Hussein and Mahdi Iraqi Journal of Science, 2025, Vol. 66, No. 5, pp: 2118-2126
DOI: 10.24996/ijs.2025.66.5.27

ISSN: 0067-2904

Measurement of the Milky Way's Rotation Curve using BURT Radio Observations at the 21 cm Line of Neutral Hydrogen

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Received: 31/ 12/2023 Accepted: 10/ 6/2024 Published: 30/5/2025

Abstract

With a small radio telescope in a high-noise area, this paper measured the Milky Way's rotation curve using the Tangent Point Method, by the Baghdad University Radio Telescope (BURT). It is placed on the Department of Astronomy and Space roof, and observes a 21-cm HI emission line, scanning the galaxy's first quadrant systematically. From 0° to 90° galactic longitude, by increasing 5°, the telescope identifies the highest recession velocity, corresponding to clouds orbiting tangent to the line of observation. The rotation curve, plotting galactic rotational velocity against distance from the centre, is anticipated to be flat, indicative of uniform mass distribution. However, observed deviations challenge this expectation, revealing non-flat curves and prompting the exploration of the dark matter problem. Anomalies in the rotation curve imply unseen mass in the galaxy, expanding our comprehension of the Milky Way's composition and contributing crucial insights into the pervasive mystery of dark matter.

Keywords: Baghdad University radio telescope (BURT), dark matter galactic mass distribution, Milky Way, rotation curve, tangent point method, 21 cm emission lines.

قياس منحنى دوران درب التبانة باستخدام BURT الارصاد الراديوية عند خط 21 سم من الهيدروجين المحايد.

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الخلاصة

باستخدام تلسكوب راديوي صغير في منطقة عالية الضوضاء، قامت هذه الورقة بقياس منحنى دوران درب التبانة باستخدام طريقة نقطة الظل بواسطة التلسكوب الراديوي لجامعة بغداد (BURT). يتم وضعه على سطح قسم علم الفلك والفضاء، ويراقب خط انبعاث HI بقطر 21 سم، ويقوم بمسح الربع الأول من المجرة بشكل منهجي. من 0 درجة إلى 90 درجة خط طول المجرة، بزيادة 5 درجات، يحدد التلسكوب أعلى سرعة انحسار، تتوافق مع السحب التي تدور مماس لخط المراقبة. من المتوقع أن يكون منحنى الدوران، الذي يرسم سرعة دوران المجرة مقابل المسافة من المركز، مسطحًا، مما يدل على التوزيع المنتظم للكتلة. ومع ذلك، فإن لانحرافات المرصودة تتحدى هذا التوقع، وتكشف عن منحنيات غير مسطحة وتحفز على استكشاف مشكلة

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المادة المظلمة. تشير الشذوذات في منحنى الدوران إلى وجود كتلة غير مرئية في المجرة، مما يوسع فهمنا لتكوين درب التبانة ويساهم في رؤى مهمة حول لغز المادة المظلمة المنتشر.

1-Introduction

The main objective of this research is to demonstrate the existence of dark matter in our galaxy through BURT observations and rotation curve measurements. In the early 1930s, Fritz Zwicky first proposed the concept of dark matter [1]. His observation of galaxies within a cluster revealed an unexpected phenomenon: some of these galaxies orbited their common center of mass at remarkably high speeds. Despite generous estimates of individual galaxy masses, the combined mass seemed insufficient to explain this rapid motion [2], [3].

In the 1970s, American astronomer Vera Rubin observed a similar occurrence in isolated galaxies. Stars located far from the galactic maintained velocities comparable to those closer, defying expectations of a slowdown due to diminishing gravity toward the galaxy's outer reaches [4], [5]. Once again, visible mass alone could not account for these observations, leading Rubin to assert the presence of dark matter in galaxies [6]. Only 5% of the total mass in the universe consists of visible matter, while the rest is categorized as dark matter and dark energy, which both represent ~ 95% of the total mass and energy in the universe [7],[8].

