Galactic Hydrogen

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Abstract

Clouds of neutral hydrogen are common throughout the interstellar regions of the galaxy. Due to the 'spin-flip' transition of the $1s$ electron they emit a characteristic 21-cm line of a very small natural width [1]. Hence, their velocities can be reliably measured by considering the deviations from that line as caused predominantly by the Doppler shift due to their relative motion with respect to the observer. This can be used to measure the relation between the galactic rotational velocity and the distance to the galactic centre in quadrants I and IV of the galactic plane of the Milky Way. Using observational data collected by the 7-m Jodrell Bank radio telescope in Manchester, the following report presents such measurements for quadrant I in the form of a galactic rotation curve. It shows that the deviation from the Keplerian model of galaxy rotation, therefore providing further evidence for the existence of dark matter.

[1] Helmut Hellwig et al. "Measurement of the Unperturbed Hydrogen Hyperfine Transition Frequency." In:IEEE Transactions on Instrumentation and Measurement(1970), pp. 200–209.

1 Introduction

The rotation curve of a galaxy is obtained by plotting the rotational velocity of objects in the given galaxy against their distance from the galactic centre. In the early 20^{th} century, it was widely expected that the curve would follow a pattern similar to that of Kepler's third law in planetary systems – the velocity of the further object would drop with distance as most of the mass of the system is concentrated in the centre. This was motivated by the observed high concentration of light close to the galactic centre and the rapid decrease towards the edges which was thought to be indicative of the mass distribution [2].

However, later performed observation seemed to show a significant deviation from the Keplerian model. Among many others, in 1957, Henk van de Hulst measured such deviation in the M31 galaxy, with great accuracy [3]. In almost all cases, including the Milky Way, it seemed that the rotational velocity was not falling with distance from the galactic centre but rather increasing with it, albeit at a declining rate. Thus, a new prediction was put forward of the existence of dark matter – a form of matter which was massive but reacted very little or not at all with light. If true, the prediction would explain the observed rotation curve as a result of a different mass distribution than that based solely on light concentration [2].

The experiment in this report aimed to measure the galactic rotation curve for the Milky Way using the Doppler shift of neutral Hydrogen's 21-cm emission line. Afterwards, it was compared with the Keplerian model to further test the possibility of the existence of dark matter. A 7-m radio telescope at the Jodrell Bank Internet Observatory (JBiO) has been used to collect all measurements.

2 Theory

This next section covers the basic theory behind radio telescopes and neutral Hydrogen clouds in interstellar space.

2.1 Basics of Radio Astronomy

The main component of a radio telescope is its primary parabolic dish. It collects the incoming radio waves and eventually redirects them towards the feed horn. There it can be converted into a digital signal by the receiver and analysed by the computer.

For a given wavelength of measured radio waves coming from a point-like object, one can define the beam-width of the telescope as the angular separation between the points in the response spectrum where the power drops to half of the maximum. It is approximately λ/d [4], where λ is the wavelength of received light and d is the diameter of the primary dish. For the 7-m JBiO telescope, the theoretical beam-width at $\lambda = 21$cm is $\sim 1.9°$. Knowing the beam-width of the telescope is crucial to plan the observations efficiently. Objects with an angular separation smaller than the beam-width will tend to be blurred together so their measurements will not be very significant.

Another widely used concept in radio astronomy is brightness temperature. It is the temperature of a hypothetical dark body that emits the same amount of radiation at a given wavelength of light. It can be derived from Planck's radiation law in the limit of radio wavelengths, also known as Rayleigh-Jeans law:

$$B_\lambda(T) = \frac{2ck_B}{\lambda^4}T, \tag{1}$$

where B_λ is the brightness of the object, λ is the wavelength of the incoming light, c is the speed of light in vacuum, k_b is the Boltzmann's constant and T is the temperature. Hence, for radio observations the temperature is proportional to brightness and it is denoted T_b (brightness temperature) [4]. The data gathered by the JBiO is by default presented in terms of brightness temperature in Kelvin.

2.2 Neutral Hydrogen Clouds

The interstellar regions of the Milky Way are filled with Hydrogen clouds.

In this experiment, clouds of primarily neutral, atomic Hydrogen (known as HI) were the main object of observation due to their very characteristic 'spin-flip' transition.

It occurs when the electron in the 1s state transitions from having a spin aligned with the proton to the anti-aligned state, hence reducing the overall energy by $\sim$ 5.87 eV. The result is an emission line at $\lambda = 21.106$ cm that has a very small natural width ($\sim 10^{-9}$cm) [1]. Therefore, it is useful at measuring the speed of distant objects relative to us with great precision since any deviation from the literature value will be almost entirely caused by the Doppler shift.

