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Influence of Dark Matter Halos on Rotation Curves of Galaxies

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Abstract

Dark matter is believed to form massive halos around galaxies, strongly influencing the rotational velocities of stars, affecting galaxy rotation curves: an effect observed when models and machine learning predictions of star velocities differ from actual measurements. These predictions were compared to actual observed circular velocities through graphical representations to assess model accuracy for this study. Scientists are actively trying to understand how dark matter halos affect galaxies and their stars because the role of dark matter in the universe poses as a knowledge gap due to its invisibility and large presence in the universe–over twenty-seven percent of the universe. This study aimed to explain how stars' velocities are changing and what aspects of the dark matter halos cause these changes. Two machine learning models, Random Forest and Support Vector Machine, analyzed the data from fifty galaxies to observe if changes in velocities occurred. Stars' velocities and other key features, unaffected by dark matter, were obtained from the SPARC database and used in the Navarro-Frenk-White (NFW) Profile to estimate the amount of dark matter present. From that, the models predicted galaxies' velocities based on halo density and mass. This approach allowed comparison between original velocities (without dark matter) and predicted ones (with dark matter). The study found that dark matter halos increased rotation curves in some galaxies, while decreasing them in others, clearly indicating that dark matter halos play a role in affecting galactic rotation curves.

Keywords: Dark Matter, Dark Matter Halos, Galaxy Rotation Curves, Circular Velocities, Navarro-Frenk-White Profile, SPARC Database, Machine Learning Models

1. Introduction

Dark matter does not emit, absorb, or reflect any light and is therefore invisible; hence, it remains undetected to date. Some gravitational effects have been detected, but they were not consistent with the presence of visible matter. This matter is believed to make up around twenty-one percent of the universe's mass distribution, which is significant compared to other components of the universe. A dark matter halo is one of the most important structures of dark matter. Spherical regions around galaxies encompassing their visible outskirts are known as "halos." These enormous tendrils produce gravitational tugs on the galaxies they wrap. The data shows that this observation is consistent with the observed rotation curves of galaxies arising from dark matter halos in accompanying suspended booms, which expand significantly beyond the distribution of visible matter. Hence, it is not hard to understand that these halos create gravitational forces that are strong enough to make stars whirl around galaxies at surprisingly high speeds compared with what you might expect based on observable matter alone (Wechsler & Tinker, 2018; Bullock & Boylan-Kolchin, 2017). Galactic rotation curves depict the rotational velocities of stars orbiting a galaxy as a function of its distance from the galaxy's center. The velocity of a star or specific matter in space is displayed on the Y-axis against the distance from the galaxy's center on the X-axis.

In 1973, Ostriker and Peebles proposed a groundbreaking theory to change the scientific consensus on dark matter. Their conjecture that disk galaxies could be stable if a substantial, massive, and spherical halo were composed of unseen matter provided a theoretical basis for validating these observational anomalies. This work was a significant step towards understanding the role of dark matter in galactic stability, enlightening the scientific community and paving the way for further research (Ostriker & Peebles, 1973).

Similarly, this work revealed results consistent with those of Ostriker and Peebles (Ostriker & Peebles, 1973). After accounting for various galactic velocities, the results showed that there was indeed a factor that accounted for increased observational velocity: dark matter. Some advantages of Ostriker and Peebles' approach are that they utilized N-body numerical simulations to explain the galactic stabilities of the galaxies, a method that was groundbreaking in enhancing the understanding of dark matter's role in the universe; used a framework that could be easily adapted or extended by future researchers to include more galaxies or complex galactic features; and employed models, which clearly displayed the impact of dark matter, making causal relationships easier to observe. However, their approach posed some disadvantages: specifically, the limited data and less computational power as opposed to present day, which the simulations relied on, leading to results being less robust, and their lack of detailed halo profiles that would contain dark matter density profiles–that could be found using the Navarro-Frenk-White Profile–making the approach less precise for quantitative predictions. Unlike Ostriker and Peebles, this study utilized the NFW Profile, a mathematical model describing dark matter distribution in halos (Navarro et al., 1996). The NFW Profile allowed for obtainability of the halos' mass and density profiles, thus allowing this study to fully interpret the extent to which these forces play in these additional gravitational forces. This detailed analysis, therefore, provided strong evidence to underline the crucial role of dark matter in galaxy-wide gravitational dynamics. Since it is so adaptable, making mass and density distributions with complete precision in the manner of the NFW Profile allowed for estimating the gravitational impacts in a much more precise way.