Dark matter comprises particles that do not interact with light or any other form of electromagnetic radiation. However, its presence can be deduced from its gravitational influence on luminous matter, such as gas and stars in galaxies[9]. Since hydrogen is the most abundant element in the universe [10], a wavelength λ=21 centimeters (at a frequency of 1.420 GHz) hydrogen line is used to measure the Milky Way's rotation curve because it is abundant in the interstellar medium of galaxies [11]. By using the Baghdad University Radio Telescope (BURT), which is a small radio telescope [12], [13], with a diameter of (3 m) [14], the focal length is (1.18 m), and the f/D ratio is 0.39. Feed is designed to operate within the L-band frequency, from (1.3 to 1.5) GHz, which includes (1.420 GHz) that allows one to observe the universe. A research study was carried out in 2023 by H. S. Mahdi utilized a C++ program to establish the ideal observing time and coordinates for the Milky Way using BURT. The findings indicated that the most favourable periods to observe the Milky Way using BURT in 2023 were January, February, March, November, and December [15], as outlined in the study. Moreover, the rotation curves' flatness in distant regions of spiral galaxies supports evidence for dark matter, challenging Newtonian mechanics' gravitational force and centrifugal balance [16].

1. Methodology

A highly effective way to determine the rotation curve of a spiral galaxy is by observing the Doppler shift of clouds emitting the HI emission line [17]. The 21 cm wavelength neutral hydrogen radio line is particularly useful, as it does not suffer from high scattering and absorption by dust in the interstellar medium. However, directly measuring the position and velocity of an HI cloud is impossible [18], [19]. Therefore, a method, known as the tangent point method, can be employed to calculate the galactic rotation curve [20], [21]. The gas cloud with the greatest radial velocity along the line of sight to the galactic center is the one closest to it. To determine the distance to the galactic center (R) and the rotational velocity (v_c) at a specific galactic position, one can utilize the following formulas [15]:

$$R = R_o \sin l \quad (1)$$

$$v_C = v_{max} + v_o \sin l \quad (2)$$

The term (v_{max}) refers to the measurement of the maximum radial velocity at various locations within the galaxy. (v_o) represents the rotational velocity of the sun around the center of the galaxy, while (R_o) stands for the distance between the sun and the center of the galaxy $R_o = 8\ kpc$. The parameter (l) corresponds to the galactic longitude. In order to study gas clouds in different parts of the galaxy and accurately determine their maximum velocity (v_{max}) using BURT, galactic coordinates (l, b) should be converted to horizontal coordinates (a, A). However, this conversion cannot be done directly. In order to perform such a conversion, galactic coordinates (l, b) should be first converted to equatorial coordinates (α, δ) and those in turn are converted to horizontal coordinates as follows: "The numbers come from the following facts about our galaxy: the north galactic pole coordinates are α = 192.25° , δ = 27.4°; the ascending node of the galactic plane on the equator l = 33°" [22], [23]:

$$\alpha = \tan^{-1}\left\{\frac{\cos(l-33^{\circ})\cos(b)}{\cos(27.4^{\circ})\sin(b)-\cos(b)\sin(l-33^{\circ})\sin(27.4^{\circ})}\right\}+192.25^{\circ} \qquad (3)$$

$$\delta = \sin\{\sin(l-33^{\circ})\cos(27.4^{\circ})\cos(b)+\ \sin 27^{\circ}\sin b\} \qquad (4)$$

$$\sin a = \sin\phi\sin\delta+\cos\varphi\cos\delta\cos H \qquad (5)$$

$$\cos A = \frac{\sin\delta-\sin a\sin\phi}{\cos a\cos\phi} \qquad (6)$$

The altitude (a), azimuth (A), hour angle (H), and observer's geographic latitude (ϕ) variables are used. The observer's geographic latitude for BURT is 33.275°, and the hour angle is calculated using formula (7).

