21 cm Radio Wave Observation on the Milky Way Rotation Curve

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Abstract. Nowadays, the scientific community has generally accepted the existence of dark matter. Astrophysicists investigate this assumption by astronomical observation. The galaxy rotation curve is one of the pieces of evidence for dark matter's existence. The TLM18 telescope detects a 21 cm radio wave from the Milky Way to measure the rotation curve of the Milky Way. This article analyzes the frequency-power data to find out the rotation curve of the galaxy. The rotation curve is compared to existing theories, including the Kepler model, the exponential disk model, and the isothermal dark matter halo. Combining the exponential disk model with the isothermal dark matter halo, the calculation fits well with observation.

1. Introduction

Radio astronomy got its start in the 1930s when Karl Jansky accidentally found that the Milky Way was an important source of radio waves. His discovery of "star static" launched a new field of science [1]. The possibility of the observable strength emission of the 21 cm line from an interstellar cloud was first suggested by Van De Hulst in 1944 [2]. The 21-cm was first observed in the early 1950s by Ewen, Purcell, and Oort [3]. Today, this radiation line is utilized in probing the structure of the Milky Way. The usefulness of the 21-cm radiation as a probe is enhanced by the velocity-induced frequency shifts that allow one to deduce not only the density of hydrogen gas clouds but also their velocity relative to the Earth.

The rotation curve is the mean circular velocity around the center of the Galaxy as a function of galactocentric distance. The rotation curve of the Milky Way has been derived from the movement of different tracers moving in the gravitational potential of the Galaxy with a corresponding method. For example, M. I. Wilkinson and N. W. Evan used a truncated, flat rotation curve (TF) model and the data on the motions of satellite galaxies and globular clusters at Galactocentric radii greater than 20 kpc to derive the rotation curve and mass distribution [4]. Yoshiaki Sofue et al. used the exponential disk model and the isothermal dark matter model to fit the existing data [5].

Today, the rotation curve and mass distribution of galaxies are still a maze to look into, especially when they are associated with the existence of dark matter. The exponential disk model with isothermal dark matter is one of the conventionally accepted models. Testing the models with more surveys will help correct them and come up with new ideas. In this paper, the 21 cm line signal collected by the TML18 telescope is analyzed through Fourier transformation on the spectrum to map out the Milky Way rotation curve.

2. Background

The Milky Way is a barred spiral galaxy with an estimated visible diameter of 100,000 to 200,000 light-years. The rotation curve of the Milky Way has been constructed using kinematical data on tracer objects moving in the gravitational potential of the Galaxy, in a large region out to a large galactocentric distance of ~ 200 kpc [6]. There are several methods to determine the total mass of the Milky Way [7]. Measuring the rotation curve provides not only the total mass of our galaxy, but also the mass distribution. The result may vary when the observation is based on different objects or signals [8].

The sky is very different when observed through the radio telescope rather than with the naked eye. Lots of information about our galaxy is buried under invisible signals. Neutral atomic hydrogen traces the interstellar medium over a broad range of physical conditions. Its 21-cm emission line is a key probe of the structure and dynamics of the Milky Way Galaxy [9].

2.1. 21 cm Hydrogen Signal
For the most part, radio astronomy employs wavelengths ranging between 1 cm and 10 m, although certain specialized studies have expanded the range down to 1 mm at the low end and up to 150 m at the high end.

Objects emit electromagnetic waves when its atom transmit to a lower level. The 21-cm line is a transition between the two hyperfine states of the $1^2S_{1/2}$ ground level of hydrogen. These states differ only in the value of the total spin angular momentum [10]. While the frequency of the received signal drifts around 21 cm, because of the Doppler effect. It goes higher when the source is moving toward the observer and goes lower when the source is moving away from the observer. The spectrum of signals received from a certain direction shows the distribution of mass with vertical velocity.

