Rotation Curve in ESO138-G014 Galaxy

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Project Report

Towards the partial fulfilment of

BACHELOR OF TECHNOLOGY
IN
ENGINEERING PHYSICS

Guidance

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20 May 2020

CERTIFICATE

*This is to certify that the work contained in this thesis entitled "**Rotation Curve in ESO138-G014 Galaxy**" is a bonafide work of **Al Ameen. P** (**Roll No. 160121006**), carried out in the Department of Physics, Indian Institute of Technology Guwahati under my supervision and that it has not been submitted elsewhere for a degree.*

Supervisor: **Dr. Malay Kumar Nandy**

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Department of Physics,

20 May, 2020

Indian Institute of Technology Guwahati, Assam.

DECLARATION

This is to declare that the project report titled **"Rotation Curve in ESO138-G014 Galaxy"**, submitted by me to the department of Physics, Indian Institute of Technology Guwahati, for the partial fulfilment of the requirement for the degree of bachelor of technology is a bonafide work carried out by me under the supervision of " Dr. Malay Kumar Nandy". The content of this work, in full or in parts, has not been submitted elsewhere for the award of any other degree or diploma. I also declare that this report is based on my personal study and/or research and I have acknowledged all materials and resources used in its preparation..

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Abstract

This work is a study of the rotation curve for the ESO138-G014 galaxy. we calculate the Newtonian velocity components, namely, HI gas velocity and Disk velocity. HI gas velocity is obtained from the observed values of the HI surface density of this galaxy, whereas the disk velocity is calculated from the observed surface brightness profile (the surface brightness profile was taken from the Two Micron All Sky Survey (2MASS) database). We plot the total velocity(HI gas plus the disk velocity)against distance from the centre of the galaxy. We found that there is a large deviation from the observed velocity curve of this galaxy. Consequently, we introduce the modified Newtonian dynamics to resolve this issue. We found that the rotation velocity obtained from the modified Newtonian dynamics are in good agreement with the observed rotation curve.

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Chapter 1

Introduction

This project is a study of the galaxy rotation curve. Various observational data show that rotation curves of galaxies are **non-Keplerian** and does not follow the Newtonian dynamics. **Modified Newtonian dynamics** and **dark matter** were two distinct theory proposed to explain this discrepancy in the rotation curves. In this work, we analyse rotation curve of the ESO138-G014 galaxy from the baryonic matter distribution obtained from the photometry. In the previous work, we obtained the rotation curve using Newtonian mechanics and we found that there is a large deviation in the calculated rotation curve from the original observed one. Consequently, in this work, we take the modified Newtonian dynamics to study the rotation curve.

Rotation curve of a galaxy or velocity curve is a plot between the velocity of visible objects in a galaxy versus their radial distance. Usually the rotation curve is flat at large distances from the centre. The existing Newtonian mechanics could not explain the flat rotation curves rotation curves of galaxies therefore we have two theories to explain the flat rotation curves, the modified Newtonian dynamics and the dark matter theory.

Dark matter is a form of matter which is thought to account for 85% of matter in the universe. Many galaxies would not have formed or move as they move now, without dark matter. So the primary evidence of dark matter comes from the galaxy rotation curve.According to this theory a velocity component of dark matter halo is also added with the other velocity components of the galaxy such as disk velocity and velocity contribution from gas.
The modified Newtonian dynamics on the other hand is an alternative for the theory of dark matter. That proposes a modification to Newton's laws to account for observed properties of galaxies. Modified Newtonian dynamics was proposed and first published by Israeli physicist Mordehai Milgrom in 1983. Rotation curves are best explained with modified Newtonian dynamics. The basic premise of modified Newtonian dynamics is that while Newton's laws

have been extensively tested in high-acceleration environments (in the Solar System and on Earth), they have not been verified for objects with extremely low acceleration, such as stars in the outer parts of galaxies. This led Milgrom to postulate a new effective gravitational force law (sometimes referred to as "Milgrom's law") that relates the true acceleration of an object to the acceleration that would be predicted for it on the basis of Newtonian mechanics. This law, the keystone of MOND, is chosen to reduce to the Newtonian result at high acceleration but leads to different ("deep-MOND") behaviour at low acceleration.

