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Probing the Rotation Curve of NGC 4501 Galaxy using Two Different Models

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Abstract: Rotation curves of spiral galaxies have become an important tool for investigating their physical properties and is usually used as evidence for dark matter presence in their haloes. This research aims to probe the rotation curve of the spiral galaxy NGC 4501. The HI data of this galaxy have been collected from Very Large Array (VLA) and nonlinear fitting techniques have been used in this research for different components: stars, gas and halo. Particularly, kinematic analysis of NGC 4501's rotation curve has been carried out in this research using two different profile models: pseudo-isothermal profile and the Moore profile. The results of this study clearly showed that pseudo-isothermal model is better at reproducing the rotation curve of NGC 4501 than Moore model. The reduced chi-square, $\chi^2_{\rm red}$ of pseudo-isothermal is found to be close to one whereas Moore model does not agree with observational data. This is due to the fact that the pseudo-isothermal model is characterized primarily by the linearity of its behavior within the inner region together with the flat profile at large radii. As a result, the dark matter distribution in NGC 4501 is one that may be represented by a core halo model.

Keywords: *Dark matter, evolution, galaxies: individual (NGC 4501).*

1. Introduction

Initial rotation curve studies of spiral galaxies showed that some of the matter in these objects were "missing" (See for example: Bosma, 1981; Sofue & Rubin, 2001; Ali et al., 2018). Since then, this "missing" substance has become an aspect of cosmology. A complex framework has been developed to explain and detail the characteristics of the Universe incorporating a constant (Λ) and Cold Dark Matter (CDM) that does not interact. The ΛCDM model offers an understanding of the Universe as evidenced by findings, like the WMAP results (Spergel et al., 2007) and the Planck results (Planck Collaboration et al. 2015). However, challenges persist on scales within galaxies as highlighted in studies, by Klypin et al. (1999). Moore et al. (1999).

Studying how galaxies rotate has proven to be quite valuable, in understanding their kinematics and mass distribution of galaxies (Oort, 1927; Babcock, 1939; de Swart, 2017). Previous studies note that the flat rotation curve profile on the outside of a galaxy. This contrasts with Kepler's Law, which predicts a decline in rotational velocity further away from the center. Others have stated that the rotational velocity should increase in the outskirts of a galaxy (Freeman, 1970). The observed flat rotational velocity implies a significant disparity between theoretical expectations and actual observations, specifically arising from inconsistencies in the distribution of light (luminous matter) compared to the matter distribution inferred from the rotation curve (Zwicky, 1933; Kahn, 1959; Ali et al., 2021). Specifically, this disagreement may be seen in the way that rotational velocity behaves. It is hypothesized that the structure of galaxies must have a component called the dark matter halo. This is thought to have a mass density that might supply galaxies with a rotation curve that is flat. Dark matter is also necessary on larger scales in order to have consistency with dynamics and the creation of structures based on observations (Bertone, 2005).

On the other hand, modified gravity theories were also suggested as an attempt to describe the behavior of the galactic rotation curves instead of dark matter theory. Gaining a knowledge of the characteristics and fundamentals of dark matter represents one of the most difficult and important topics in modern cosmological studies (Mannheim, 2006; Moffat, 2013).

NGC 4501 (or M88) is a spiral galaxy in Coma Berenices, which is between 50 and 60 million light-years away. It was one of the first galaxies of its kind to be discovered within the Virgo Cluster (Binggeli, 1985). According to Mollenhoff et al., (2001), the spiraling arms of the galaxy exhibit an exceptionally regular pattern that can be tracked into the center of the galaxy. A type 2 Seyfert galaxy displays narrow line emissions caused by ionised gas located at its core. A concentrated mass of gas measuring 230 parsecs in diameter can be identified at the core of this galaxy. The condensation is mainly supported by the flow coming from the spiral arms as mentioned by Onodera et al. in 2002. Numerous previous studies have delved into the properties of NGC 4501 and similar galaxies with diverse characteristics to comprehend the structure of galaxies. This research provides a study of the rotation curve of NGC 4501 and fitting two different models to the observational data of HI.

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2. Data

Data for NGC4501 is available publicly and obtained via the Very Large Array (VLA) radio telescope. Observations were carried out on January 20th, 1991, and required 552060s of integration time. The spectra were collected using 63 channels at LL and RR polarizations with a bandwidth of 3.027 MHz, and a primary focus on the HI 21-cm line. The 27-antenna C configuration was used for the L-band observations.