However, measuring the intensity of radio waves around 21-cm line along a given line of sight (say line B in Figure 1) will produce many peaks for different clouds in that direction. In general, there is no way to tell the distance to each of those clouds, only their relative speed can be measured. Consequently, most cannot produce a galaxy rotation curve. However, assuming that objects orbit the galactic centre in circular orbits, any line of sight similar to A (seen in Figure 1) that looks "inward" into quadrants I and IV of the galactic coordinates ($90° > \phi > -90°$ and latitude $= 0°$) will necessarily be tangent to one of those orbits. A cloud located at this tangent point will have all of its rotational velocity v_r pointed directly away or towards the Solar system, hence will appear the most Doppler shifted and easily identifiable. Using trigonometry one can show that:

$$R = R_0 \sin(\phi) \tag{2}$$

and

$$v_r = v_{rel} + v_0 \sin(\phi), \tag{3}$$

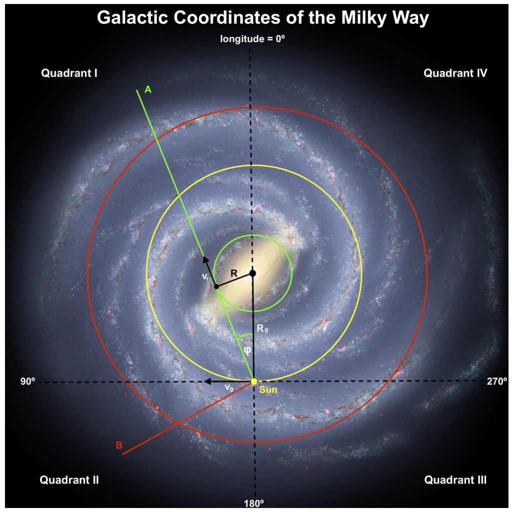


Figure 1: An image of the Milky Way with the Sun-centred galactic coordinates superimposed on it, showcasing three orbits around the galactic centre and two lines of sight coming from the Solar system (A and B). [5]

where ϕ is the galactic longitude, R and R_0 are the distances of the cloud and the Sun to the galactic centre respectively, v_0 is the rotational velocity of the Sun, v_{rel} is the measured relative velocity of the cloud and v_r is the rotational velocity of the cloud.

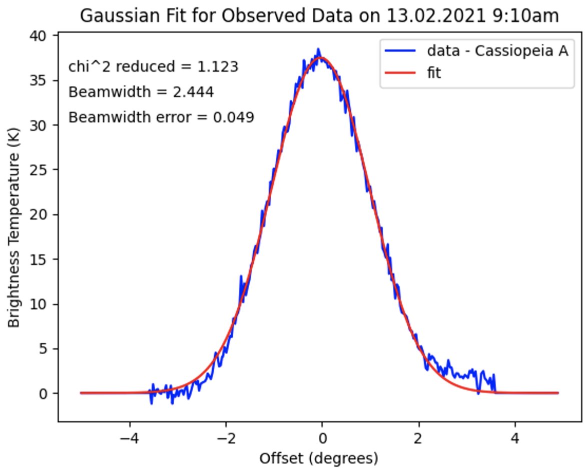
3 Methodology

Firstly, to determine the accuracy of our spectral data of the galaxy, the beam-width of the radio telescope had to be found. Later, this was used for creating the rotation curve.

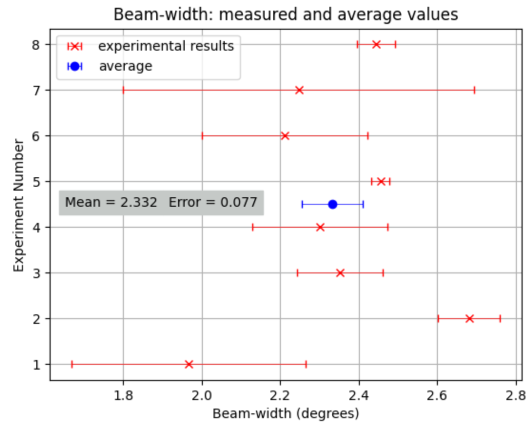
3.1 Establishing the beam-width

To calculate the beam-width, the "Total Power Scan" feature of the JBiO 7-m telescope was used. The telescope was aimed at point sources (objects with small angular size). For this experiment Cassiopeia A, Cygnus A, Taurus A and Virgo A were chosen. This scan provided a graph of how the brightness temperature varied with the scan offset and, knowing that the brightness temperature is proportional to the power, the beam-width could be found as the full width at half maximum (FWHM) [6]. The background noise on the measurements was subtracted with the JBiO plotting applet, and then data was exported as a CSV file, which was fitted with a Gaussian using python's SciPy module, as seen in Figure 2(a).