1.1 Rotation curve analysis using Newtonian mechanics

In this section we will analyse the rotation velocity of an object in a galaxy at a distance r from the centre of the galaxy. A galaxy consists of several components such as gas, stars etc. The composition of different components that form the galaxies changes from one galaxy to other. Therefore analysis of rotation curve or the velocity curve gives us an idea of how mass is distributed in galaxies.

1.1.1 HI mass

HI mass is the free hydrogen mass or the atomic hydrogen mass in the galaxy. We assume the galaxy is extremely flat and HI surface density $\sigma(r)$ has an azimuthal symmetry, then the total HI mass can be calculated as

$$\begin{aligned} M_{HI} &= \int_0^r dm \\ dm &= \sigma(r)dA \\ dA &= rdrd\phi \\ M_{HI} &= \int_0^{2\pi} d\phi \int_0^r r\sigma(r)dr \end{aligned}$$

we obtain the HI mass as

$$M_{HI} = 2\pi \int_0^r r\sigma(r)dr \tag{1.1.1}$$

using the real data of $\sigma(r)$ we solved equation 1.1.1. The cumulative HI gas mass from the centre to distance r is given in the figure 1.2. Now we can find the velocity of HI gas, V_{gas} by equating the centripetal force with the gravitational force, $\frac{V_{gas}^2}{r} = \frac{GM_{HI}(r)}{r^2}$

$$V_{HI} = \sqrt{\frac{GM_{HI}(r)}{r}} \tag{1.1.2}$$

using 1.1.2 HI velocity curve was obtained(figure 1.3)

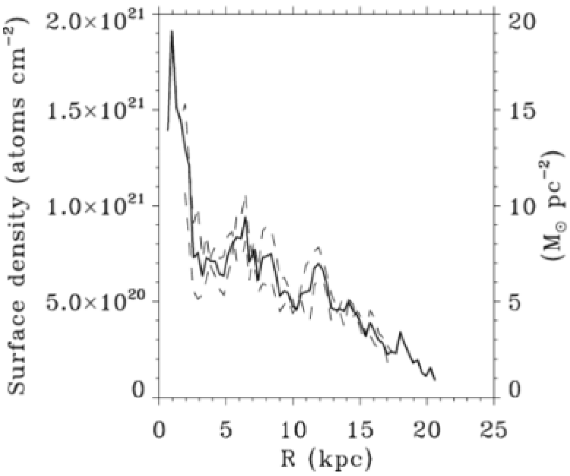

Figure 1.1: The real data of HI surface density is given by[4]