The Common Astronomy Software Application (CASA) was used for the image processing and data reduction tasks. The task 'uvconsub' gives the HI map cube from the continuum subtracted instabilities. Multi scale clean with Briggs weighting produces the cleaned images. Beam size is 16.83"× 16.41" with PA = 140°, corresponding to the angular linear scales of 1.38 ×1.35 kpc at distance of 17 Mpc (see Figure 1).

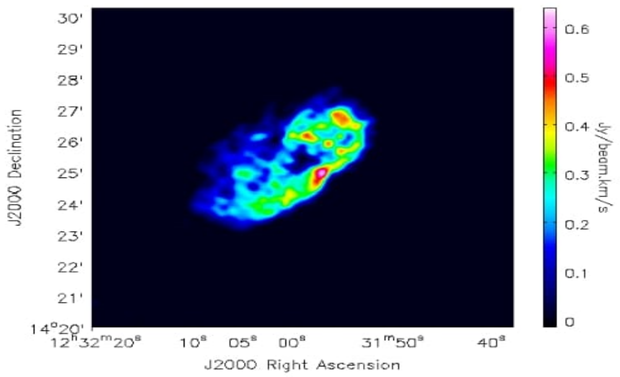

Figure 1. Integrated-intensity image of NGC 4501 at 21cm.

3. Methodology and Results

Rotation Curve of NGC 4501

Using the 3DBarolo software (Teodoro & Fraternali, 2015), we obtained rotation curves from the HI data cube of NGC 4501. The software produces tilted-ring models and compares them in 3D, allowing for comprehensive control of observational effects, particularly beam smearing, which can alter the derivation of rotational velocities within galaxies.

Three geometrical parameters define the model: the galaxy center coordinates (x0, y0), position angle (PA), and inclination (i). The kinematic parameters include the redshift (z), rotation velocity (Vrot), and velocity dispersion (σ). The systemic velocity, Vsys, was assumed to be 2280 km/s, and all rings were centered on the center of NGC 4501 as in Chung et al. (2009) (see Table 1). After considering these assumptions, the only fitting parameters that remain are i, PA, Vrot, and σ. To obtain initial estimates for the kinematic parameters (i and PA), 3DBarolo fitted the HI cube map and used the results as starting points. Two steps were used to determine the rotation and dispersion: an initial fit with all four parameters left free, followed by fixing the geometric parameters and performing a new fit with only Vrot and σ.

The 3DBarolo software is a tool used for analysing galaxy rotation curves using VLA cube data. It surpasses methods, like Woods et al. (1990) Guhathakurta et al. (1988) Sofue et al. (2003). Nehlig et al. (2016) by incorporating 3D fitting to address challenges such as beam smearing of solely depending on velocity field maps. Its reliability, capability to detect sources and ability to predict conditions greatly enhance the efficiency of automated analysis especially when dealing with datasets. This software is an asset for scientists those studying galaxies, with different data resolutions.

Figures 2 and 3 reveal the velocity and variations, between the model and actual data using a position velocity (PV) chart along both the major and minor axes. The rotating velocity of the galaxy is shown to increase linearly from its innermost core to its farthest regions, remains almost constant at the outside. The rotation curve can be described as a combination of influences, from stars, gas and halo components (Ali et al. 2018).

$$V_{\text{total}}^2 = V_{\text{disc}}^2 + V_{\text{gas}}^2 + V_{\text{halo}}^2 \quad (1)$$

Using Mathematica software, the rotation curve's contribution from each component is calculated. We might determine the star, gas, and halo values that are the most correct by adding up the disk, gas, and halo components in all possible configurations before choosing the one that best fits the observed data (Tan et al., 2022).

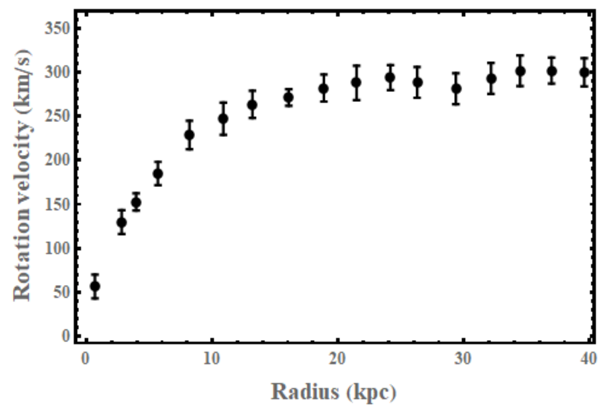

Figure 2. Velocities at different radii of NGC 4501 obtained from data cube with 3DBarolo, indicating the rotation curve profile.