The beam-width was found from the Gaussian fit. The error has been estimated by taking a difference of this value and 2.355σ, where σ is the standard deviation of the data itself (based on the derived relation between the standard deviation and FWHM of a Gaussian). This process was repeated for all different measurements and later averaged to find our beam-width, which



(a) Fitted data for the power scan of Cassiopeia A.



(b) All beam-width measurements and the average.

Figure 2: Plots of measured brightness (K) over the angular offset (°) and the resulting beam-widths (°)

can be seen on Figure 2(b). This beam-width was found to be $2.332 \pm 0.077°$, which is greater than the theoretical value (which was found to be 1.9°).

3.2 Measuring the rotation curve

From the northern hemisphere, only certain galactic quadrants are available. These are the quadrants I, II and III, the region from 0° to 270° [6]. Equations (2) and (3) only work for quadrants I and IV. The telescope will have physical resolution limitations given by its beam-width, and JBiO only allows for increments of 2° on the measurement. Taking it all into consideration, we decided to take data points throughout quadrant I in increments of 4° in the range $0° \leq \phi \leq 40°$ (where most rapid differences in rotational velocity should be observed) and in increments of 10° in the range $40° < \phi \leq 90°$.

The possibility of observation for each point was determined using the tracker feature on JBiO, which confirmed quadrant IV as largely unobservable. The spectrum data given by the telescope graphed brightness temperature with respect to frequency or velocity (which was provided by JBiO through Doppler shift analysis of the frequency data). This report only considers the temperature over velocity graphs.

These graphs were analysed visually, finding the cloud of hydrogen moving the fastest with respect to the Earth (this is the most Doppler-shifted power peak, e.g. the black point in Figure 3). The error was calculated as the velocity difference between this peak and what can be considered background noise. The process was repeated throughout quadrant I data. A plot for the rotation curve of the galaxy was obtained in python using equations (2) and (3).

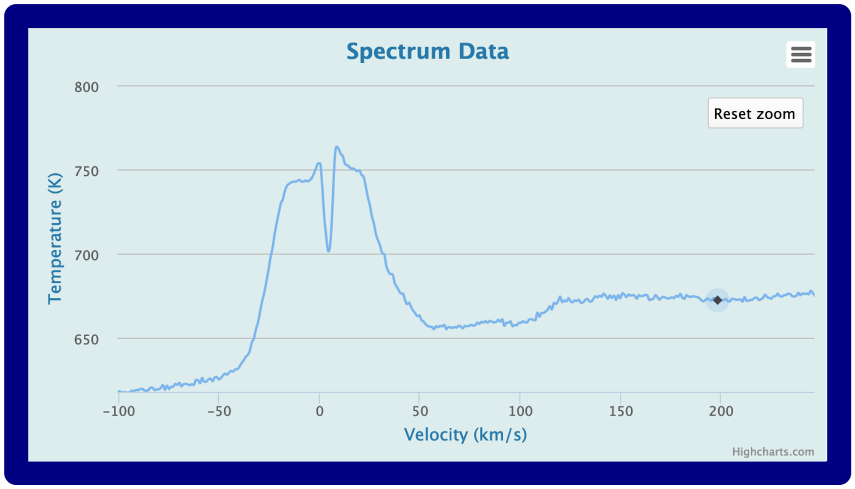
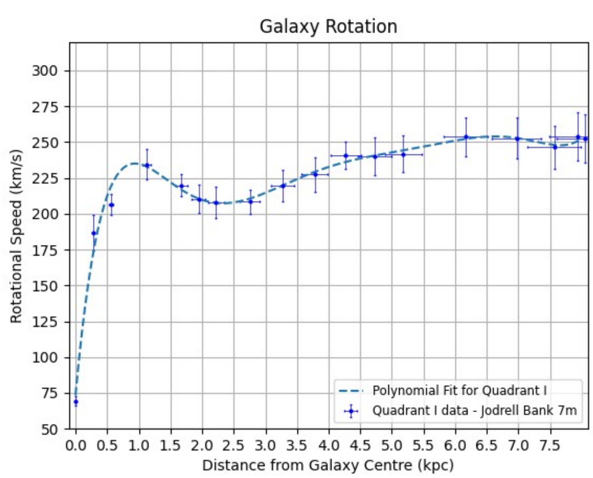


