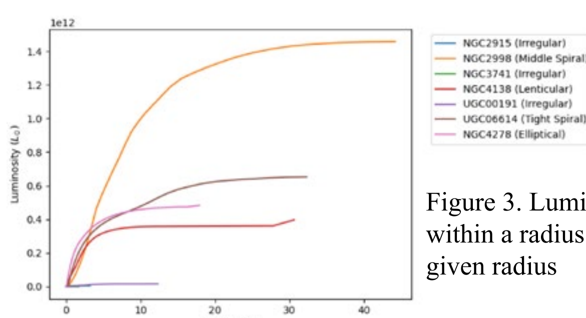

Figure 3. Luminosity within a radius vs. given radius

Because the radii were different in the Newtonian Mass Models and Photometric Profiles data, we calculated M/L ratios using the provided Newtonian Mass Model radii to compute mass values and then derived luminosity values through linear interpolation on the luminosity graph (Ding, 2023). We used equations (1) and (2) to calculate and graph the M/L ratio of the galaxy contained within a given radius, shown in Figure 4.

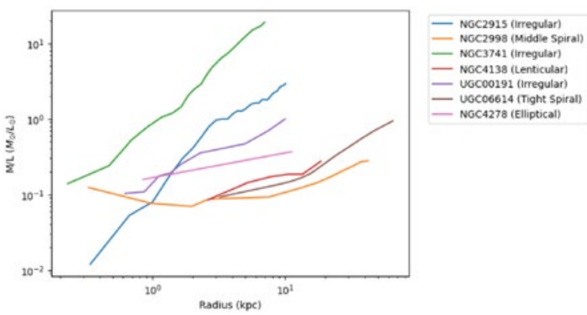

Figure 4. M/L ratio within a radius vs. given radius

Results

In Figure 3, the luminosity curves for all galaxies flatten out at the top, which is to be expected since the stellar density decreases as the radius increases, leading to a decrease in the growth of the overall luminosity. As seen in Figure 4, the M/L ratio starts low for all galaxies and increases.

Initially, the low M/L ratio suggests that there is a smaller amount of mass compared to the luminosity of the galaxies. This suggests that visible matter, such as stars, gas, and dust, and not dark matter, is the dominant contributor to the observed luminosity and that compared to other parts of the galaxy, there is less dark matter in the center.

However, as the radius continues to increase, the M/L ratio begins to rise again. This is likely due to the presence of dark matter. Dark matter is a form of matter that does not emit or interact with light, yet it exerts gravitational effects on the visible matter within galaxies. So, as the radius increases, the gravitational influence of dark matter becomes stronger relative to the luminous matter, causing an increase in the M/L ratio. In other words, the total mass, which includes both visible and dark matter, increases more rapidly than the luminosity alone.

As can be seen from Figures 3 and 4, both mass and luminosity increase for any galaxy as the radius in which both are measured increases. It seems that mass has an approximately linear relationship with the radius, while luminosity seems to have an exponential or power relationship with the radius. Interestingly, the M/L ratio, as seen in Figure 4, follows a similar general trend for all the galaxies: it starts low and increases.

A higher M/L ratio represents more mass for a given luminosity. The mass in a galaxy is composed of normal, luminous matter and dark matter. However, only normal matter has luminosity, as dark matter does not give off light or interact with electromagnetic forces. For a given luminosity, a higher mass would mean more dark matter (as dark matter cannot shine), and less mass means less dark matter. Thus, a higher M/L ratio indicates more dark matter. Spikes in the M/L ratio graph could indicate more dark matter at that radius in the galaxy.

Discussion

We chose to compare our research with Sipols, A., & Pavlovich's dark matter research (Sipols & Pavlovich, 2020) due to similarities in the research process, despite the absence of similar papers. Although we did not find publications with methodologies or findings identical to ours, we observed comparable approaches and techniques used in the other study. Additionally, both studies utilized the SPARC database to examine galaxies, facilitating a straightforward comparison of our respective datasets.

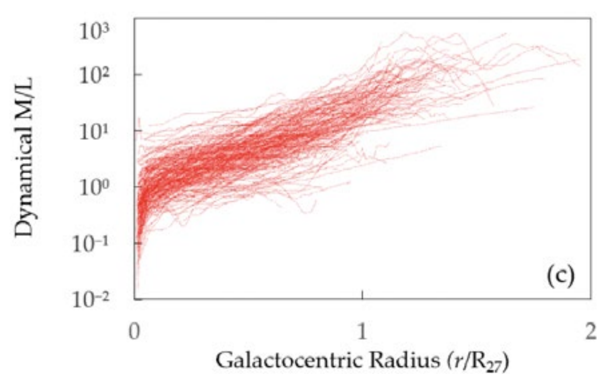

Figure 5. M/L ratio within a radius vs. given radius (Sipols et al., A. 2020)

As we compare Figure 4 and Figure 5, we can see that they both follow a similar trend: the M/L ratio starts low and then rises.

Reflecting on our research, we have made significant progress in understanding the distribution of dark matter in galaxies and its relationship with mass and luminosity. Through the analysis of data from the SPARC database, we were able to examine the M/L ratio within different radii and observe intriguing trends.

One of the most notable findings was the increase in the M/L ratio with radius for all galaxy types. This suggests that as we move further away from the center of a galaxy, the influence of dark matter becomes more prominent relative to the visible matter. This aligns with the concept of dark matter forming a halo around galaxies and exerting gravitational effects on the luminous matter. Comparing our research with Sipols, A., & Pavlovich, we found similarities in the research process and the use of the SPARC database. Although our methodology differed, the overarching results, as well as techniques, were comparable.

One of the main issues that we look forward to fixing and improving upon is our mass calculation. Our mass calculation did not account for velocity dispersion, something which we will add to future research on this topic. Addressing the issue of not accounting for velocity dispersion in our mass calculations is a significant step forward in improving the accuracy and reliability of our research. Moving forward, further investigation is required to delve deeper into the complexities of dark matter distribution and its implications for galaxy formation and evolution. Additionally, exploring the connection between dark matter distributions in field galaxies and those in clusters would provide valuable insights into the influence of the environment on dark matter structures.

Examining the detailed profiles of dark matter halos is also an intriguing area for research. While our research focused on the distribution of dark matter within specific radii, further exploration of density profiles and inner slopes of dark matter halos can provide insights into its properties.

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