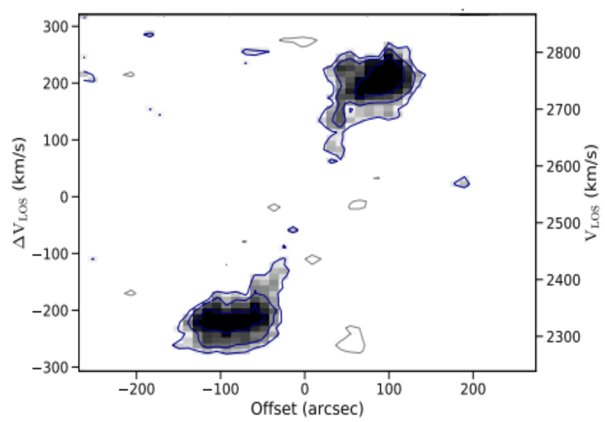

Figure 3. PV diagrams of galaxy NGC 4501 along major axes. The data are shown in grey, while the model is shown in blue.

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Table 1. Properties of galaxy NGC 4501.

Parameter	Value
R.A.	12h31m59s.0
Dec.	+14°25′10.0″
Adopted distance	17 Mpc
PA	140°
i	59°
Systemic velocity	2280 km s^{-1}
z	0.007641

Dark Halo Profile

Researchers are expanding their study of dark matter by employing a broader theoretical framework in order to provide better tools for studying it directly. Our analysis of the NGC 4501 rotation curve considers both core and cusp dark halo profiles, allowing us to find the dark matter mass and distribution. The cored profile used is Pseudo-isothermal. While we used the Moore profile for the cuspy profile.

The density of a pseudoisothermal profile indeed approaches a constant density, typically denoted as ρ_0 at the center and transitions to a power-law behavior at larger radii. (de Blok et al., 2001). Simultaneously, the mass distribution adheres to a power law with a dependence on radius (R) of R^{-2} at large radii, ultimately approaching zero at infinity. Here are the dark matter density and velocity equations (Jimenez et al., 2003; Ali et al., 2021) for the pseudoisothermal profile:

$$\rho_{Iso}(R) = \frac{\rho_0}{1+(R/R_c)^2} \tag{2}$$

$$V_{\rm ISO}(R) = \sqrt{4\pi G\rho_0 R_c^2\left(1-\frac{R}{R_c}\text{atan}\left(\frac{R}{R_c}\right)\right)} \tag{3}$$

Where G represents the gravitational constant, ρ_0 and R_C are the central density and the core radius of the halo. The definitions of these parameters are exactly the same for another model. Dark halo density and velocity are given by Moore model (Moore et al., 1999):

$$\rho_{Moore}(R) = \frac{\rho_0}{\left(\frac{R}{R_c}\right)^{1.5}\left(1+\left(\frac{R}{R_c}\right)^{1.5}\right)} \tag{4}$$

$$V_{Moore}^2(r) = \frac{8.38G\rho_0 R_c^3}{R}\left(\ln\left(1+\left(\frac{R}{R_c}\right)^{1.5}\right)\right) \tag{5}$$

Baryonic Velocities

Star Velocity

The majority of the luminosity is taken up by stars, while the remainder, which is less than 10%, is made up of interstellar gas. As a result, the distribution of the luminosity of the star disc nearly represents the distribution of the luminous mass (Sofue 2013). The velocity of the star disc (exponential disc) is given by the equation below

$$V_{disc}^2 = \frac{GM_d R^2}{2R_d}(I_o K_o - I_1 K_1) \tag{6}$$

Where I_n and K_n are the first and second kinds of modified Bessel functions, respectively, measured at 1.6x, where x = $\frac{R}{R_d}$. R_d is the disc scale length, which is measured in kpc and M_d represents the mass of the galactic disc, which is the total mass of the flattened, rotating disk component within a galaxy, and it is treated as a free parameter in our analysis. The assumed disc scale length for NGC 4501 is 45.53 arcsec (Möllenhoff 2001), which corresponds to 5.75 kpc.