$$H = LST - \alpha \qquad (7)$$

Where (LST) is the local sidereal time, to calculate (LST) use the next equation (8) [24], where the longitude (l) of BURT is (44.380°) [25] and GTS (Greenwich Sidereal Time) to get it, the Julian date calculated by function (**juliandate**) with MATLAB [26].

$$LST = GTS + \left(\frac{l}{15}\right) \qquad (8)$$

To collect the (v_{max}), we used the BURT from (January to April) 2023 in a range from (8:30 a.m. to 12:30 p.m.), which is the most appropriate time for observing and measuring the Milky Way's rotation curve according to previous research entitled "Determine the Time and Coordinates Required for Measuring the Milky Way's Rotation Curve Using BERT" [15], for galactic coordinates when the latitude (b = 0°) and the longitude (0° ≤ l ≤ 90°) with 5° difference between each. The optimum spectrometer parameters of the radio telescope used in this work are span, sweep time, centre frequency, Resolution Band Width (RBW), and Video Band Width (VBW). The values of those parameters are listed in Table (1).

Table 1: The Spectrometer Parameters Values.

Center frequency (Hz)	Sweep Time(s)	VBW	Span	Sweep Perc-N=0, A=1	RBW	Atten(dBm)	Preamp-On=1, Off=0
1.42E+09	30	1000	1E+07	0	1000	0	1

2. DATA ANLAYZING

The data from BURT was received in text format. To convert it into a table, Excel is used. After the conversion, frequency (f) has to be converted into velocity (v) using the Doppler shift equation (10)[27].

$$\Delta f = \frac{v}{c} f_o \tag{9}$$

$$v = c\,\frac{(f - f_o)}{f_o} \tag{10}$$

Where v is the radial velocity, which is the velocity of a source with respect to the line of sight of an observer, c is the speed of light (2.99792458$\times 10^8$ m/s), f is the observed frequency (the range of frequencies in the research is (1418.0×10^6 Hz – 1421.987×10^6 Hz)), f_o is the rest frequency of HI 21-cm (1420.4058 $\times 10^6$ Hz). Additionally, one needs to convert power from dBm (dBm) to milliwatts (P_mW) using the equation:

$$P\_mw = 10^{\frac{dBm-30}{10}} \tag{11}$$

By brightness temperature formula, the power in milliwatts (P_mW) is converted to brightness temperature (T_k), as shown in the following formula[28]:

$$T_k = \frac{P\_mw\, \lambda^4}{2\, k\, c} \tag{12}$$

When (T_k) is the brightness temperature, (λ) is the wavelength, **(**k) is the Boltzmann's constant (1.380649$\times 10^{23}$ J/K). Finally, to make the collected data smoother, we use the Savitzky-Golay filter, which is a digital signal processing (DSP) technique used for smoothing and differentiating data [29], [30]. It has a wide range of applications in various fields, such as