After extensive investigation, the research question: "How does the mass and density profile of dark matter halos influence the rotation curve of different galaxies?" was settled. This question, which lies at the heart of scientists' understanding of the universe, was systematically examined to understand how galaxy rotation curves vary depending on the degree of concentration and distribution of dark matter. By studying various kinds of galaxies and comparing their rotation curves with characteristics of surrounding dark matter halos, a clear picture of the fundamental forces responsible for galactic structures can be obtained. Despite decades of research, a specific gap persists in scientists' understanding: how the detailed mass and density profiles of dark matter halos quantitatively determine the observed rotation curves of different galaxies, especially when accounting for galactic diversity and using modern modeling techniques (Bullock & Boylan-Kolchin, 2017; Kamada et al., 2020). While older studies like Ostriker & Peebles from 1973 and Navarro, Frenk & White from 1996 established the need for dark matter halos' understanding, recent work has shown that no single model consistently explains the rotation curves of all galaxy types such as those in Bullock & Boylan-Kolchin from 2017 and Kamada et al. from 2020. In addition, using machine learning models to address this problem is being implemented increasingly, and their ability to predict observed star velocities based on dark matter halos' mass and density is still being investigated (Katz et al., 2017; Ren et al., 2019). Addressing this gap is essential for refining the models of galaxy formation and evolution, and for testing the limits of the ΛCDM paradigm. This study aims to bridge this knowledge gap by applying Random Forest and Support Vector Machine models to a dataset of 50 galaxies, using NFW-derived parameters, and rigorously comparing predicted versus observed rotation curves.

2. Materials and Methods

One tool that was highly important was the NFW Fit Profile Formula to draft a line of fit, which considers the mass and density profiles of dark matter halos surrounding different galaxies. The line of fit can be manipulated to find the dark matter's velocity, which is an important component in determining how the rotation curve of a specific galaxy had been impacted. Another vital tool was the SPARC database, which provided a dataset with visible matter velocities and the observed circular velocity. This dataset along with the dark matter velocity and NFW line of fit allowed for the creation of models depicting the influence of dark matter on the observed circular velocity of a star orbiting around a galaxy.

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2.1 Navarro-Frenk-White Profile

$$p(r) = \frac{p_0}{(\frac{r}{r_s})(1 + \frac{r}{r_s})^2}$$

The density profile formula of Navarro-Frenk-White (NFW) describes the change in dark matter density as a function of distance from galaxies' centers (Navarro et al., 1996). $p(r)$ corresponds to the dark matter density at radius r, p_0 is the initial density and r_s is the scale radius. This formula determines how the mass is distributed in dark matter halos, which also affects their impact on galactic rotation curves. This is a direct consequence of trying to fit observed rotation curves with this profile and thereby indicating the presence and distribution of dark matter because its gravitational effects account for the high velocities seen in these outer regions of galaxies.

2.2 SPARC Database

The SPARC (Spitzer Photometry and Accurate Rotation Curves) database is a large, even, database of accurate photometric and kinematic data for over 150 galaxies with disks. Data in SPARC are most important because of high-quality rotation curves with high spatial resolution, invaluable for studies on the existence and distribution of dark matter in galaxies. Observations consistently show that the outer regions of galaxies rotate with greater speed than can be explained by visible matter alone, implying the presence of dark matter (Corbelli & Salucci, 1999; van den Bosch & Swaters, 2001; Burkert, 1995). A dataset that had all of the velocities of visible matter was obtained from SPARC to create a rotation curve model for specific galaxies. Fifty galaxies' key features were compiled into one dataset, which was trained and tested by two unique machine learning models–the Random Forest Regression Model and the Support Vector Machine Model.

2.3 Random Forest Regression Model

The Random Forest Regression model is an ensemble machine learning method whereby, during training, it constructs many decision trees. This combines their predictions for improved accuracy with reduced overfitting. In this analysis, the model used the galactocentric radius, gas velocity contribution, disk velocity contribution, and bulge velocity contribution as features from the dataset to predict the observed circular velocity of stars in galaxies. The Random Forest model used many trees, from which it averaged the predictions to predict the circular velocities; this prediction was reliable. It could, in these ways, model complicated non-linear relationships between features with the target variable, contributing towards an understanding of dynamics driven by both visible and dark matter within galaxies.

