Using 21-cm hydrogen line data to determine the internal motion of the Milky Way

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Abstract

Using the remote controlled 7-meter telescope at Jodrell Bank, we obtained data for 21-cm hydrogen line emissions through numerous lines of sight in the Milky Way (varying galactic longitude). Using this data, we can find the velocity of the gas at the point of closest approach to the galactic centre (GC) along any given line of sight (LOS). Plotting the velocity of H1 against its distance from the GC yielded a rotation curve, which showed that dynamics of the galaxy are roughly soft-body until 3.5kpc with a bulge mass of $3.8 \pm 0.5 \times 10^{10} \mathrm{M}_{\odot}$ and then flat ($V = V_0 = 237 \pm 7 \mathrm{kms}^{-1}$), hence suggesting that there is more matter than is visible, and pointing to the existence of dark-matter.

1 Introduction

The 21-cm hydrogen line is a frequency of light seen by a change in energy state on neutral hydrogen atoms. It is exceptionally rare but due to the amount of hydrogen in the galaxy, it can be seen from earth. The 21-cm hydrogen line has a known frequency [1] and wavelength[1] meaning the speed of H1 in the galaxy can be determined by its widened profile due to Doppler shift. Radio waves can travel nearly unhindered through the galaxy, meaning that any emission taken down a given LOS will be of all gas in that direction. This experiment aims to take numerous H1 measurements along lines of sight with galactic longitude $l < 90$ and constructing a rotation curve of the galaxy for radii less than or equal to the solar distance to the GC.

2 Theory

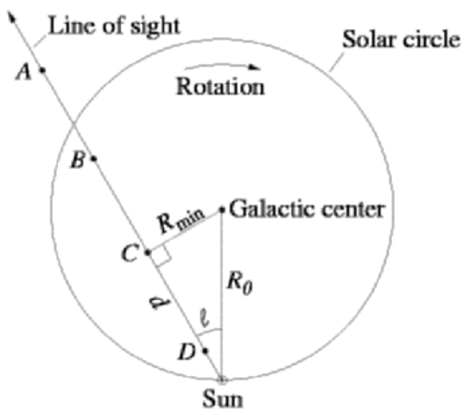

Figure 1: This diagram displays the geometry of the galaxy. Image courtesy of [2]. This diagram uses d as the distance between the point C and the sun, whereas this report refers to d as the distance from the GC to the gas. (R_{min} on this image).

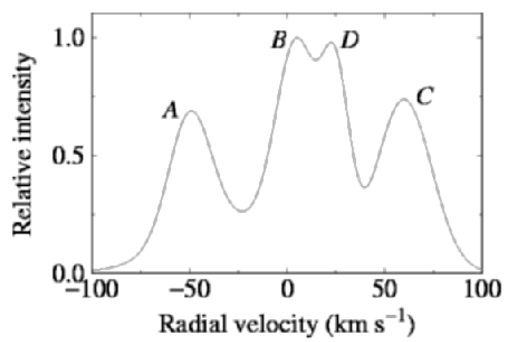

Figure 2: This figure shows an example of what telescope data from a LOS shown in figure 1 might look like. Image courtesy of [2].

The exact origins of the hydrogen spin-flip transition comes from quantum-mechanics, and a complete explaination is beyond the scope of this lab report. Spin is a property of both the proton and electron in neutral hydrogen, and between the two particles they can have parallel or anti-parallel spin. The preferred state (lower energy) is when the spins are anti-parallel, and reaching this state from the other emits a photon of wavelength 21.106cm. The excited state of neutral hydrogen (higher energy) has a lifetime of around 10 million years [3]. The frequency of the photons from the spin-flip transition falls in the range of radio in the electromagnetic spectrum; radio waves can very easily pass through not only the plentiful amounts of dust in the

[1] hence its name.

galaxy itself but the atmosphere of earth too, allowing us to take useful measurements from the ground with radio telescopes.

