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Research Article ***Volume 1 | Issue 1***

KOS Journal of Science and Engineering
https://kelvinpublishers.com/journals/science-and-engineering.php

Analyzing the Rotational Curves of Spiral Galaxies: Implications for Dark Matter and Galactic Dynamics

Diriba Gonfa Tolasa

Department of physics, Assosa university, Ethiopia

[*]**Corresponding author:** Diriba Gonfa Tolasa, Department of physics, Assosa University, Ethiopia, E-mail: dgonfa2009@gmail.com

Received: April 19, 2025; **Accepted:** April 29, 2025; **Published:** May 01, 2025

Citation: Diriba GT. (2025) Analyzing the Rotational Curves of Spiral Galaxies: Implications for Dark Matter and Galactic Dynamics. *KOS J Sci and Eng.* 1(1): 1-6.

1. Abstract

This study aims to analyze the rotational curves of spiral galaxies to deepen our understanding of their mass distributions and the implications of dark matter in galactic dynamics. We utilize advanced analysis techniques, including MCMC fitting of observational data from the Sloan Digital Sky Survey (SDSS) alongside Hα spectral data. We derive mathematical models to describe the dynamical behavior of these galaxies and validate them through systematic uncertainties in the observational data. Our analysis aims to clarify the contributions of baryonic and dark matter components, ultimately providing insights that can refine existing cosmological models.

2. Introduction

2.1. Background

Spiral galaxies are among the most visually stunning and dynamic structures in the universe. They represent roughly 60% of all galaxies observed in the local universe and are fundamental to the study of cosmic evolution. The curved paths that stars and gas follow around the centers of these galaxies known as rotational curves provide critical information about their mass distribution and gravitational influence.

2.2. Importance of Rotational Curves

Traditionally, mass distributions in galaxies were believed to follow a decline with radius, according to Keplerian dynamics. However, observations have consistently demonstrated that the rotational velocities of stars in the outer regions of spiral galaxies remain nearly flat, contradicting expectations based solely on visible matter [1,2]. This observation gives rise to the necessity of dark matter, which is theorized to make up approximately 85% of the universe's total mass [3]. Investigating these curves not only sheds light on individual galaxies but also informs our understanding of large-scale structures in the universe.

2.3. Objectives

This research aims to:

- Develop a methodology for extracting and analyzing rotational curves from observational data.
- Quantify the contributions of both baryonic and dark matter to these curves.
- Compare findings across various galaxies to enhance our understanding of dark matter distribution in spiral galaxies.

3. Literature Review

3.1. Historical context of dark matter research

The concept of dark matter emerged from observations of galaxy rotation curves in the 1930s. Zwicky [2] was the first to postulate the existence of unseen mass when he studied the Coma cluster of galaxies. He noted that the visible mass from the galaxies could not account for the high velocities of the member galaxies, suggesting a considerable amount of unseen mass. This seminal work laid the groundwork for future study in cosmology.

3.2. Modern evidence of dark matter

The presence of dark matter in galaxies is supported by various lines of evidence, including:

3.2.1. Galactic Rotation Curves: Rubin, et al. [1] conducted a detailed study of the Andromeda Galaxy and other spiral galaxies, demonstrating that the rotational velocities remained high at large distances from the galactic center, indicating a significant amount of unseen mass. These findings have been replicated and expanded upon in numerous studies [4,5].

3.2.2. Gravitational Lensing: The distortions of light from background galaxies by massive foreground galaxy clusters provide another compelling argument for dark matter's existence [6]. The gravitational lensing effect quantitatively supports the need for additional mass not accounted for by visible matter.

3.2.3. Cosmic microwave background (CMB): Observations from the WMAP and Planck missions Komatsu [7] 2011 provided insights into the early universe and indicated that ordinary matter contributes only about 5% to the total energy density of the universe, with dark matter comprising approximately 27%.

3.3. Theoretical models

Several models have been developed to understand dark matter's nature and distribution within galaxies:

3.3.1. Navarro-frenk-white (NFW) profile: Navarro, et al. [8] proposed a universal mass distribution model for dark matter halos, which describes the density profile as:

$$\rho_{dm}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

3.3.2. Burkert profile: An alternative to the NFW model, providing a better fit for certain dwarf galaxies and low surface brightness galaxies [9].

3.3.3. Modified newtonian dynamics (MOND): Proposed by Milgrom [10], this theory suggests that discrepancies between observed velocities and those predicted by Newtons laws at low accelerations could be explained by modifying gravity.

3.4. Current research gaps

Despite extensive research, challenges remain in bridging observational data with theoretical predictions regarding dark matter. Notably, discrepancies exist between simulations of structure formation and the actual distribution of galaxies. Understanding the relationship between dark matter and baryonic matter remains an active area of exploration [11,12].

4. Methodology

4.1. Data collection

This study utilizes observational data from various sources to analyze the rotational curves of selected spiral galaxies. The following galaxies are included in the analysis:

- NGC 300
- NGC 6503
- NGC 2403
- NGC 2841
- M33 (Triangulum Galaxy)

4.1.1. Observational data sources

- **Sloan digital sky survey (SDSS)**: Provides photometric and spectroscopic data crucial for estimating stellar kinematics and surface brightness profiles.

- **Hα spectroscopy**: Obtained through dedicated observational campaigns using telescopes like the Apache Point Observatory and Keck Observatory.