2.4 Support Vector Machine Model

The SVM model is a very powerful machine learning technique that can be adapted as Support Vector Regression. In the present study, galactocentric radius, gas velocity contribution, disk velocity contribution, and bulge velocity contribution were used to regress on the target variable of observed circular velocity of stars in a galaxy. The SVM model found nonlinear relationships between features and the target variable by constructing an optimal hyperplane and showing good generalization performance to define data within a specified margin. It provides accurate estimates for circular velocities and showcases how dark matter influences galactic dynamics.

3. Results

3.1 Rotation Curves of Galaxies

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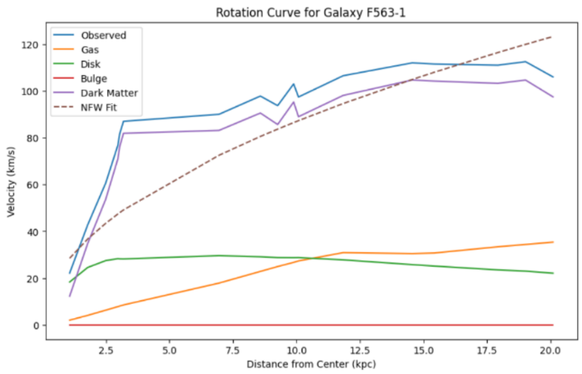

Figure 1. The rotation curve, velocity versus distance from center of the galaxy, for the galaxy F563-1 with all visible matters, calculated NFW line of fit, and calculated dark matter velocity.

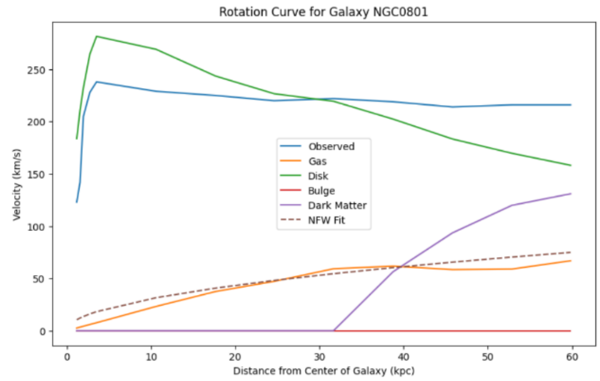

Figure 2. The rotation curve, velocity versus distance from center of the galaxy, for the galaxy NGC0801 with all visible matters, calculated NFW line of fit, and calculated dark matter velocity.

Figures 1 and 2 depict the rotation curves of two different galaxies within the study's dataset. The galaxies are F563-1 and NGC 0801, and the graphs show the distribution of the velocities of visible matter, which is represented by the bulge, disc, and gas velocities. The NFW Fit is derived from the NFW Profile formula to gather the density and mass profiles of a dark matter halo surrounding the galaxy.

3.2 Mass and Density Profiles

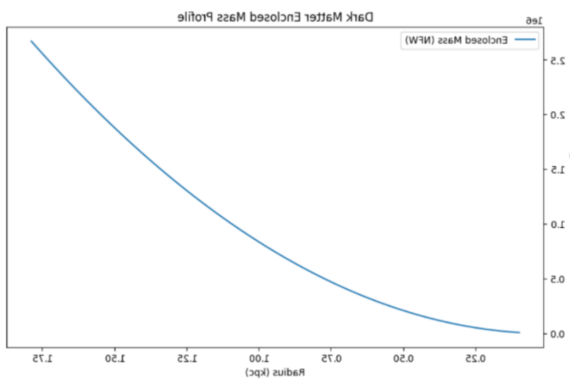

Figure 3. The mass profile of a dark matter halo, which shows the correlation between the mass of the dark matter halo and the radius of a galaxy.

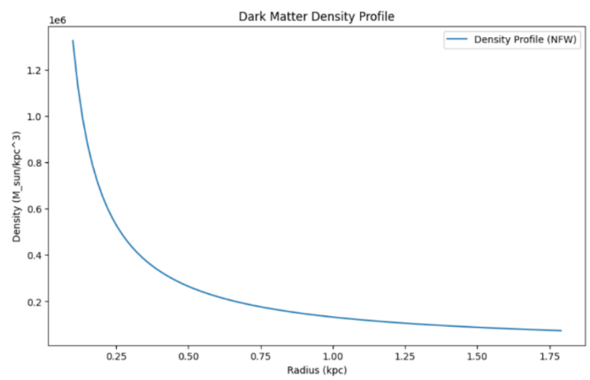

Figure 4. The density profile of a dark matter halo, which shows the correlation between the density of the dark matter halo and the radius of a galaxy.