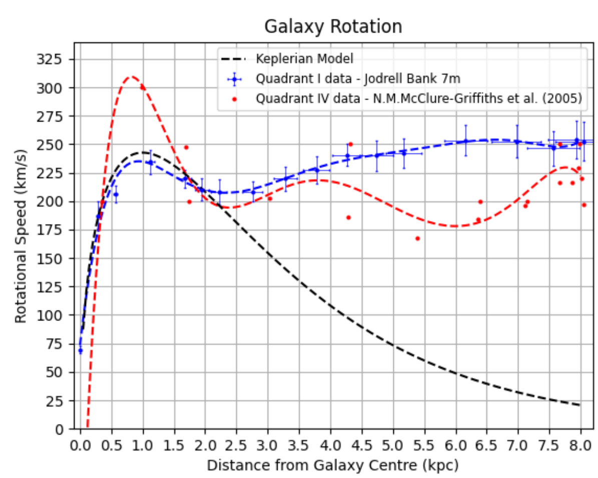
Figure 3: Spectrum data of temperature (K) over velocity (km/s) for the observation at $\phi = 8°$ on 20.02.2021 at 8:10am as presented on JBiO. The black point shows the fastest HI cloud.

4 Results and Analysis

The galactic rotation curve was then obtained and plotted in Figure 4(a). The value used for the Sun's velocity with respect to the Milky Way's centre, and the value for the radius of the Sun's orbit were $R_0 = 8.05 \pm 0.45$ kpc and $v_0 = 238 \pm 14$ km s^{-1}[7]. The errors in velocity and position of each point were derived by applying the general formula for the propagation of errors to equations (2) and (3).



(a) The galactic rotation curve plotted using the data collected via JBiO in this experiment.



(b) Results of this experiment compared to the data from quadrant IV [8] and the Keplerian model.

Figure 4: The results plotted as rotational velocity (km/s) over the distance from the galactic centre (kpc).

The other errors come from various sources. When performing observations of an object with a radio telescope the temperature of the dish and the atmospheric conditions are the primary sources of error in the brightness temperature. However, these are random errors (hence the 'zigzag' line in Figure 2(a)), therefore they can be greatly reduced by averaging out over measurements. Likewise, they can be lowered by increasing the integration time of the observation as the magnitude of the error is proportional to (integration time)$^{-0.5}$ [9]. In particular, the integration time was increased for the observation at $\phi = 0°$ since that observation suffers both from the amount of noise near the galactic centre and the orientation of the Earth, which causes it to be barely observable by the JBiO. Another way of reducing error is to keep track of the conditions at the time of the observation and then estimate their magnitude and perform a background (noise) subtraction. Finally, one can use an algorithm which estimates the magnitude of noise in the spectrum and removes it. JBiO provides a system that performs the background subtraction automatically. Nonetheless, some noise always remains and results in an uncertainty of the Gaussian fit, for one (to see how this particular error has been estimated, look at section 3.1).

Another source of systematic error comes from the Sun-centred choice of coordinates. As a result, equations (2) and (3) have been derived from the frame of reference of a stationary observer at the Sun's location. However, since Earth moves relative to the Sun with an orbital speed of ~ 30 km/s the measured relative velocities of HI clouds will be systematically offset. Yet again, JBiO performs an automatic correction based on the motion of Earth around the Sun at the time of the measurement, so this source of error is negligible in the analysis.

Next, the obtained results were plotted in Figure 4(b) against a schematic representation of the Keplerian model and results of observation of quadrant IV performed in the Southern hemisphere by Griffiths and his team [8]. The data collected in this experiment differs from the one from quadrant IV. It has a lower peak and then falls off less significantly. We believe the higher peak was observed because Griffiths had access to a radio-telescope of a higher resolution. Hence, he obtained more detail in the region close to the galactic centre where differences in velocity are more rapid. Thus, the natural suggestion for future improvements would be to use a telescope with a larger primary dish and, consequently, a lower beam-width. Griffiths' lower values in the farther region of the plot, on the other hand, could be explained by the usage of different values for R_0 and v_0. Our current best values for these were only well-established around 2012 [7], while Griffiths performed his analysis in 2005 [8].

However, both this report's data and the data collected by Griffiths seem to follow a different trend to that shown by the Keplerian model schematic plot (which follows the inverse square root law but was not made using precise calculations). For that reason, we conclude that the results provide supporting evidence of the existence of dark matter.

5 Conclusion

The results obtained in this experiment differ slightly from other literature data but show a non-Keplerian trend overall. However, the method is unsuitable for any measurements over the range of 8 kpc. Thus, to study the outer rotation curve of the galaxy, a different method is needed [10]. One approach could be to observe Cepheid variables, as their distance from the Sun is easily measurable. Alternatively, one could use the parallax method on bright stars in quadrants II and III and then perform the Doppler shift analysis. Both approaches come with the obvious difficulty that, unlike HI clouds, those stars will not have easily identifiable emission lines. Finally, we recommend performing a similar analysis of the inner Galactic regions but using stars as objects of observations (rather than HI clouds) to confirm the presented results.

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