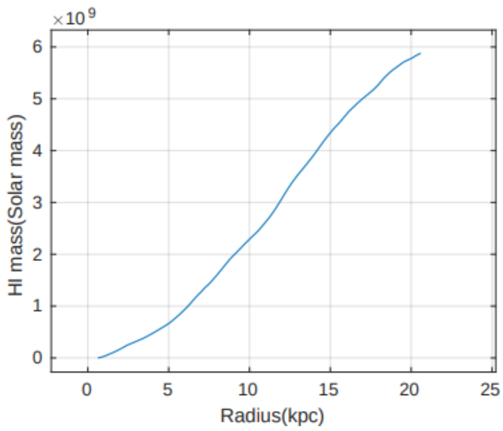

Figure 1.2: The total HI mass obtained from 1.1.1

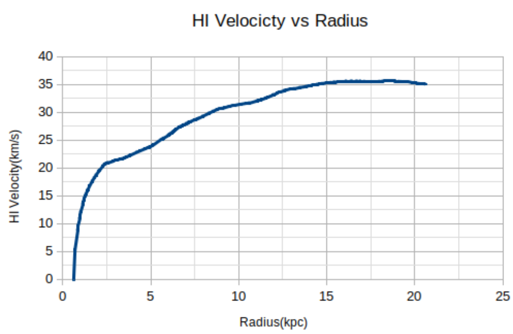

Figure 1.3: V_{gas} vs r plot as obtained from 1.1.2

1.1.2 Surface Brightness and Stellar Mass

Stellar surface density of galaxies is often derived from their surface brightness profiles. The surface brightness has an exponential decay with the distance from the centre of the galaxy and the proposed law has the following form

$$\Sigma(r) = \Sigma_0 e^{\frac{-r}{R_D}} \tag{1.1.3}$$

where $\Sigma(r)$ is the surface brightness at a distance r from the centre of the galaxy, Σ_0 is the central brightness of the galaxy and R_D is the stellar scale length of the galaxy, stellar scale length is defined as the distance at which brightness reduces by a factor of $e(\approx 2.718)$ from its maximum value. The luminosity profile of ESO138-G014 was taken from 2MASS database (Figure 1.4). The stellar surface density is directly proportional to the surface brightness i.e., surface density also has an exponential decay from the centre of the galaxy. From figure1.5 we have

$$log(\Sigma(r)) = log(\Sigma_0) - \frac{r}{R_D} \tag{1.1.4}$$

after linear fitting the plot in Figure(1.5) we obtained the below given linear equation

$$f(x) = -0.01555x + 0.8094 \tag{1.1.5}$$

comparing equations 1.1.4 and 1.1.5 we found $log(\Sigma_0) = 0.8094$ and $\frac{1}{0.0155} = 64arcsec$. here

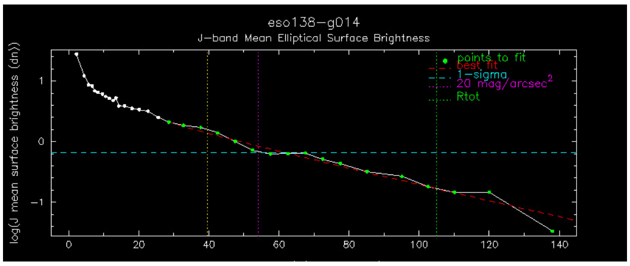

Figure 1.4: The surface brightness profile of ESO138-G014 from 2MASS database

the $64arcsec$ corresponds to two times the scale length of the galaxy

$$\therefore \quad R_D = 32arcsec$$

So now we can calculate the radius in kpc, since we have the distance to the galaxy given by[4]. which is $d = 15.8Mpc$. $\therefore$ Now we have

$$\frac{R_D}{d} = \frac{32 \times \pi}{3600 \times 180} rad$$

$$R_D = 2.45kpc$$

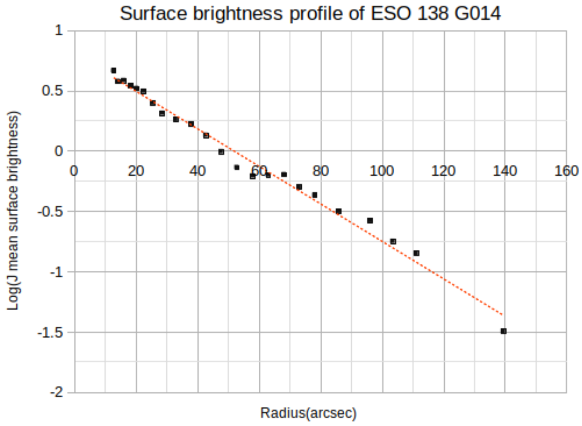

Figure 1.5: Surface Brightness profile of ESO138-G014 with linear fit

which is in good agreement with the values calculated in [2] and [5].