Gas Velocity

The gas velocity of NGC 4501 can be calculated by taking into account the equation shown below (Ali et al., 2018),

$$V_{gas}(r) = \sqrt{\frac{GM_{HI}(R)}{R}}, \tag{7}$$

where M_{HI} is the mass of the HI gas as determined by the following equation:

$$M_{HI}(R) = 2\pi\int_0^R r\,\Sigma\,(R)dR \tag{8}$$

where Σ represents the surface density of the HI gas, calculated using 3D-Barolo as shown in Figure 4. The HI mass value of galaxy NGC 4501 galaxy can then be determined. Therefore, the rotational velocity of the HI gas might be estimated as revealed in Figure 5.

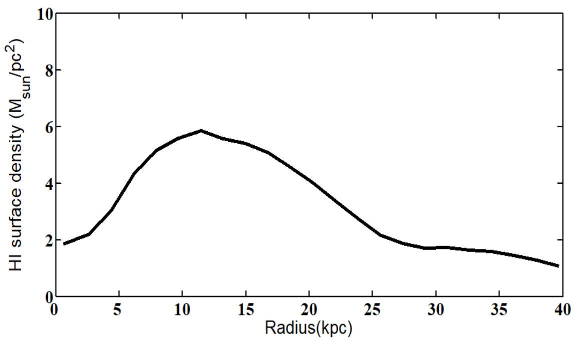

Figure 4. HI gas surface density of NGC 4501.

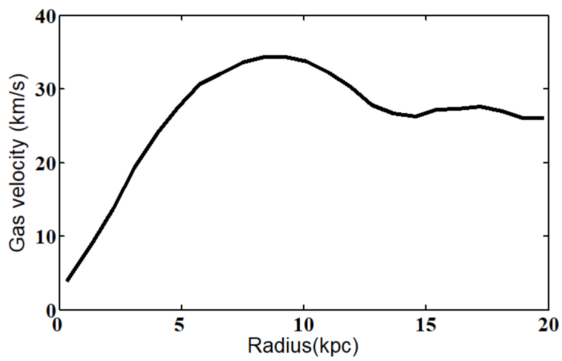

Figure 5. HI velocity of NGC 4501.

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4. Discussion

In this study, the nonlinear least square approach was utilized to match observations with equation (1) by taking into consideration either the ISO model (see Eq. 3) or the Moore model (see Eq. 5). In order to evaluate a model, it is common practice to compare the actual data to the expected data from the model and find the correlation between the two. Consequently, we performed the chi-square function to evaluate rotation curve fitting. The parameter, χ^2, that needs to be minimized is (Bevington et al., 1969):

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{\left(y_i - y(x_i, a, b, c)\right)^2}{\sigma_i^2} \right) \tag{9}$$

Where y_i and σ_i refer to number i of data points and their associated uncertainty for the NGC 4501 galaxy, respectively. $y(x_i, a, b, c)$ represents the model function values computed at the radius, x_i and (a, b, c) are the fit parameters. Then, we applied the reduced chi-square, χ^2_{red} to perform the goodness-of-fit test. A good model would give a χ^2_{red} value close to one.

The rotation curve obtained in Figure 6 and the χ^2_{red} test in Table 2 show that the rotation curve of pseudo-isothermal model has a linear increase in the inner region, but it flattens out as the radius gets larger. Over this, the pseudo-isothermal model is able to obtain the best fitting with χ^2_{red} equal to 0.89, which is the value that is closest to one and NGC 4501 has a core missing matter distribution. However, at radii less than 10kpc, the Moore profile generates a dark matter velocity that exceeds the total rotational velocity. Above 10 kpc to larger radii, the Moore profile constantly gives a lower dark matter velocity than the total rotational velocity. Based on our results, the Moore profile is inappropriate for NGC 4501.

The expected curve falls inside the confidence bands also provides support for the best-fit V_{ISO} model (χ^2_{red} value ~ 1). Figures 7 and 8 show the confidence bands that were calculated using the two different models. It shows graphically how well the match of the data and the best-fit curve. Confidence bands for the rotation velocity as a function at various points from the galactic centre are shown in purple here as solid purple lines, with the corresponding purple shaded area representing the 68% confidence level. The error bars on the rotation curves seen can also be viewed as confidence bands, with 95% confidence that the curves are contained within the blue bands. The green shaded area, representing a 99% confidence bands, can be interpreted in the same way. Otherwise, one data point with an error bar in Figure 8 is seen to be outside these confidence limits.