Figure 3 shows the mass profile of a dark matter halo, illustrating how cumulative dark matter mass increases with distance from the galaxy center, based on the Navarro-Frenk-White (NFW) profile. The observed circular velocities and contributions from gas, disk, and bulge, help isolate and calculate the influence of dark matter, fitting the NFW profile to demonstrate its significant role.

Figure 4 shows the density profile of a dark matter halo, depicting how dark matter density decreases as distance increases from the center of the galaxy. This calculation, like the mass profile of the dark matter halo, was derived from the theoretical model/formula NFW profile. The observed circular velocities and contributions from visible matter velocities, allow the isolation and calculation of dark matter's influence, fitting the NFW profile to portray dark matter's large role in explaining the high rotational velocities observed in galaxies.

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3.3 Predicted Observed Velocities vs. Actual Observed Velocities by the Machine Learning Models

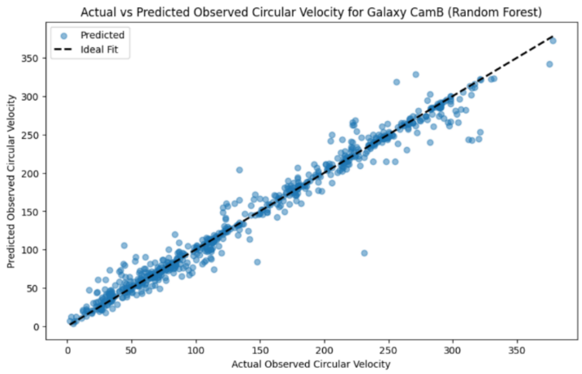

Figure 5: The comparison between Random Forest's prediction of the observed circular velocity and the actual observed circular velocity based on calculations for galaxy CamB.

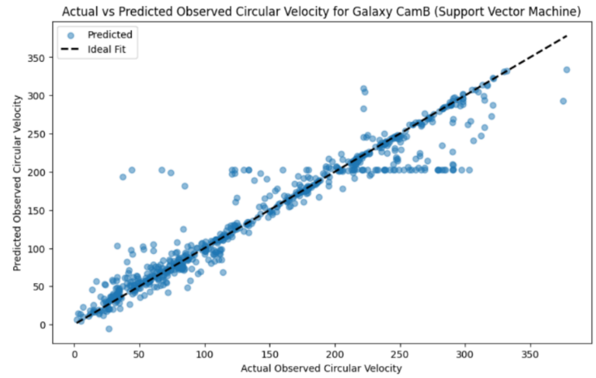

Figure 6: The comparison between Support Vector Machine's prediction of the observed circular velocity and the actual observed circular velocity based on calculations for galaxy CamB.

Figure 5 compares the predicted observed velocity against the actual observed velocity of stars located in galaxy CamB from a Random Forest model. Figure 6 compares the predicted observed velocity against the actual observed velocity of a star located in galaxy CamB from a Support Vector Machine model.

4. Discussion

Of the fifty galaxies that were analyzed, F563-1, NGC0801, and CamB were all chosen to be represented for this study because they each exhibit distinct rotation curve characteristics and robust, high-quality data. Specifically, after NFW profile calculations, each galaxy showed varying dark matter density and mass profiles, resulting in unique lines of best fit for their respective NFW profiles (Navarro et al., 1996). Other galaxies in the dataset exhibited relatively similar features, so including them would not have added much variety to the analysis.

In figure 2, as seen for the galaxy NGC0801, whenever the graph displays a low NFW fit, the dark matter velocity is also low, signifying a direct correlation. However, for the galaxy F563-1 in figure 1, it is the opposite, and the dark matter velocity is much higher due to the high NFW fit. Both factors ultimately affect the total observed rotational velocity, which is lower in NGC0801 due to the low dark matter velocity, while in F563-1, it is higher due to the high dark matter velocity. Essentially, this states that the higher the mass and density of a dark matter halo, the higher the dark matter velocity, which directly influences the observed velocity.