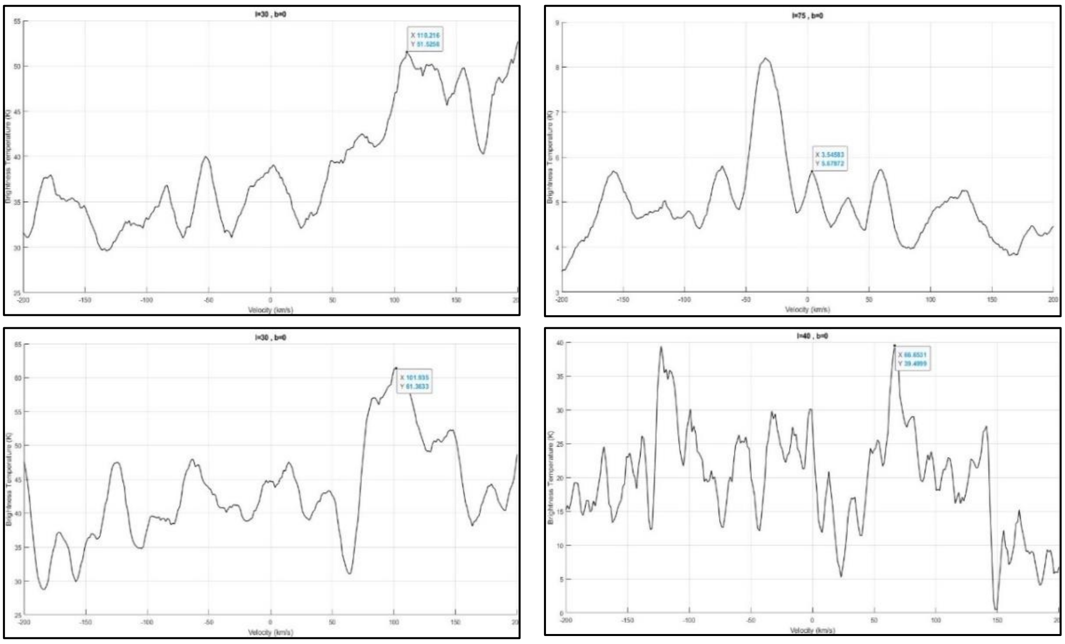


Figure 1: Graphs show the result from BURT from (January to April) 2023

data analysis [31], image processing, and spectroscopy [32]. The filter is named after its developers, Abraham Savitzky and Marcel J. E. Golay, who introduced it in 1964 [33]. A

MATLAB code is written using the "sgolayfilt" function[34], [35]. After that, the brightness temperature is plotted against radial velocity as the Gaussian shape, as shown in figures (1, 2) for several observations. Table 2 shows the maximum velocity of graphs, v_{max} is deduced from it (from the positive side).