Furthermore, we estimated the mass of pseudo-isothermal dark matter (M_{Iso}) to be approximately 7.4×10^{11} $M_\odot$. This value exceeds the total luminous mass (1.41×10^{11} $M_\odot$) of the entire galaxy, which includes the disk and the gas. These findings emphasize the significant contribution of dark matter to the overall mass distribution in NGC 4501 (see Figure 9).

This research makes a contribution to the study of how dark matter's distribution within galaxies. Our study shows a remarkable consistency between the mass models and observed rotation curves providing evidence for the presence of dark matter in galaxy systems (Frusciante et al., 2012; Hashim et al., 2015). This study stands out when compared to analyses of previous rotation curves. It is especially noteworthy given the controversy in the scientific literature concerning the distribution of cuspy profile (Ali et al., 2018). Since it is consistent with the cored profile trend, our research contributes significant new information to the ongoing debate on the nature of the dark matter distribution in galaxies, underscoring the requirement for a deeper and more thorough comprehension of galactic dynamics.

Table 2. Free parameters with χ^2_{red} for the two dark halo profiles.

Halo models	$\boldsymbol{M_D}$ ($M_\odot$)	$\boldsymbol{\rho_0}$ ($M_\odot$ kpc^{-3})	R_c (kpc)	$\boldsymbol{\chi^2_{\text{red}}}$
Pseudo-isothermal	(1.25±0.12) × 10^{11}	(1.16±0.38) ×10^{7}	15.57	0.89
Moore	(8±6.93) × 10^{10}	(1.77±6.24) ×10^{6}	29.34	4.59

5. Conclusion

Studying the rotation curves is a way to investigate the existence and characteristics of dark matter in galaxies. Using a gradient-based nonlinear least-squares fitting method, we find that the best-fitting model function, ISO model, is a fits well with the measured rotation curve of the NGC4501galaxy, as compared to another model, Moore model. According to this result, a cored dark matter halo should be expected for the NGC4501 galaxy if ISO model is used to explain the dark matter distribution. Therefore, we can describe the structure of the NGC4501 galaxy's missing matter, which tends more toward a cored missing matter distribution with a halo mass of 7.4×10^{11} $M_\odot$.

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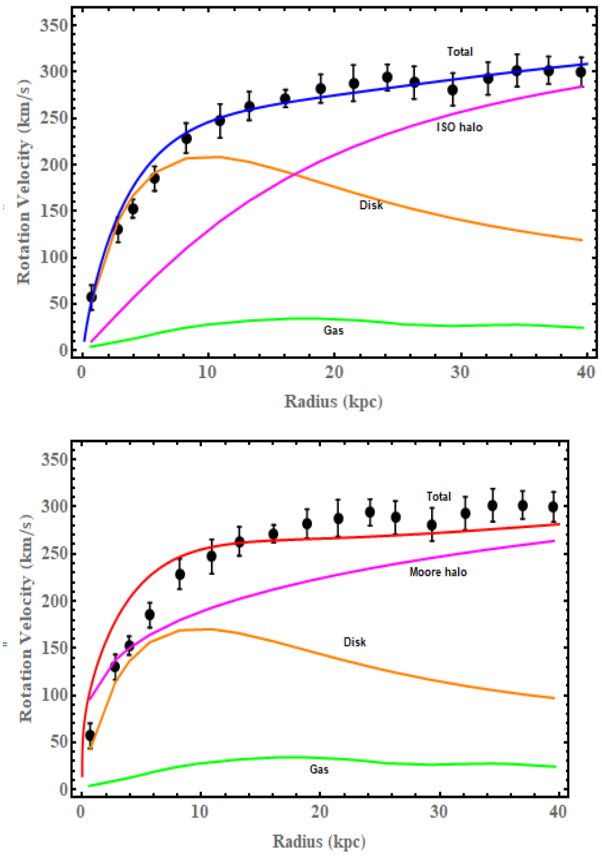

Figure 6. The nonlinear rotational velocity of NGC 4501 by employing two halo models. The contributions of dark matter halo, star, and gas velocities are represented, respectively, in purple, orange, and green.

