The Rotation Curve of the Milky Way Galaxy as Evidence for Dark Matter

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Abstract. We present neutral hydrogen observations of the plane of the Milky Way galaxy between $0^{\circ} < l < 80^{\circ}$ galactic longitude on the 20-meter telescope at the Green Bank Observatory. These radio spectroscopic signatures returned the 21-cm line of neutral hydrogen at various offsets due to the Doppler shift. By calculating orbital speeds relative to the galactic center, velocity was plotted against radial distance to map the rotation curve of the Milky Way galaxy. The distribution of luminous matter suggests that orbital velocity should fall off at large distances, but empirical observations show otherwise. An abundance of mass which cannot be detected is responsible for this phenomenon, known as dark matter. Although its nature is not understood, dark matter is easily observed indirectly by galactic rotation curves. Our observations confirm that the velocity of the Milky Way's disk is fairly constant even at large distances from the center of our galaxy, Sagittarius A*.

INTRODUCTION

In 1933, Swiss astronomer Fritz Zwicky found surprising results when taking radial velocity measurements of galaxies in the Coma cluster [1]. Using the virial theorem for the first time in astronomy, he estimated the mass of the galaxy cluster and found its corresponding velocities. At far distances from the galaxy cluster's center he found that the velocity dispersions were much larger than expected, suggesting that the cluster's density was higher than the one calculated from observable luminous matter [2]. The presence of this seemingly invisible matter in abundance around the edges of galaxies was named dark matter [2]. Evidence for dark matter increased over the next few decades. One of the most prominent studies to confirm its presence was conducted by Vera Rubin et al. [3], mapping galactic rotation curves of spiral galaxies. Neutral hydrogen (HI) emissions are easily detectable over the entire radial extent of spiral galaxies, and this is the most commonly used method while measuring rotation curves [4].

There are two major methods of indirect detection of dark matter; Zwicky's method, using velocity dispersions in galactic clusters, and Rubin's method, measuring velocity as a function of radius in individual galaxies. Currently, dark matter's composition remains largely unknown. Massive compact halo objects (MaCHOs) are unassociated baryonic celestial objects that emit little to no radiation [5]. MaCHOs, although contributing to the dark/luminous matter ratio, only comprise a tiny fraction of dark matter as a whole [6].

Weakly interacting massive particles (WIMPs) are the current leading candidate for dark matter but have never been detected. Particle observation and research regarding WIMPs remains a fundamental goal in astrophysics and the field of cosmology today [5]. There are several other models for dark matter particles such as axions, Higgs doublets, sterile neutrinos, and supersymmetric particles among other candidates that are active areas of research in direct detection [7].

This research aims to confirm known results of the rotation curve of the Milky Way galaxy using neutral hydrogen emissions along the galactic plane to reveal that velocity does not have a Keplerian falloff like $r^{-1/2}$. Instead, velocity tends to flat-line like r^{0}. Using classical mechanics, this inconsistency is revealed, which suggests the presence of a large amount of dark matter compared to normal luminous matter. The relationship between apparent luminosity of matter, L, and its mass, M, is given by the mass-luminosity relation [6]:

$$L \propto M^{3.5}. \tag{1}$$

Simply put, dark matter's existence is derived from the observation that material in the Milky Way is moving too fast. Mass is the only factor, according to classical mechanics, that can increase orbital velocity in this manner. To show this, only classical equations are necessary with the assumption of spherical mass distribution of luminous matter. Equation (2) is Newton's universal law of gravitation set equal to Newton's second law where acceleration is represented as angular acceleration. Here, G is the gravitational constant 6.67×10^{-11} m^3 kg^{-1} s^{-2}, r is radius from the galactic center, M is enclosed mass within the radius r, v is orbital velocity, and m is an arbitrary mass at radius r.

$$G\frac{Mm}{r^2} = \frac{mv^2}{r} \tag{2}$$

Equation (2) can be algebraically simplified to give the orbital velocity in Eq. (3).

$$v = \sqrt{\frac{GM}{r}} \tag{3}$$

If Eq. (3) is rearranged, it is easier to see how mass affects the change in velocity with respect to r. Since G is a constant, the only variable in the equation affecting the observed result v is the mass. Here, Eq. (4) shows how v falls off like $r^{-1/2}$, the definition of a Keplerian falloff.

$$G^{-1/2}v = M^{1/2}r^{-1/2} \tag{4}$$

The Milky Way galaxy is more complicated than a spherical model suggests in that it is shaped like a disk and is not cylindrically symmetrical. However, more sophisticated models taking this geometry into account still predict a Keplerian falloff [8].

Velocity empirically does not fall off like $r^{-1/2}$; rather, previous studies, including Fig. 1, indicate that velocity levels off to r^0 [6,9,10,11,12]. Therefore, for velocity to be higher, mass must be greater than what we can estimate with luminous matter.