Disk velocity is due to the stellar matter content of the galaxy. The disk velocity is usually calculated by assuming a cylindrical symmetry. In the present work we assume 1) *the galaxy is extremely flat i.e, $z \approx 0$* and 2 *the galaxy has azimuthal symmetry i.e, the potential is ϕ independent.* This reduces the problem to solve the two dimensional Laplace equation , this was previously shown by Alar Toomre [6]. The gravitational potential $\Phi(r, z)$ is given by the solution of the laplace equation,$\nabla^2\Phi = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) + \frac{\partial^2\Phi}{\partial z^2} = 0$. The solution of the above equation in terms of velocity is given by

$$V_{Disk} = \sqrt{\frac{\frac{1}{2}M_D G y^2\left[I_0 K_0 - I_1 K_1\right]}{R_D}} \tag{1.1.6}$$

where I and K are modified Bessel functions of the first and second kind and they are computed at $\frac{1}{2}y$ where $y = \frac{r}{R_D}$. Figure 1.6 plot V_{Disk} as function of r for the galaxy ESO138-G014 with $M_D = 3.0 \times 10^9 M_\odot$.

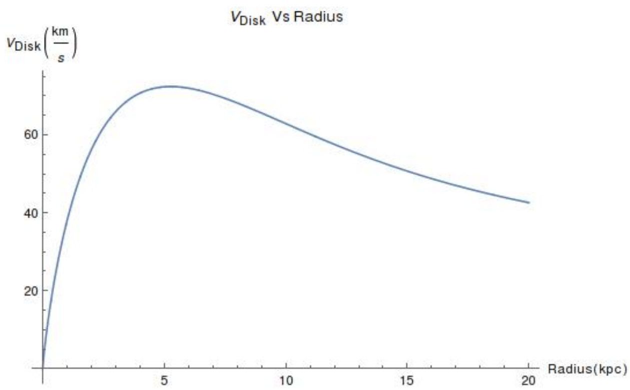

Figure 1.6: V_{Disk} vs r plot, where $M_D = 3.0 \times 10^9 M_\odot$[2]

We calculated the different Newtonian velocity curve of ESO138-G014 and its comparison with the observed velocity curve is given in the figure 1.9. From Figure 1.9 it is obvious that there is large deviation in Newtonian velocity curve with the observed one.

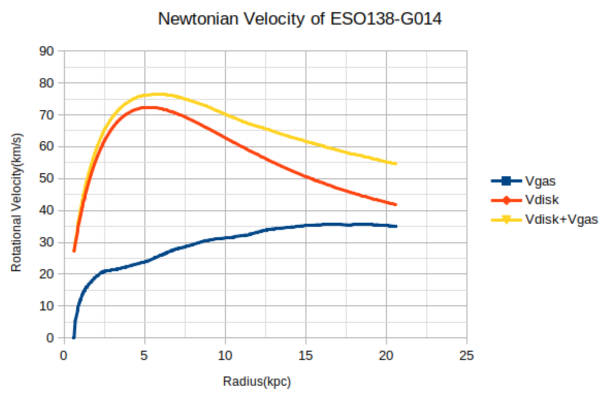

Figure 1.7: Newtonian Velocity of ESO138-G014 galaxy(where the the total velocity(yellow line) $V_{total} = \sqrt{V_{Disk}^2 + V_{Gas}^2}$)

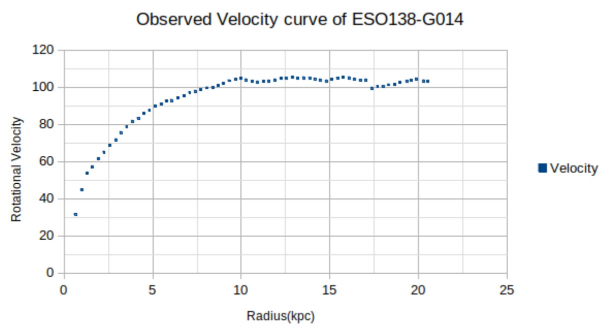

Figure 1.8: Observed Velocity curve of ESO138-G014[2]