2.2. TLM18 Telescope
The TLM 18 telescope is a 60' dish located in Belmar, NJ, a few miles from the Atlantic shore, which was the former site of Camp Evans, a U.S. Army R&D site. This site was used for the first "moon bounce" experiment in 1947 and 1960. This dish received the first weather satellite images from space (TIROS), and was used in research until 1980 or so, then refurbished by a Princeton team in 2012-2015.

3. Theory

3.1. Galactic Coordinates
Equator coordinates, horizontal coordinates, and galactic coordinates are commonly used to describe the sky. Since this paper is a study of our galaxy, our work is based on galactic coordinates.

The coordinate origin was set on the Sun. Two angles are used in this case, galactic latitude (b) and galactic longitude (ℓ). The angle between a line and its projection on the galactic plane is the galactic latitude (b), and that between the projection line and the direction of the Sun and the galactic center is the galactic longitude (ℓ). On the galactic plane, the galactic latitude (b) is 0.

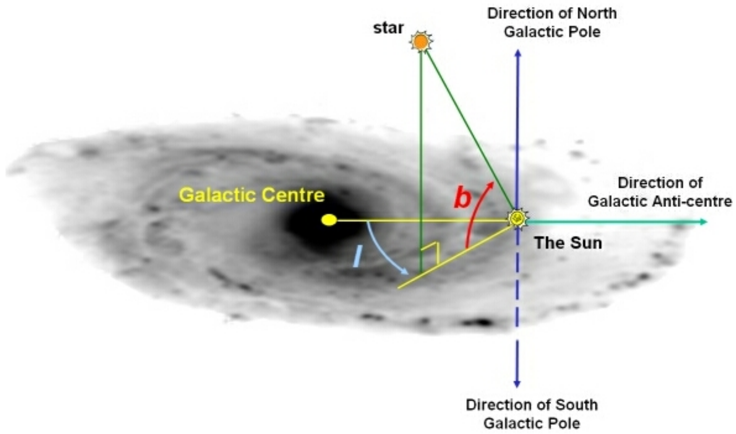

Figure 1. The galactic coordinate system. Positions of objects are measured in terms of their galactic longitude (ℓ) and galactic latitude (b). The galactic equator slices the Galaxy in half (top and bottom) [11]

3.2. The Keplerian Model

The simplest assumption of mass distribution in our galaxy is to assume that all of the mass is concentrated at the center of the galaxy. The gravitational attractive force F is in a simple form:

$$F = G\frac{M_t m}{r^2} \tag{1}$$

where G is the gravitational constant, M_t is the total mass of the galaxy, m is the test mass, and r is the distance between the test mass and the galactic center.

Newtonian mechanics are applied to a planetary system,

$$F = ma = m\frac{v^2}{r} \tag{2}$$

where a is the centripetal acceleration, and v is the orbit speed.

Then the rotation curve can be described as:

$$v(r) = \sqrt{\frac{GM_t}{r}} \tag{3}$$

Obviously, when distance r approaches 0, the velocity approaches infinite, which is not acceptable as a realistic galaxy model.

3.3. Exponential Disk Model

Astronomers have made careful observations of the amount of light emitted by galaxies per unit surface area and find that many galaxies are well-described by

$$I(r) = I_0 e^{-\frac{r}{R_D}} \tag{4}$$

where $I(r)$ is light intensity at distant r from the galactic center, R_D is galactic scale constant.

Assuming that the amount of mass is proportional to the amount of light, the amount of mass per unit area for a galaxy is

$$\mu(r) = \mu_0 e^{-\frac{r}{R_D}} \tag{5}$$

where $\mu(r)$ is the mass density at distant r from the galactic center, μ_0 is a constant.

According to the shell theorem, the gravity force is

$$F(r) = \int_0^r \frac{\mu(r)m}{r^2}\, dr \tag{6}$$

The rotation curve function can be calculated for the case of the exponential disk.

$$v^2(r) = \frac{GMr^2}{2R_D^3}\left[I_0(u)K_0(u) - I_1(u)K_1(u)\right] \tag{7}$$

where $u = r/2R_D$, and I and K are "modified Bessel functions".