Looking down any LOS towards the centre of the galaxy in the radio region will show light from every neurtral hydrogen cloud that that LOS passes through. Due to the geometry of the solar system, we know that the fastest observed gas is gas moving entirely towards or away from us, meaning that all of the velocity we measure is a portion of its orbital velocity at a tangent to the GC. This can be seen in figure 1 as point C. To find the tangential velocity of the cloud, the equation

$$V_{T/GC} = V_{obs} + V_{sun} \sin l \tag{1}$$

can be used, where $V_{T/GC}$ is the velocity of the gas tangential to the GC, V_{obs} is the observed velocity from the telescope, V_{sun} is $V_0 = 220\text{kms}^{-1}$ and l is the azimuthal angle from the GC. The distance d from the GC can be found using the equation

$$d = R_0 \sin l \tag{2}$$

where $R_0 = 7.6\text{kpc}$ and l is defined as before.

Plotting $V_{T/GC}$ against d gives a type of graph known as a 'rotation curve'. We would expect the rotation of matter around the centre of the galaxy to act solid body up to a certain point[2], showing a straight line with positive gradient from the origin, $d = 0$. After this point, we expect the rotation curve to act Keplarian if we assume that most of the mass is in the centre. Luminous[3] observations show that matter traces a $\frac{1}{\sqrt{r}}$ relationship, which is similar to Keplarian motion in terms of its rotation curve representation.

A flat rotation curve is when tangential velocity remains constant regardless of the distance from the GC and would not be the expected result based on the visible/luminous matter within the Milky Way. Galaxies that exhibit a flat rotation curve can only be explained to do so if we propose the existence of matter which cannot be seen (dark matter) [4] or if we assume that Newton's laws of physics need to be altered on galactic scale (MOND).

3 Experimental approach

The most important part of this experiment is the usage of the JBiO 7m telescope dish at Jodrell Bank. It can be accessed remotely through a website we have been given special access to, and presents its data in an easy to manipulate way, as shown in figure 3. Our first step was to make a large number of observations along multiple lines of sight between $0 < l \leq 90$ degrees. In total we took data from 20 different lines, and decided to take them more frequently closer to $l = 0$,

[2]This is because as distance increases, the amount of matter within the orbital circle also increases.

[3]An important difference.

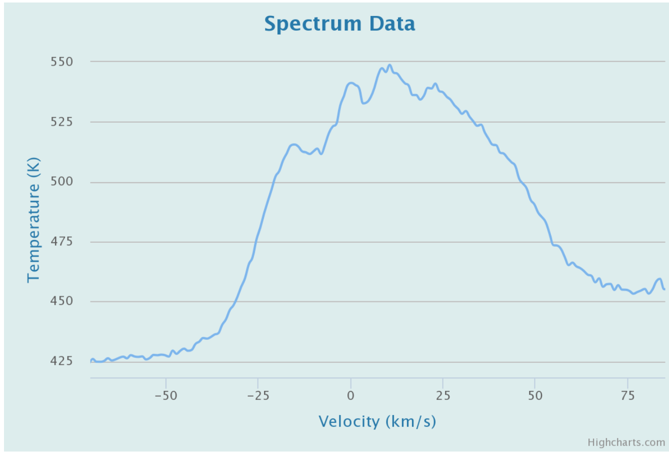

Figure 3: An example of the data taken along one LOS by the Jodrell 7m dish.

as this is where a small change in angle meant a more significant change in observed velocity.

Making observations using the scope proved difficult to some capacity. The telescope can only be observing one point in the sky at a given time. Therefore, as a single LOS observation took anywhere from 10 to 20 minutes depending on the start orientation of the dish, having enough time on the dish in our allocated slots was a challenge. Luckily, previous observations are saved in the telescope's archive and can be accessed, so for missing data points when the telescope was unavailable for use we used the most recent observations along the lines of sight we had intended to point the telescope at.