METHODS AND OBSERVATIONS

Specifications of the 20-Meter

In order to map the rotation curve of the Milky Way galaxy, observations were taken on the 20-meter telescope every 5-10° declination along the galactic plane beginning at -30°, the location of Sagittarius A*. These coordinates were converted to galactic longitude l and translated to observations taken between $0^\circ < l < 80^\circ$. The telescope was configured to take “on/off” observations of each set of coordinates for a duration of 60 seconds and an integration time of 1 second. Off observations were taken -5° right ascension (α) and -5° declination (δ) from the target observation. On/off observations show a difference in the amount of detected neutral hydrogen on the galactic plane compared to neutral hydrogen off the galactic plane. Since the galactic plane is very rich in hydrogen and dense with stars and material, there is a very strong neutral hydrogen detection on the plane which can be reliably used to calculate velocity at radial increments from the galactic center. We checked that the on observations were correctly aligned on the plane of the galaxy by visually confirming that the off observations were only noise. Optical problems such as extinction do not affect this data, since these observations are taken in the radio frequency. In radio frequencies, we can see all of the hydrogen in the entire line of sight to the other end of the galaxy.

Our observations were taken on high-resolution mode, which has a bandwidth of 15.625 MHz and 1024 channels. The frequency associated with neutral hydrogen is 1420.41 MHz, also known as the 21-centimeter line. For observing neutral hydrogen, we used a center frequency of 1420 MHz and a secondary frequency of 1480 MHz, meaning that the range of the collected data was 1420-1480 MHz. These parameters were chosen to ensure a clear measurement of the 21-cm line while avoiding public radio frequency interference (RFI) that would compromise the data. The 20-meter telescope is connected to the SkyNet Robotic Telescope Network through the University of North Carolina Chapel Hill to be operated remotely. SkyNet does not produce FITS files for on/off observations that yield spectral line results; rather, SkyNet has its own user interface which cannot be exported. Peak frequencies from our observations could be ascertained within 0.005 MHz on the interface and recorded for mathematical manipulation within Mathematica and JupyterLab, using Python [13-15].

Calculating Velocity from the Peak Frequency

Neutral hydrogen emits an electromagnetic wave resulting from a transition between a hyper-fine splitting of the ground state. This detected emission line is commonly referred to as the 21-centimeter line and corresponds to a classically forbidden spin flip transition of neutral hydrogen [16].

Observed peak frequencies of neutral hydrogen, however, are offset from the known frequency due to its velocity relative to Earth. Therefore, a speed can be calculated using the Doppler shift equation, Eq. (5), and the difference in observed frequency and known frequency, where v_{rel} is the velocity relative to the observer in km s^{-1}, c is the speed of light at 3×10^5 km s^{-1}, and f_{obs} is the peak frequency from the observation in MHz [6]:

$$v_{rel} = c\left(\frac{1420.41MHz - f_{obs}}{1420.41MHz}\right). \quad (5)$$

The Doppler shift equation yields the velocity of the gas relative to the observer, but not an orbital velocity relative to the galactic center. To calculate the orbital velocity relative to the galactic center, v_{orb}, we used the tangent point method (TPM) [17]. The TPM, Eq. (6), relies on the assumption that the extremum of an HI observation is tangent to the galactic center. V_{LSR} is a constant called the local standard of rest, which is the average velocity of material at the solar circle R_{solar}. R_{solar} is the distance of our sun from the galactic center. We take V_{LSR} to be 220 km s^{-1} and R_{solar} to be 8 kpc according to Sofue et al. [17,18]. Here, l is the galactic longitude of the measurement and R is the radius of the measurement from the galactic center in kpc.

$$v_{rel} = R_{solar}\sin(l)\left(\frac{v_{orb}}{R} - \frac{V_{LSR}}{R_{solar}}\right) \quad (6)$$

Using the v_{rel} values calculated from Eq. (5), we rearrange Eq. (6) to find values for both the distance from the galactic center and the orbital velocity for every observation. Algebraic manipulation of Eq. (6) yields both of these equations, Eq. (7) and Eq. (8).

$$R = R_{solar}\sin(l) \quad (7)$$

$$v_{orb} = v_{rel} + V_{LSR}\sin(l) \quad (8)$$

These equations provide the necessary information to plot the velocity v_{orb} as a function of radius R.

RESULTS

A total of 13 observations were taken between $0^\circ < l < 80^\circ$. Passing the maximum frequencies through Eqs. (5)-(8), a distance and orbital velocity relative to the galactic center is obtained for each observation and represented in Fig. 1. Collected data is overlaid with the curve fit parameters of an array of rotation curve samples from more comprehensive papers. This figure suggests that the results of this study are in close agreement with several different surveys containing data from over a thousand galaxies at distances $R > 4$ kpc [19].

