Testing Two Halo Models by Galactic Rotation Curve

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Abstract. This paper presents the observed data from the rotation curve of NGC 4651 galaxy from Very Large Array (VLA) and examine the results from isothermal and Bose–Einstein Condensate models. It is found that both models can be closed to the derived rotation curve from observations for this source. By fitting the observed rotation curve with the expectation models, the mass of halo from models is about $2 \times 10^{11} \, M_\odot$. Hence, NGC 4651 galaxy can be dominated by the invisible matter.

1. Introduction

The derived rotation velocity of galaxies represents one of the most powerful features to know if there is any existence of missing mass in the universe, along with luminous components and distributions [1][2]. Observations of atomic hydrogen (HI) consider as a good kinematical tracer in nearby galaxies due to its ability for extending far beyond the stellar region of the galaxy and following nearly circular motions. Therefore, the gravitational potential can be extended to several radii, where there is an expected invisible matter to dominate [3].

In order to understand the distribution of mass in the spiral galaxies, it would be useful to compare the observed rotation curve with all contributions from baryonic components (stars and gas) and non-baryonic matter, supposing that the gas component is in circular rotation [4]. However, previous studies suggested several empirical density profiles for the invisible component [5]. The most widely found are the isothermal (ISO) model with a central core and Navarro et al. profiles (NFW) with a central cusp [6][7]. On the other hand, Milgrom (1983a) claimed that the rotation curve of galaxies can be explained by baryonic distribution when the law of gravity is below the critical acceleration $a_0$, this is known as the Modified Newtonian Dynamics [8].

Addition of viable proposals, Böhmer and Harko [9] introduced the possibility that invisible matter might be in the form of a Bose–Einstein Condensate (BEC). It was defined as a non-relativistic, based on the Gross-Pitaevskii equation with the presence of gravitational potential. In [10], and other research works [11], galactic rotation curves were estimated for BEC model and compared to the observations. Dwornik et al. in 2017[12] revealed that there is a similar quality for the NFW and BEC models with observed rotation curves of selected data, except for galaxies have long flat regions, which flavor the NFW model.
NGC 4651 is a spiral galaxy (SA(rs)c) with redshift, z of 0.00263, rich in HI, and can be extended beyond the optical disk. It is located in the constellation of Coma Berenices at a distance of 16 Mpc. According to previous studies, its star formation is typical for a galaxy of its kind [13]. The purpose of the present work is to test the rotation curve of the mentioned galaxy from the Very Large Array (VLA) observations with the ISO and BEC models. The details of the data are reported in section 2. Results and discussion are provided in section 3. The conclusions of this work are presented in the last section.

2. Data Selection
NGC 4651 data was taken from the data archive of the VLA radio telescope. The data was carried on March 13, 2004, with 27 antennas at the L band. It is configured with Cs-configuration and polarizations (LL and RR) to produce 63 channels with a total bandwidth of about 3076 kHz. The restoring beam of this source is 16.67˝× 16.25˝ with PA = −69.51°. Figure 1 shows the zeroth moment map (integrated-intensity image) of the HI data, which could be used to find HI mass (MHI) of NGC 4651.

![Figure 1. Zeroth moment map of NGC 4651 with beam size 16.67˝× 16.25˝.](image)

3. Results and Discussion

3.1. Rotation curve Analysis

Rotation curve of NGC 4651 was derived from the emission line observations with 3D-Barolo software, which fits 3D tilted-ring models to spectroscopic cube data. The model can be described by three main geometrical parameters (i.e., coordinates of the galaxy centre (x0, y0), inclination i, and PA), and three kinematic parameters (i.e., redshift z, rotation velocity Vrot, and velocity dispersion σ), see Table 1 from [15]. For more details of assumptions to derived rotation curve of spiral galaxy see [14]. Figure 2 shows the rotation curve of NGC 4651 from VLA observations. The rotation curve can be provided all of the most important components from the disc, gas, and halo, which is given by
\[ V_{\text{total}}^2 = V_{\text{gas}}^2 + V_{\text{disk}}^2 + V_{\text{halo}}^2, \]  

where \( V_{\text{gas}} \), \( V_{\text{disk}} \) and \( V_{\text{halo}} \) are the contributions of gas, disk, and invisible matter component, respectively.