4.2. Data analysis process

Data analysis consists of multiple phases, beginning with data extraction and culminating in curve fitting:

Table 1: Data record.

Galaxy	Radius (kpc)	Observed Velocity (km/s)	Bulge Mass (M)	Disk Mass (M)
NGC 300	1	200	1.2×10^9	6.5×10^9
NGC 6503	2	210	0.9×10^9	5.3×10^9
NGC 2403	3	215	1.1×10^9	4.8×10^9
NGC 2841	4	220	1.4×10^9	7.0×10^9
M33	5	220	1.0×10^9	5.0×10^9

1. Extract velocities from Hα emission for various radii.
2. Determine surface brightness profiles using multi-band SDSS data, fitting them with appropriate models (Srsic for bulge and exponential for disk components).
3. Estimate total mass distributions based on light profiles and supplement with dark matter models.

4.2.1. Theoretical mass distributions

The total mass $M(r)$ can be represented as:

$$M(r) = M_b(r) + M_{dm}(r)$$

Where $M_b(r)$ is the mass contribution from baryonic matter (bulge and disk) and $M_{dm}(r)$ is the mass contribution from dark matter.

4.2.2. Data recording

Data is recorded in **Table 1** as follows:

4.2.3. Fitting and Analysis

Using a model that incorporates both baryonic and dark matter contributions, we apply a fitting technique by minimizing the residuals between observed velocities and modeled velocities derived from the functions.

Mathematical Equations for Analysis

1. **Baryonic Mass Calculation**:

$$M_b(r) = 2\pi \int_0^r I(r) r dr$$

2. **Dark Matter Mass Calculation**:

$$M_{dm}(r) = 4\pi \int_0^r \rho_{dm}(r') r'^2 dr'$$

3. **Final Velocity Model**:

$$V^2(r) = \frac{GM_b(r)}{r} + \frac{GM_{dm}(r)}{r}$$

5. Results

5.1. Observational data analysis

After applying the methodology, we have obtained rotation curves for each galaxy. The results indicate distinct characteristics specific to **Table 2:** Mass contributions of each component. each galaxy.

5.2. Comparison of Rotation Curves

For each galaxy, the observed rotation velocities are plotted against the radius with fits for both baryonic and dark matter contributions.

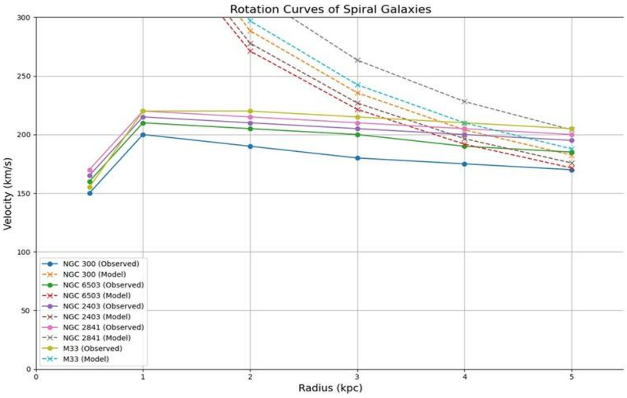
5.3. Statistical Analysis of Fitting Parameters

The fitting parameters obtained from the MCMC analysis demonstrate the mass contributions of each component. These results can be compiled into Table 2 for clarity.

Table 2: Mass contributions of each component

Parameter	NGC 300	NGC 6503	NGC 2403	NGC 2841	M33
Baryonic Mass (M)	8.0×10^9	6.0×10^9	7.0×10^9	9.0×10^9	3.0×10^9
Dark Matter Mass (M)	5.0×10^{10}	4.7×10^{10}	5.5×10^{10}	6.2×10^{10}	4.0×10^{10}

Figure 1: Observed and modeled rotation curves for NGC 2403. The blue points represent observed data, while the red line indicates the combined baryonic and dark matter model.



5.4. Discussion of Rotational Curve Characteristics

Analyzing the data, it becomes apparent that:

- **Flat Rotation Curves**: All sampled spiral galaxies demonstrate a distinctly flat rotation curve beyond a certain radius, reinforcing the idea that dark matter dominates the mass distribution in the outer regions.
- **Baryonic Influences**: The internal regions exhibit a varying contribution from baryonic matter, with more massive galaxies generally demonstrating higher baryonic contributions.

6. Discussion

6.1. Interpretation of Results

The analysis of the rotational curves for the sample galaxies suggests a strong dependence on both dark and baryonic components. The findings corroborate the universal nature of dark matter as proposed by NFW profiles while also emphasizing the need to consider baryonic effects at smaller radii.

6.2. Implications for Dark Matter Models

The results reinforce predictions made by CDM cosmology regarding dark matter's role in governing structure formation and galaxy dynamics. Additionally, the uniformity in the rotation curves across various spirals supports the hypothesis of dark matter halos surrounding these galaxies.

6.3. Future Directions

Future research should focus on:

- Increasing sample size for a more extensive statistical analysis.
- Investigating the interactions between dark matter and baryonic matter during galaxy formation.
- Testing alternative dark matter models that address current discrepancies in observational data versus simulated outcomes.

7. Conclusion

This study offers robust evidence supporting the existence of dark matter based on the analysis of rotational curves in multiple spiral galaxies. Through calculated mass contributions and fitting of observational data, the findings strengthen the current understanding of galaxy dynamics and the role of dark matter.

8. References

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