Upon collecting all the raw data, we used a Python program to process it into the form presented in the following section, making use of the equations in section 2. In order to find values for the mass of the GC and the velocity of the flat portion of the rotation curve, we plotted straight lines and fitted our parameters such that we minimised the value of χ^2. This method easily gives a velocity for a flat rotation curve but to retrieve the mass within a certain radius we must use the equation

$$\text{gradient} = \sqrt{\frac{4\pi}{3}\rho_0 G} \tag{3}$$

$$\rho_0 = \frac{3}{4\pi G}\text{gradient}^2 \tag{4}$$

where ρ_0 is the density (which we assume to be constant within the central bulge) which we can then use in

$$M_{bulge} = \frac{4\pi}{3}r^3\rho_0 \tag{5}$$

where r is the radius to which the solid-body rotation appears to act until.

Figure 3 shows an example of the data given for a single LOS. To find the velocity of the gas along this LOS, we picked the highest velocity on the data which had a temperature greater than the background noise, of which a decent amount had already been removed by the interface of the telescope. This reveals a mistake that we made in taking data for this experiment. While we should have been taking the data from the fastest peak of the hydrogen (i.e. the velocity at point C in figure 1), we were actually taking data from the fastest hydrogen overall, which is not a good estimate for the overall velocity at the point and therefore will have introduced some unnecessary error on the final result.

To calculate the error on the distance for each of the lines, the general formula

$$\Delta y = \frac{\mathrm{d}y}{\mathrm{d}x}\Delta x \tag{6}$$

was applied to equation 2 from to obtain a final uncertainty on the distance to each gas cloud using the equation

$$\Delta d = \Delta R_0 \sin l \tag{7}$$

where ΔR_0 is the uncertainty on the given value of R_0, which we took to be $\Delta R_0 = 0.3\text{kpc}$

4 Results

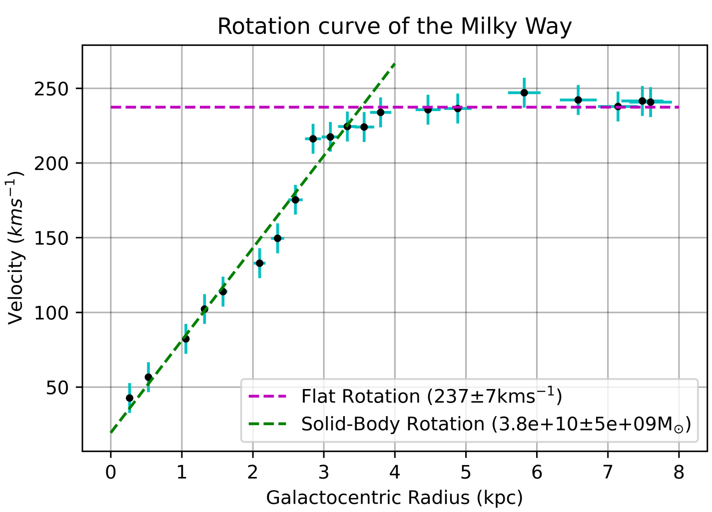

Figure 4: A graph showing solid-body and flat curve behaviour for the Milky Way on longitudes $0° < l < 90°$. Each data point is a different LOS. The data points give a $\chi^2_R = 0.70$.

Table 1 shows all the collected and processed data for a each of the 20 lines of sight we observed.

Table 1: Data collected for azimuthal angles $0 < l \leq 90$.

l (degrees)	V_{obs}(kms^{-1})	$V_{T/GC}$(kms^{-1})	d (kpc)
2	35.0	43 ± 10	0.27 ± 0.01
4	41.3	57 ± 10	0.53 ± 0.02
8	51.69	82 ± 10	1.06 ± 0.04
10	64.06	102 ± 10	1.32 ± 0.05
12	68.19	114 ± 10	1.58 ± 0.06
16	72.31	133 ± 10	2.09 ± 0.08
18	81.59	150 ± 10	2.35 ± 0.09
20	100.15	175 ± 10	2.6 ± 0.1
22	133.76	216 ± 10	2.85 ± 0.11
24	128.0	217 ± 10	3.09 ± 0.12
26	128.0	224 ± 10	3.33 ± 0.13
28	120.78	224 ± 10	3.57 ± 0.14
30	123.88	234 ± 10	3.8 ± 0.15
36	106.34	236 ± 10	4.47 ± 0.18
40	95.0	236 ± 10	4.89 ± 0.19
50	78.5	247 ± 10	5.82 ± 0.23
60	51.69	242 ± 10	6.58 ± 0.26
70	31.07	238 ± 10	7.14 ± 0.28
80	24.89	242 ± 10	7.48 ± 0.3
90	20.77	241 ± 10	7.6 ± 0.3

The constant error on $V_{T/GC}$ was based on what we thought was a reasonably degree of accuracy that we could estimate the velocities within.