The exponential model differs significantly from the Keplerian model when $r < 15{,}000\ \mathrm{l.y}$, but is not so different at large radii.

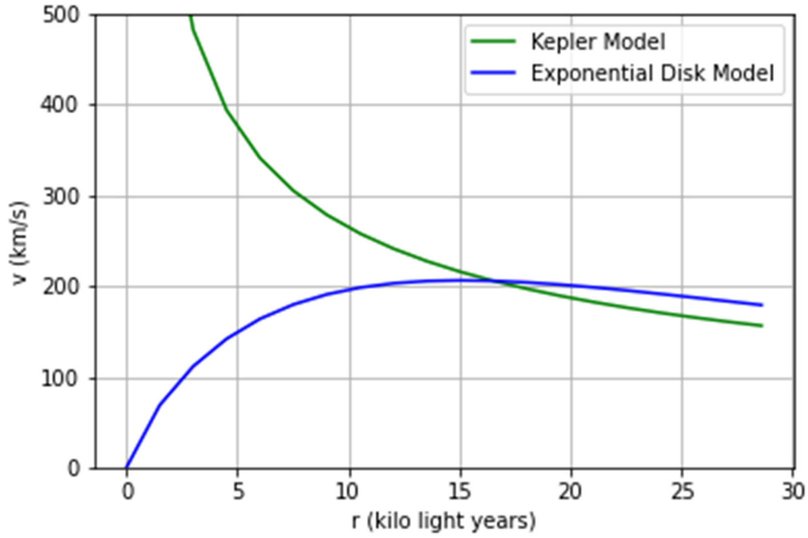

Figure 2. Rotation curves of Kepler Model and exponential disk model.

3.4. Isothermal Dark Matter Halo

The exponential disk model is more realistic than the Keplerian model, but it is still falling behind observation when the radius goes larger than about $10{,}000\ \mathrm{l.y.}$ Previous researchers have revealed the existence of dark matter. In our research, we try to make up the gap by combining the exponential disk model with a dark matter halo permitting in the galaxy.

There have been many kinds of precise models of the dark matter halo. But in our research, the simplest Isothermal Sphere model is good enough.

Given the density described by

$$\rho(r) = \rho_0 \frac{R^2 + a^2}{r^2 + a^2} \tag{8}$$

where R is Sun's orbital radius, and a is the scale parameter, the mass for a radius smaller than r is

$$M_<(r) = 4\pi \int_0^r \rho(r')r'^2\, dr' = 4\pi\rho_0 (R_0^2 + a^2)\left[r - a\tan^{-1}\frac{r}{a}\right] \tag{9}$$

The additional force introduced by the dark matter halo is

$$F_{halo}(r) = \frac{GM_<(r)m}{r^2} \tag{10}$$

The total force is

$$F(r) = F_{disk}(r) + F_{halo}(r) = m\frac{v^2}{r} = m\frac{v_{disk}^2}{r} + m\frac{v_{halo}^2}{r} \tag{11}$$

thus,

$$v^2 = v_{disk}^2 + v_{halo}^2 \tag{12}$$

4. Method

The telescope scans across the sky, and the galactic longitude increases from 0 (pointing at the galactic center) to 90 degrees, while the galactic latitude is fixed at zero. In other words, it is a scan of the galactic plane. In each direction, the signal emitted by hydrogen on the line is collected by the telescope. A power distribution curve on frequency is plotted.