For distances $R < 4$ kpc, the collected data points are below the model curves. This deviation may be due to the TPM itself, since this method is considered difficult to use at distances very close to the galactic center and beyond 90° galactic longitude. The tangent point method can present several potential problems in calculating orbital velocities relative to the galactic center. The TPM relies on the assumption that the extremum of the HI measurement is tangent to the galactic center. However, at distances less than 4 kpc the bar of the Milky Way galaxy can produce highly noncircular orbits [20]. The HI measurements are often broadened by turbulence, which can affect the observed peak frequency. Additionally, the highest velocity gas is not necessarily directly on the galactic plane at a galactic latitude of $b = 0^\circ$ [21].

The deviation, however, may be a real feature of the Milky Way galaxy. The TPM is a valid method of calculating velocity close to Sagittarius A* [17]. Reid et al. makes a similar observation of low velocity values in the $0 < R < 4$ kpc range in Fig. 11 of [20] using trigonometric parallaxes and proper motions.

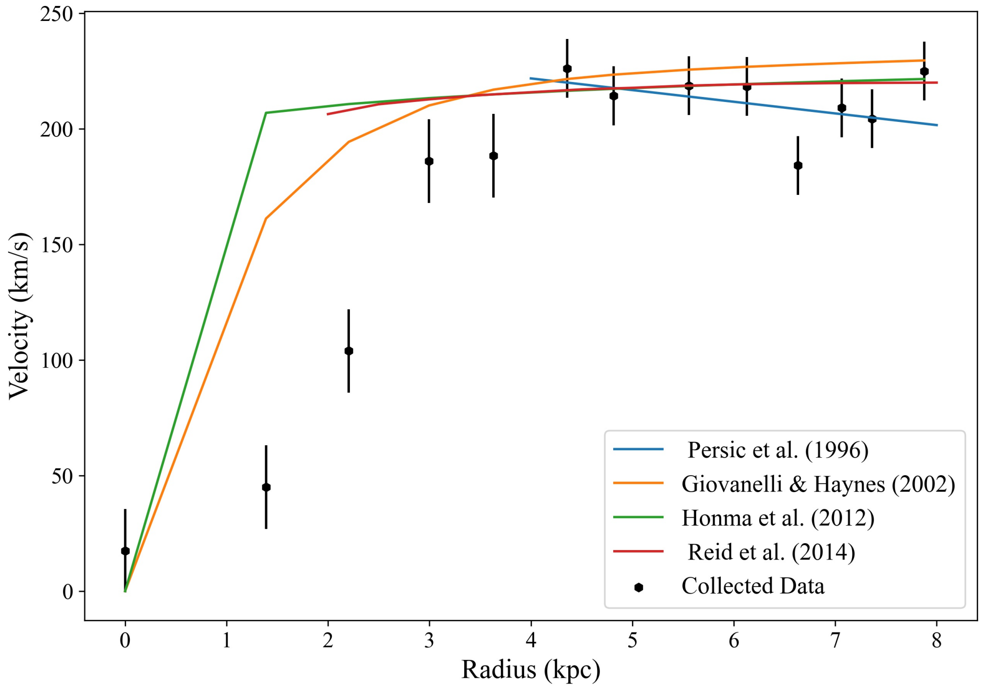

FIGURE 1. Velocity, as calculated using Eq. (8), is plotted against distance from the galactic center at $l = 0^{\circ}$ to $l = 80^{\circ}$. These data points show a stabilization in velocity near 200-220 km s^{-1}. Collected data is compared with several expressions for the rotation curve by Persic et al. [12], Giovanelli and Haynes [9], Honma et al. [11], and Reid et al. [10]. Error bars represent random error as described in the text.

Velocity appears to stabilize at around 220 km s^{-1}, which is similar to the LSR. In order to estimate the random error in our data, we calculated the average distance between a line of best fit and the collected points. For points $R <$ 4 kpc, we assume a linear curve, and for points $R > 4$ kpc we assume a flat rotation curve.

CONCLUSION

Here we have presented novel HI observations of the galactic plane taken on the Green Bank Observatory's 20-meter telescope. By mapping the velocity of gas between $0^{\circ} < l < 80^{\circ}$ using the TPM, we have shown that the rotation curve of our galaxy does not fall off like $r^{-1/2}$ but stabilizes even at large distances from the galactic center. In comparison to more sophisticated maps of the Milky Way's rotation curve, our data is consistent.

These results suggest a large discrepancy in the amount of luminous matter present in our galaxy compared to the total mass. Such an empirical disagreement with theoretical expectations implies the existence of dark matter in large proportions. The mass of the dark matter halo of the Milky Way galaxy is known to be roughly 5.4×10^{11} solar masses, where the luminous matter of the galaxy is $9{\times}10^{10}$ solar masses [6]. Rotation curves remain one of the most ideal methods of indirect observation of dark matter.

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