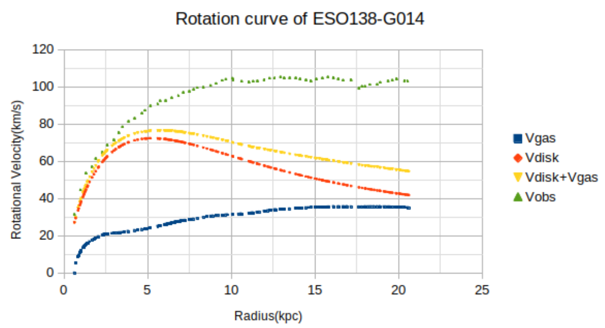

Figure 1.9: Comparing the observed and Newtonian velocity curves

Chapter 2

Modified Newtonian Dynamics(MOND)

Since the above Newtonian velocity was obtained from the observed(light emitting) distribution of matter, and this velocity does not coincide with the observed one, it is obvious that there must be additional unobserved mass in the galaxy. This additional mass is usually called the dark matter. However the amount of dark matter is not known a priori. Consequently a proper distribution of dark matter needs to be included in addition to the observable matter in the galaxy. This dark matter scenario can be used to explain the rotation curve of any galaxy by properly tuning its distribution in different galaxies. Several experiments are being carried out to detect dark matter however so far there has not been any evidence for its existence. Another scenario for explaining the rotation curves was put forward by Milgrom [3] called the modified Newtonian dynamics. He proposed that the Newton's law $F = ma$ is not valid in the ultra-low acceleration regime and it needs to be modified as

$$\mathbf{F} = m\mu(\frac{a}{a_0})\mathbf{a} \tag{2.0.1}$$

where a_0 is a constant often called as the critical acceleration, $a_0 = 1.35 \times 10^{-8} \frac{cm}{s^2}$, the function $\mu(x)$ behaves as

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x \tag{2.0.2}$$

here $\mu(x)$ is given by

$$\mu(x) = \frac{x}{1+x} \tag{2.0.3}$$

which is the most recently adopted form of $\mu(x)$, since equation 2.0.3 is compatible with the relativistic theory of MOND[1]. Using this form of $\mu(x)$ the velocity curve can be found using equation 2.0.4

$$V_{Mond}^2(r) = V_{bar}^2(r) + V_{bar}^2(r)\left(\frac{\sqrt{1+\frac{4a_0 r}{V_{bar}^2}}-1}{2}\right) \tag{2.0.4}$$

where $V_{bar} = \sqrt{V_{gas}^2 + V_{stars}^2}$. The second term in the RHS of equation 2.0.4 acts as pseudo dark matter term. We have already calculated V_{gas} and V_{stars} in section 1.1.1, they are equivalent to V_{HI} and V_{Disk}. Using equation 2.0.4, V_{mond} is plotted against radius (Figure 2.2). The second term in the equation 2.0.4 is multiplied with a factor $k = 0.7$ to get the best result, equation 2.0.4 modifies to

$$V_{Mond}^2(r) = V_{bar}^2(r) + k \times V_{bar}^2(r)\left(\frac{\sqrt{1+\frac{4a_0 r}{V_{bar}^2}}-1}{2}\right) \tag{2.0.5}$$

This additional multiplication with factor k is done because our assumption of exponentially decaying stellar mass density is a rough approximation, in most of the cases the exponential model of stellar mass density fails to give accurate results. From figure 2.2 it is clear that the MOND rotation curve is in good agreement with the observed one.