4.1. Doppler Effect

It is a fact that the orbital speed of the Earth around the Sun is much slower than the drifting speed of the solar system and hydrogen gas, which is far slower than the speed of light. The Doppler relation between received frequency f and approaching velocity v is leaner, and the speed of light c and the emitted frequency f are constants.

$$f' = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \approx \left(1+\frac{v}{c}\right) f \tag{13}$$

4.2. Data Procession

Before the data was collected on the computer, the band-pass filter picked out a signal around 1422 MHz (the frequency of 21 cm microwave), which ranges from 1418 to 1426 MHz. It is easy to calibrate the data with approaching velocity because the Doppler relation is linear. The power is also corrected according to the gain curve of the telescope. And a signal spur at 1420 MHz is removed manually. Some physical defects in the telescope caused it.

The scan across the galactic plane collects data on the relation between approaching velocity and power in the direction of a longitude. In our research, we make measurements once when the galactic longitude increases by two degrees.

A heat map is plotted by putting all the curves into one figure, and power is converted to color temperature linearly.

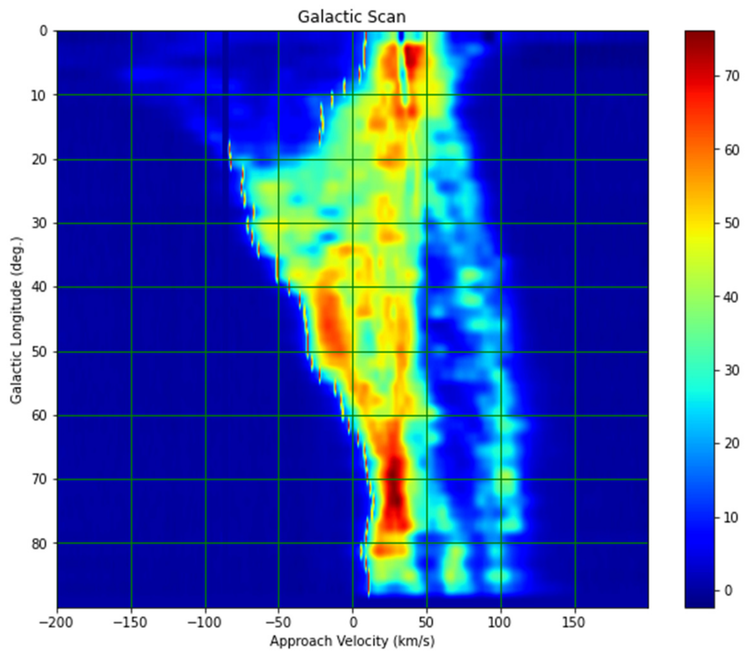

Figure 3. Heat map of the radio signal. Two independent variables are the Doppler velocity v and the galactic longitude ℓ. The boundary data is marked by short color lines.

4.3. Rotation Curve

On the heat map, the left edge of the 'island' is marked, which represents the maximum approaching speed observed from a certain galactic longitude.

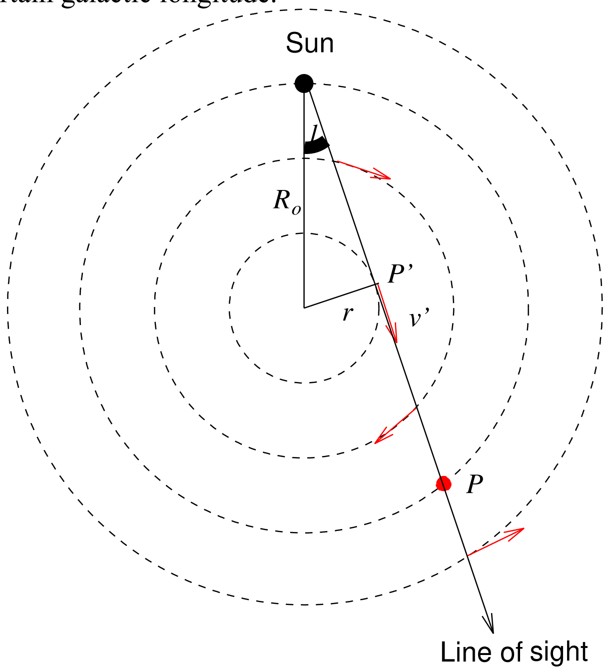

Figure 4. Geometric construction for determining the rotation curve of the galaxy.