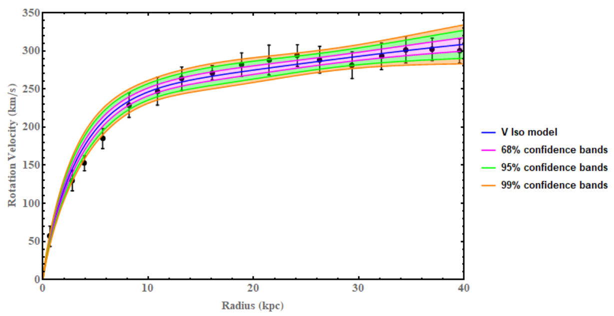

Figure 7. Confidence level band with Pseudoisothermal model.

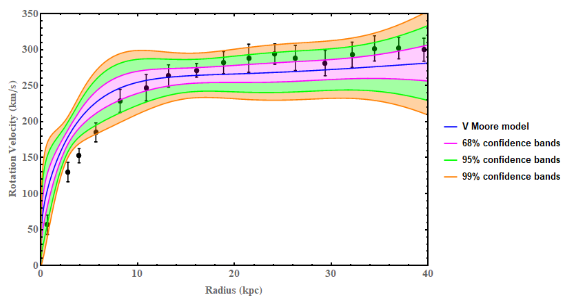

Figure 8. Confidence level band with Moore model.

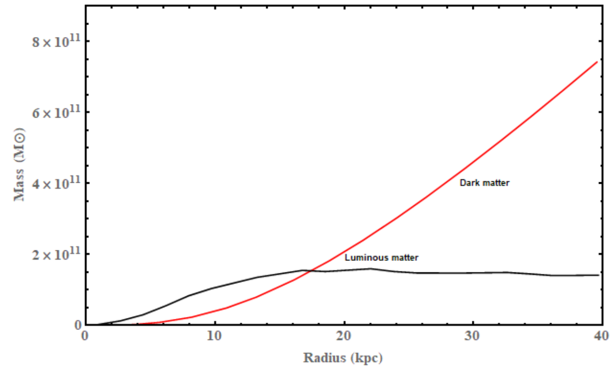

Figure 9. Variation of dark matter and luminous matter in the galaxy NGC 4501 as a function of radius.

6. References

Ade, P. A., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., ... & Matarrese, S. (2016). Planck 2015 results-xiii. cosmological parameters. *Astronomy & Astrophysics*, 594, A13.

Ali, I. A. M. (2021). Testing Two Halo Models by Galactic Rotation Curve. In Journal of Physics: Conference Series (Vol. 1818, No. 1, p. 012197). IOP Publishing.

Ali, I. A. M., Hashim, N., & Abidin, Z. Z. (2018). The dark matter distribution of NGC 5921. *Indian Journal of Physics* 92(4): 409-415.

Babcock, H. W. (1939). The rotation of the Andromeda Nebula. Lick observatory bulletin, 19, 41-51.

Bertone, G., Hooper, D., & Silk, J. (2005). Particle dark matter: Evidence, candidates and constraints. *Physics reports* 405(5-6): 279-390.

Bevington, P. R., & Robinson, D. K. (1969). *Data reduction and error analysis for the physical sciences.* New York, 19692, 235.

Binggeli, B., Sandage, A., & Tammann, G. A. (1985). Studies of the Virgo Cluster. II-A catalog of 2096 galaxies in the Virgo Cluster area. *The Astronomical Journal* 90: 1681-1759.

Bosma, A. (1981). 21-cm line studies of spiral galaxies. II. The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types. *The Astronomical Journal 86*: 1825-1846.

Chung, A., Van Gorkom, J. H., Kenney, J. D., Crowl, H., & Vollmer, B. (2009). VLA imaging of virgo spirals in atomic gas (VIVA). I. The atlas and the H i properties. *The Astronomical Journal 138*(6): 1741.

de Blok, E., McGaugh, S., & Rubin, V. (2001). High-resolution rotation curves of LSB galaxies: Mass Models. arXiv preprint astro-ph/0107366.

DOI:https//doi.org/10.22452/mjs.vol44no2.6
Malaysian Journal of Science 44(2): 63-68 (June 2025)

de Swart, J., Bertone, G., & van Dongen, J. How dark matter came to matter. Nature Astron. 1, 0059 (2017). arXiv preprint arXiv:1703.00013.

Freeman, K. C. (1970). On the disks of spiral and S0 galaxies. *The Astrophysical Journal* 160: 811.

Frusciante, N., Salucci, P., Vernieri, D., Cannon, J.M. & Elson, E.C. (2012). The distribution of mass in the Orion dwarf galaxy. *Monthly Notices of the Royal Astronomical Society* 426(1): 751-757.