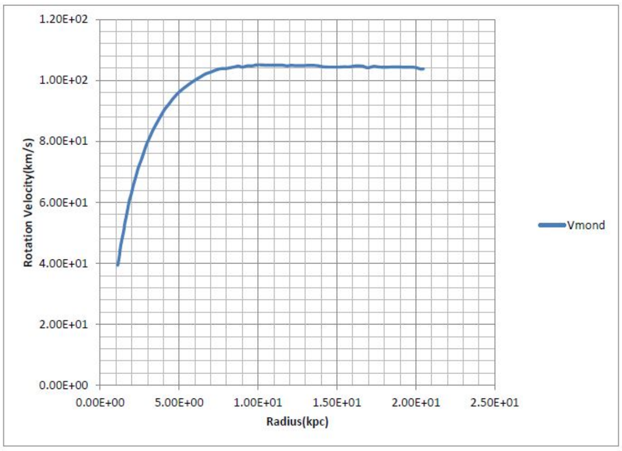

Figure 2.1: V_{Mond} vs r plotted using 2.0.4

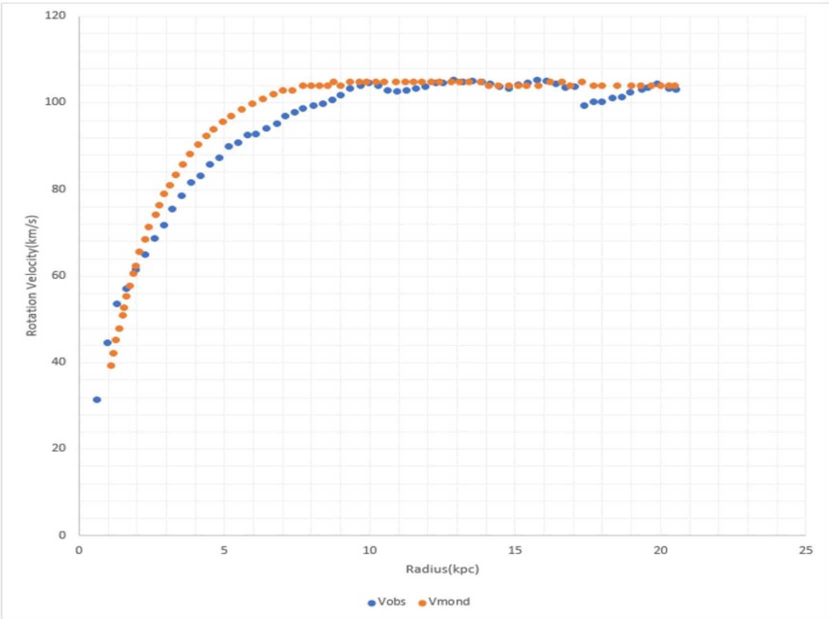

Figure 2.2: Observed Rotation curve(blue dots) and MOND(orange dots)

Chapter 3

Conclusions

In the present work we analyse the rotation curve of the galaxy ESO138-G014. We first estimate the Newtonian rotation curve which includes contributions from HI gas and Stellar matter content. We found that there is a large deviation in the calculated rotation curve from observed rotation curve of the same galaxy. Consequently, we analyse the rotation curve in the framework of modified Newtonian dynamics. We found that for $k = 0.7$ the obtained rotation curve given by the equation 2.0.4 is in good agreement with the observational data. The correction enters via k is attributed to the assumption that the density given by the stellar mass is not correct always. This is due to the fact that, while deducing the surface density from the surface brightness profile we assume that the M/L ratio is constant through out the galaxy. This assumption might not be true always and this might contribute additional mass to the estimate baryon content. So to get accurate distribution of surface density we need to employ a technique which deduces stellar surface densities from density of the stars rather than surface brightness and M/L ratio. However stellar surface density distribution of ESO138-G014 is not available at the moment. In fact, the stellar surface density distribution is available for many other well known galaxies. In our future work we would analyse the rotation curve of other galaxies in the frame work of modified Newtonian Dynamics by taking the proper stellar surface density.

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