The stars move relative to the Sun at speeds indicated by the red arrows. The galactic plane (galactic latitude $b = 0$) is the page. The angle ℓ is the galactic longitude. The figure assumes that the angular velocity decreases with radius.

The coordinate transformation from the Sun to the galactic coordinates gives the relationship between the maximum approaching speed and the rotation speed of the galaxy.

The rotation curve is given by

$$v(r) = v' + r\left(\frac{2\pi}{T}\right), \quad (14)$$

where

$$r = R_0 \sin \ell, \quad (15)$$

$v(r)$ is rotation speed, v' is maximum approaching speed, T_0 is the orbital period of the Sun about the center of the galaxy.

Given

$$R_0 = 2.7 \times 10^{14}\ \text{km} \quad (16)$$

and

$$T_0 = 237{,}000\ \text{yrs} = 7.47 \times 10^{12}\ \text{s} \quad (17)$$

It is important to mention that, the above assumes that the rotation speed is a constant on a certain radius.

4.4 Model Fitting

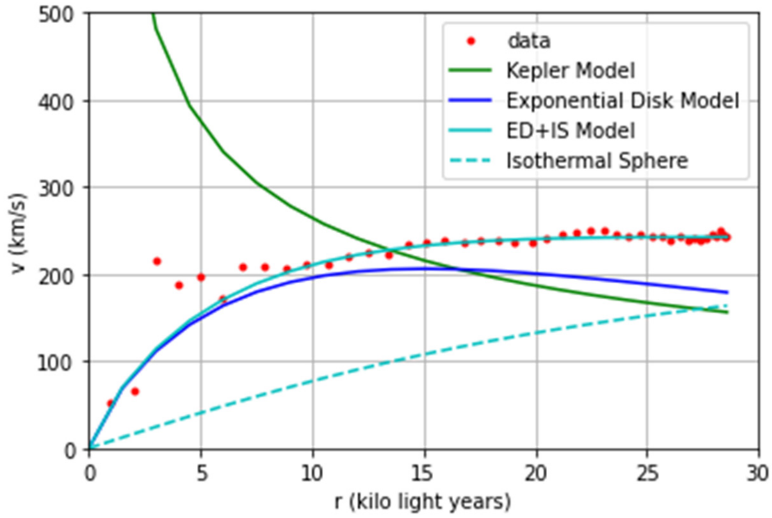

Figure 5. The rotation velocity of different models is plotted. Combining the exponential disk model with the estimated isothermal sphere (ED+IS Model) fits best with our observed data.

Rotation curves of different models are plotted, and it is obvious that combining the exponential disk model with the estimated isothermal sphere (ED+IS Model) fits best with our observation. A certain threshold of intensity is set to mark out the edge on the heat map, as the level is regarded as a considerable number of sources.

5. Measurement Uncertainty

An arbitrary threshold is set to mark the edge on the heat map. Setting the threshold lower, makes the detection more sensitive. After that, the dim blue part on the left-top part of the heat map would be attributed to the calculation.