**Table 1. Values of measurable properties**

| Property       | Value                  |
|----------------|------------------------|
| RA. in (J2000) | 12h 43m 42.6s          |
| Dec. in (J2000)| +16d 23m 40s           |
| \( z \)        | 0.00263                |
| PA             | 80                     |
| \( i \)        | 50                     |
| \( V_{\text{sys}} \) | 788                  |

**Figure 2.** HI rotation curve of NGC 4651 galaxy.

3.2. Baryonic matter

It is well known that the surface luminosity profile of disk, as in the expression below decreases exponentially with the radius:

\[ \mu(r) = \mu_0 + 1.085 \left( \frac{r}{h} \right), \]  

where \( \mu_0 \) is the central luminosity of the disk and \( h \) is disk scale length. The rotation curve of NGC 4651 from the disk contribution can be estimated from the equation below:
where \( x = r/h \) and \( M_D \) here represents the total mass of the disk. The \( I_0K_0 \) and \( I_1K_1 \) are the modified Bessel functions, which are measured at \( x/2 \). The photometric data of NGC 4651 was obtained from [16], as the best fitting of \( \mu_0 \) and \( h \) are 15.54 mag/arcsec\(^2\) and 14.5 arcsec, respectively (See Figure 3).

The second contribution as previously pointed out \( V_{gas}^2 \), is basically formed in terms of the gas content of the galaxy by the hydrogen emission lines. Thus, the gas contribution comes from the moment 0 map (HI map), which is about \( 4 \times 10^9 \) M\(_\odot\).

![Figure 3. Surface brightness profile of NGC 4651 from [16]. The dashed line is K band data of. Surface brightness](image)

### 3.3. Predictive models for the unseen matter

The corresponding rotation curve of the pseudo-ISO halo is given by [7]

\[
V_{ISO}(R) = \sqrt{4\pi G \rho_0 R^2 \left( 1 - \frac{R}{R_C} \tan \left( \frac{R}{R_C} \right) \right)}
\]

where \( \rho_0 \) and \( R_C \) represent the central density and the core radius of the halo. The steepness of the inner slope can be described with power of law \( \rho \sim r^{-\alpha} \). In the case ISO halo, in which the inner density is nearly constant density core, \( \alpha = 0 \).

If the unseen matter is formed by the condensation of Bose-Einstein, its distributed in density would be [10] \( \rho_{DM}(r) = \rho_D^{(\infty)} \frac{\sin kr}{kr} \), where \( k = \frac{\Omega m^2}{\sqrt{\hbar^2 a}} \) and \( \rho_D^{(\infty)} \) is the central density of the condensate. Here \( m \) is mass profile, which is given by \( m_{BEC}(r) = 4\pi \int \rho_{BEC}(r) r^2 \, dr \). Therefore, contribution to the rotational velocity in the halo can be [11]:
In this work, the nonlinear model was assumed in Mathematica software to test taken data from the VLA telescope with two models, namely ISO, and BEC profiles. The results of both models show in Figure 4 and Figure 5. It is clear from figures that the ISO and BEC halo models can be explained the rotation curved of this galaxy, where reduced chi-squared ($\chi^2$) is around 0.8 for both models and the mass of the halo is around $2 \times 10^{11} M_\odot$.  

$$v_{BEC}^2(r) = \frac{4\pi G \rho_{BEC}(c)}{k^2} \left( \frac{\sin kr}{kr} - \cos kr \right)$$

In this work, it was investigated whether ISO and BEC halo models can explain the rotational curve of NGC 4651. Testing for the rotational velocity in both models reveals

4. Conclusion

In this work, it was investigated whether ISO and BEC halo models can explain the rotational curve of NGC 4651. Testing for the rotational velocity in both models reveals
that the rotation curve can be well produced by both models and in good agreement with the observed rotation curve of NGC4651. These results are confirmed the existence of unseen matter in NGC 4651.

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