Figure 3 highlights that dark matter mass accumulates at larger radii, supporting the idea that most of a galaxy's mass lies in its extended halo. Figure 4 shows that dark matter density decreases with distance from the center but remains prominent enough to affect star velocities even far from the core, which aligns with the belief that dark matter is most concentrated towards the core of the halo.

For figures 5 and 6, the dots above the line of fit indicate that the predicted velocity was higher than the actual velocity meaning that the prediction was off because the dark matter halo's density is higher than anticipated. Dots below the line of fit mean that the predicted velocity was lower than the actual velocity, indicating that the prediction was most likely off due to not accounting for the fact that dark matter velocity and gravitational influence play a large role in changing the circular velocity. Dots on or along the line of fit imply that Random Forest was accurate in predicting the actual observed velocity and was close to a perfect estimate. All three locations of the dots in figure 6 have the same meaning as the three locations of the dots for figure 5.

The assessment of this study was mainly determined by the factors of data, implementation, and results. Overall, this study has successfully answered a great portion of the research question. For starters, in terms of data, this study succeeded a great deal, due to the SPARC Database. As mentioned, it is mainly centered upon rotation curves, and the various galactic velocities associated with it. Through this, by discovering and utilizing the dark matter velocity, the study was able to incorporate algorithms and programs to plot out the mass and density profiles of each halo. Also, by implementing various machine learning models, such as Random Forest, this study was able to radicalize the process, by applying code to greatly increase the study's efficiency. Through this, this study was able to systematically determine the correlations between each variable in this question. Furthermore, this study's approach has yielded a more stringent framework for future studies based on in-depth analyses and refinements. This both validates the study's methods and points toward future work that will examine the subtle dynamics taking place in dark matter halos.

The study's original prediction was slightly accurate: dark matter would increase the observed circular velocities. However, this was incorrect. Due to its variability in form, dark matter also caused decreases, as shown in Figures 5 and 6. Overall, the study's hypothesis was correct to an extent.

The results of this study strongly build on the theoretical framework used to understand the influence of dark matter on galactic rotation curves and, in turn, overall galactic stability. Therefore, the behavior and properties of the dark matter manifest through these galactic rotation curves of the dark matter halos, which scientists can ascertain. Thus, an essential consideration regarding dark matter is that it and its halos are vital in providing the gravitational forces necessary to explain the observed rotation curves. Also, the issue of how the dark matter halos affect the galactic rotation curves is a question, for the most part, that needs to be answered for it underlies cosmology and galaxy formation. This link is of significant interest to the scientific world in the way it determines the nature of galaxies and their role in the universe. Its answer can also help towards understanding the universe and explain its properties, variability, and interactions. This, in turn, feeds into a greater understanding of the universe at large, its composition, and evolution, potentially leading to breakthroughs in understanding of the cosmos.

5. Conclusion

In these dense, massive halos, the study's results showed that the density leads to a significant upward bias in observed stellar velocities. The analysis on NFW indicated an increasing mass of dark matter cumulatively moving away from the center of a galaxy as its density decreases, which means dark matter's effect is more dominated at the outer ends of the galaxies. This study predicted the circular velocities of stars based on machine learning models, namely, random forest regression and support vector machine. These models allowed the survey to understand better complex but non-linear relationships between different galactic components, which show that the density and mass of dark matter halos have essential roles in these predictions. Discrepancies between predicted and actual velocities were then observed, which might be accounted for in some density fluctuations of dark matter halos, thereby pushing for the importance of shape and galaxy dynamics. While these discrepancies may initially seem to challenge the accuracy of the models, they highlight the need for further research and the potential impact of density fluctuations on galaxy dynamics. This study, therefore, supports the idea that dark matter applies additional gravitational forces to objects to enable the explanation of different velocities in the outer part of galaxies, thus being another big tool in understanding galactic behavior.

These results hint at the need for further investigation into the properties and effects of dark matter on galaxy formation and evolution. Such studies, conducted with advanced techniques and larger datasets, could significantly improve model accuracy and pave the way for the exploration of different types of galaxies. This potential for further discovery is hopeful, promising a brighter future for the understanding of the universe.

The unification of information from scientific fields is a powerful concept. This study's work, merging observational data with sophisticated modeling methods, not only sets the stage for comprehensive studies but also inspires a sense of connection and collaboration among scientists. Through such unification, the mysteries of dark matter in the universe can be unraveled, existing theories can be confirmed, and further research in the dark sectors of the cosmos can be laid down.

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