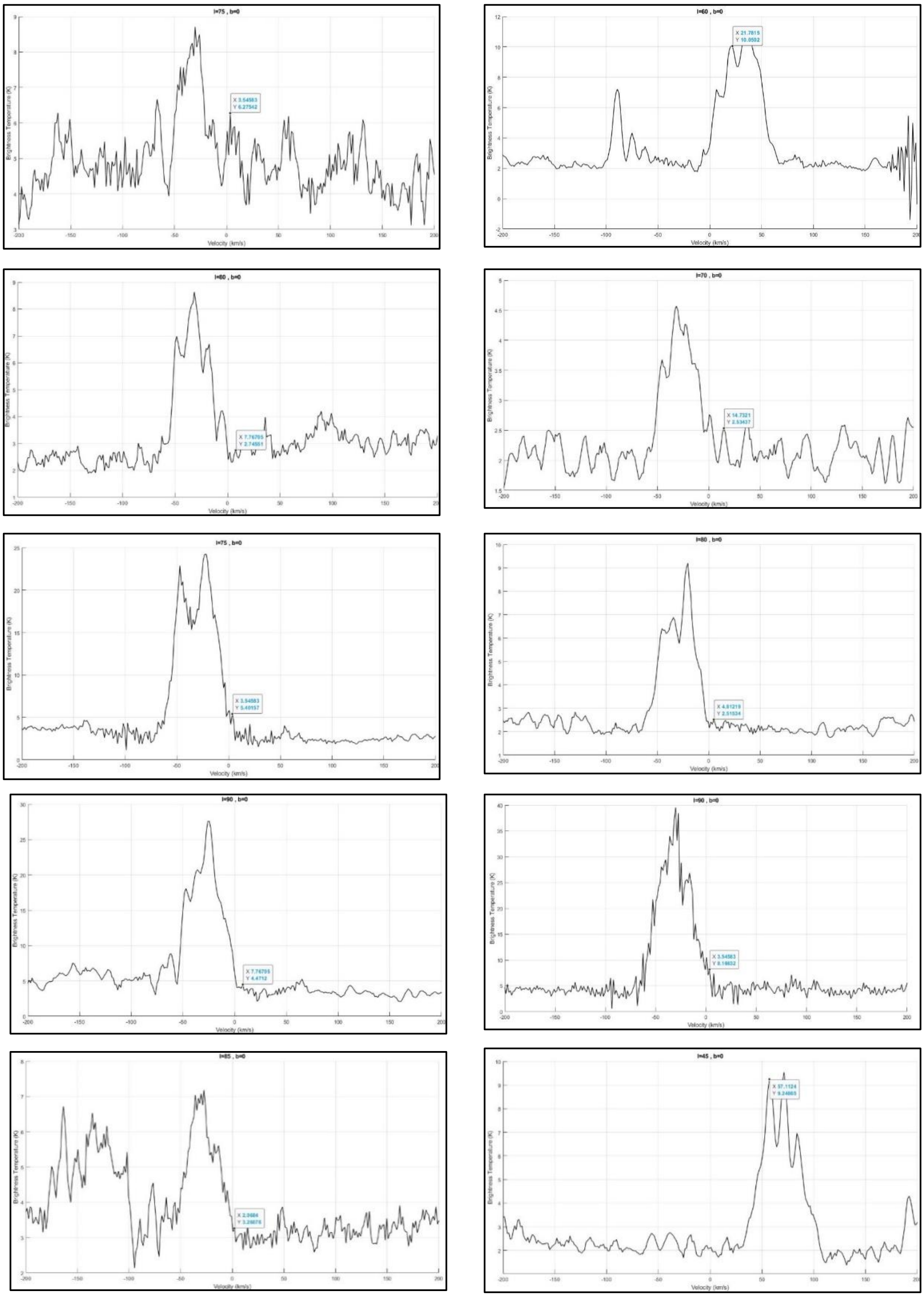
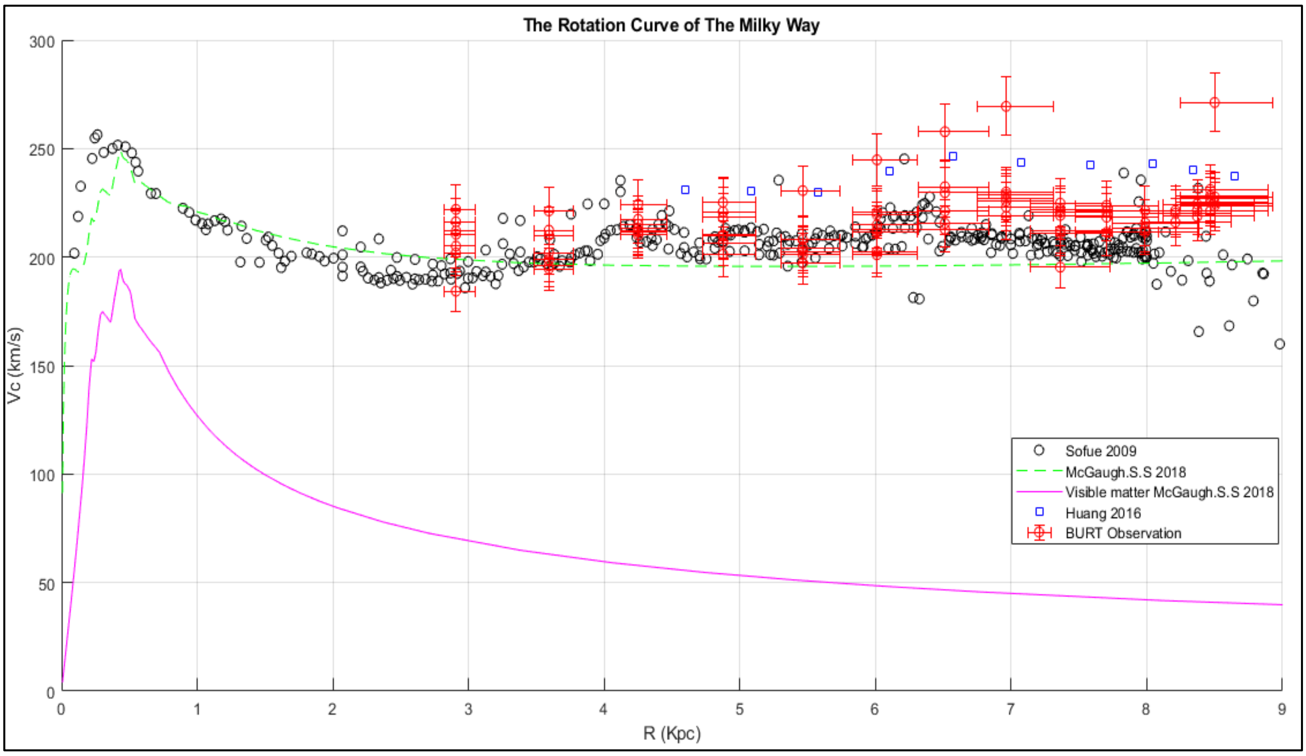