Guhathakurta, P., Van Gorkom, J. H., Kotanyi, C. G., & Balkowski, C. (1988). A VLA HI survey of the Virgo cluster spirals. II-Rotation curves. Astronomical Journal (ISSN 0004-6256), vol. 96, Sept. 1988, p. 851-866., 96, 851-866.

Hashim, N., Abidin, Z. Z., Ibrahim, U. F. S. U., Hassan, M. S. R., Hamidi, Z. S., Umar, R., & Ibrahim, Z. A. (2015). The nonlinear least square fitting for rotation curve of Orion dwarf spiral. *Sains Malaysiana*, 44(3), 457-462.

Jimenez, R., Verde, L., & Oh, S. P. (2003). Dark halo properties from rotation curves. *Monthly Notices of the Royal Astronomical Society* 339(1): 243-259.

Kahn, F. D., & Woltjer, L. (1959). Intergalactic Matter and the Galaxy. *The Astrophysical Journal* 130: 705.

Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. (1999). Where are the missing galactic satellites?. The Astrophysical Journal, 522(1), 82.

Mannheim, P. D. (2006). Alternatives to dark matter and dark energy. P*rogress in Particle and Nuclear Physics* 56(2): 340-445.

Moffat, J. W., & Rahvar, S. (2013). The MOG weak field approximation and observational test of galaxy rotation curves. *Monthly Notices of the Royal Astronomical Society* 436(2): 1439-1451.

Möllenhoff, C., & Heidt, J. (2001). Surface photometry of spiral galaxies in NIR: structural parameters of disks and bulges. *Astronomy & Astrophysics* 368(1): 16-37.

Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G. (1999). Cold collapse and the core catastrophe. *Monthly Notices of the Royal Astronomical Society* 310(4): 1147-1152.

Nehlig, F., Vollmer, B., & Braine, J. (2016). Effects of environmental gas compression on the multiphase ISM and star formation-The Virgo spiral galaxies NGC 4501 and NGC 4567/68. Astronomy & Astrophysics, 587, A108.

Onodera, S., Sofue, Y., Koda, J., Nakanishi, H., & Kohno, K. (2002). CO (J= 1-0) Observations of the Non-Barred Seyfert 2 Galaxy NGC 4501. In 8th Asian-Pacific Regional Meeting, Volume II (pp. 199-200).

Oort, J. H. (1927). Observational evidence confirming Lindblad's hypothesis of a rotation of the galactic system. *Bulletin of the Astronomical Institutes of the Netherlands* 3: 275.

Sofue, Y., & Rubin, V. (2001). Rotation curves of spiral galaxies. *Annual Review of Astronomy and Astrophysics* 39(1): 137-174.

Sofue, Y., Koda, J., Nakanishi, H., & Onodera, S. (2003). The virgo high-resolution CO survey: II. Rotation curves and dynamical mass distributions. Publications of the Astronomical Society of Japan, 55(1), 59-74.

Sofue, Y. (2013). The mass distribution and rotation curve in the galaxy. arXiv preprint arXiv:1307.8215.

Spergel, D. N., Bean, R., Doré, O., Nolta, M. R., Bennett, C. L., Dunkley, J., ... & Wright, E. L. (2007). Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: implications for cosmology. *The Astrophysical Journal Supplement Series* 170(2): 377.

Tan, W. S., Abidin, Z. Z., & Hashim, N. (2022). A comprehensive analysis using 9 dark matter halo models on the spiral galaxy NGC 4321. *Indian Journal of Physics* 96(3): 671-687.

Teodoro, E. D., & Fraternali, F. (2015). 3D BAROLO: a new 3D algorithm to derive rotation curves of galaxies. *Monthly Notices of the Royal Astronomical Society* 451(3): 3021-3033.

Woods, D., Madore, B. F., & Fahlman, G. G. (1990). Luminosity-velocity diagrams for Virgo Cluster spirals. I-Inner rotation curves. The Astrophysical Journal, 353, 90-102.

Zwicky, F. (1933). Die rotverschiebung von extragalaktischen nebeln. Helvetica Physica Acta, Vol. 6, p. 110-127, 6, 110-127.

DOI:https//doi.org/10.22452/mjs.vol44no2.6
Malaysian Journal of Science 44(2): 63-68 (June 2025)