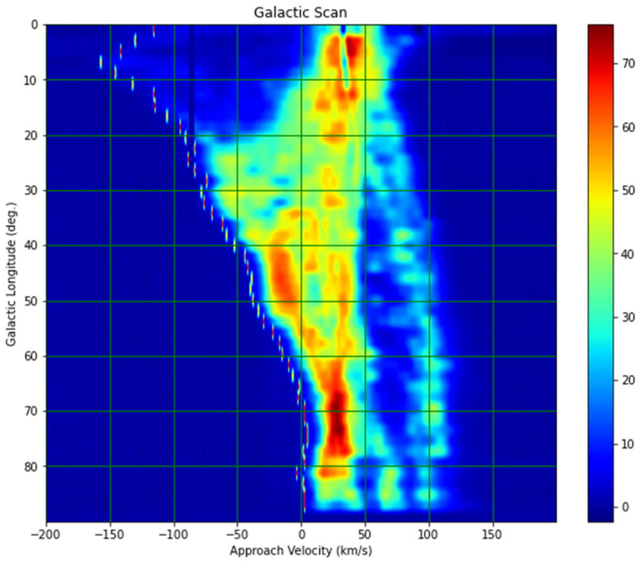

Figure 6. On this heat map, the edge testing threshold is set lower, making the observation more sensitive to signal intensity. The dim blue part on the left-top part of the heat map would now attribute to rotation curve calculation.

The edge moved leftwards, which means the approaching velocity is greater, especially at lower galactic longitude.

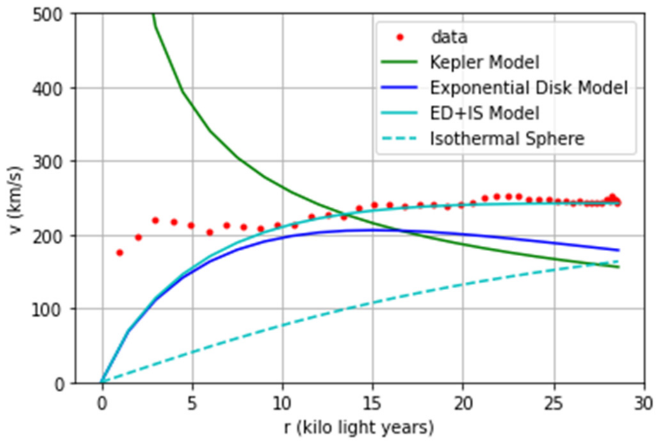

Figure 7. The rotation curve slightly changed, but still fits well with ED+IS Model, suggesting that the result is not sensitive to edge detect threshold.

The rotation curve did not change much after we made the threshold lower. The curve of the exponential disk model combined with the isothermal sphere dark matter halo still fits the data well, when the radius $r > 8{,}000$ l. y.

Other factors may bring errors to this research, such as the telescope gain and signal spur. Based on previous results on the TLM18 telescope, gain correction is carefully done and data spurs are removed in this research. Despite the above, our result is not precise enough to be sensitive to other errors.

6. Results

The exponential disk model combined with isothermal dark matter halo is conventionally accepted. The data from our survey is compared with it. The exponential disk model alone falls a little below the data, suggesting that there is another source of gravity. Filling the gap with dark matter in the form of an isothermal sphere turned out to be successful. And eventually, the combination makes the combined model which can explain our spectrum data from the TLM18 telescope. It also complies with the widely accepted assumption of the existence of dark matter. The data is systematically processed, and the final result is robust.

7. Conclusion

In this paper, a 21 cm radio wave detection aiming to learn about the rotation curve of the Milky Way is made. The spectrum of hydrogen emission was analyzed to calculate the rotation velocity. Compared with the Keplerian model and the barely exponential disk model, the model that combines exponential disk with isothermal sphere dark matter fits the data best.

After all, a simple model that combined exponential disk with isothermal sphere dark matter is good enough to describe the rotation of our galaxy, when the radius is larger than 8,000 light years. However, some limitations should be noted. First, the motion of neural hydrogen atoms does not reflect every part of the galactic system accurately. A more credible conclusion can be made, if in the survey different varies of trackers are compared. Second, the model does not fit well with the empirical data within the radius range of 8,000 light years from the galactic center. Further study is required to reveal the fine structure in such areas around the galactic center. Except for this convoluted area, in the vast Milky Way region, the simplified model combined exponential disk with isothermal sphere dark matter simulates the galaxy rotation very well, which makes the existing dark matter model convincing on an astronomical scale.

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