Figure 2: Graphs show the result from BURT from (January to April) 2023

Table 2: The maximum velocity of graphs in Figures 1 and 2 is in sequence starting from the left.

Observation Date	Longitude (degree)	Latitude (degree)	Maximum Velocity (km/s)
10/4/2023	30	0	110.216
5/3/2023	75	0	3.54
2/4/2023	30	0	101.93
2/4/2023	40	0	66.65
2/4/2023	75	0	3.54
2/4/2023	60	0	21.78
3/4/2023	80	0	7.76
2/4/2023	70	0	14.73
3/4/2023	75	0	3.54
2/4/2023	80	0	4.81
3/4/2023	90	0	7.76
5/3/2023	90	0	3.54
5/3/2023	85	0	2.06
3/4/2023	45	0	57.112

Milky Way survey results of b = 0 and various galactic longitudes are depicted in Figures 1 and 2. The maximum radial velocity extracted by equations 1 and 2 are employed to establish the galaxy's rotation curve, as demonstrated in Figure 3. This figure also presents a comparison between the rotation curve acquired through BURT observations, Huang's 2016 rotation curve, and Sofue's 2009 rotation curve using a different method than the tangent point, as displayed in Figure 3. The rotation curve determined for comparison, reveals that our



.**Figure 3:** Comparison curve measurements from observation using the 21 cm by BURT are shown with red-error bars.

The visible matter is demonstrated by the "McGaugh.S. S. 2018'' curve with a magenta color. It has overlaid existing rotation curve measurements from McGaugh.S. S. 2018 (green dotted line), Sofue 2009 (black circles) and Huang 2016 (blue square). [37]

measurements align with theirs. Also, when comparing the BURT observation with the expected curve from the visible matter in the disk, the discrepancy between the two curves proves the existence of dark matter.

This figure also presents the rotation curve determined for comparison, revealing that our measurements align with theirs. The rotation curve's constancy at greater radial distances suggests the presence of dark matter [36], as Newtonian dynamics would predict a decline in rotational velocity if all matter were luminous. It is worth noting that the velocities in the Milky Way's inner portion are highly uncertain, so our work focuses on the outer region ($l \geq 20^o$). Nevertheless, this does not undermine our work, as our primary objective is to prove the rotation curve's flatness in the galaxy's outer regions.

3-Conclusion

The objective of this research was to ascertain the rotation curve of our own Milky Way galaxy using observations of HI clouds at a wavelength of 21 cm. Our work reveals that the Milky Way's rotation curve measured with a small radio telescope (BURT) in a high-noise area is consistent with a previously published work. The uniform rotational velocity in the outer regions suggests that dark matter is present within the Milky Way. If all the matter within the Milky Way is observable, then according to Kepler's laws, the circular velocity should decrease at large radial distances from the galactic center. However, our observations make it clear that the rotation velocity remains nearly constant at great distances. This deviation between the anticipated and observed behavior of the rotation curve indicates a considerable amount of invisible matter in the galactic halo. Moreover, this study's outcomes demonstrate that despite BURT's small size, it has advantages and it is useful for exploring astrophysical issues that involve radio observations at a 21 cm wavelength.

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