Forming a rotation curve graph using the data results in figure 4. Using one/two variable fitting (fitting the first 3.5kpc of data to an upwards sloping line and the rest to a flat line) we can find a χ^2_R of 0.70, which is within the amount of statistical variation you might expect away form a perfect χ^2_R of 1, especially for an experiment with only 20 data points.

An interesting observation that can be noted from figure 4 is that different values of speed and bulge mass can be found if we are to change the assumption of which data points are part of the solid-body portion of the graph and which ones are part of the flat rotation portion. This is to say that specifically around the data points clumped between GC radii 2.6kpc and 4kpc, it is unclear which type of rotation curve they exhibit on their own. It is very obvious that they alone form a relatively flat line but in the context of the rest of the data points, they could easily be considered as part of the upwards pointing line. Depending on what is decided, the values for mass and velocity change, and so we opted to to consider half ($l = 20, 22$ in table 1)[4] of the points as part of the solid body curve, giving us a mass inside 3.5kpc (a known radius for the bulge [5]) of $3.8 \pm 0.5\mathrm{M}_\odot$.

It would have been possible to achieve a better chi^2_R value of each individual portion of the graph (solid-body or flat) by altering each of the curves individually. For instance, if our goal was to achieve a low χ^2_R on only the solid-body curve, we could consider much fewer points to be a part of the solid-body acting portion of the galaxy, as the data near perfectly forms a straight line considering only angles $0 \leq l \leq 20$. Of course, this leaves more points left to determine the velocity of the flat portion, with a visually clear decrease in certainty (i.e. the more points that make up the flat portion, the less clearly a horizontal line can be defined). In the end, picking the number of points which made up each portion was an exercise in trial and error to find the lowest value of χ^2_R that was assisted by the foresight of other experiments in the field determining the radius of the galactic bulge [5], which is often assumed to behave like a solid body.

The mass of the whole galaxy up to at least radius R_0 can be estimated with the use of the equation

$$M_{gal} = \frac{v^2 r}{G}, \tag{8}$$

where r is 7.6kpc and v is the value obtained for $V_0 = 237 \pm 7\mathrm{kms}^{-1}$. This gives $M_{gal} \approx 9.9 \times 10^{10}\mathrm{M}_\odot$, within the order of magnitude that we would expect of $10^{11}\mathrm{M}_\odot$.

An extremely obvious method to improve the quality of these results with minimal work is to take data between $270 \leq l < 360$, as this region is nearly the same as where this experiment is already looking, but the gas is on average receding rather than approaching, due to it being on a smaller orbit than the sun, and moving faster around the GC. Additionally, data could

[4] Obviously there are only 5 of these data points and so 2 were used for the solid-body portion of the graph; using 3 was considered, but gave an overall higher value for χ^2_R

be taken between $90 < l < 270$, to find values for GC radii greater than the sun's orbiting radius.

5 Conclusions

The results of this experiment show a crude but obvious flat rotation curve for the milky way, at a velocity of approximately $237 \pm 7\text{kms}^{-1}$, which is just over two standard deviations from the generally accepted value of 220kms^{-1} [6]. This overestimate of the accepted value is likely to be attributed to the overestimate of the tangential velocity from the telescope data. Using the solid-body portion of the rotation curve, we have determined that the central bulge of the galaxy has a mass of $3.8 \pm 0.5 \times 10^{10}\text{M}_{\odot}$, which is much above the value given by other papers of $\approx 1.85 \pm 0.05 \times 10^{10}\text{M}_{\odot}$ [7] due to not only the overestimates in gas velocity, but also some of the assumptions made. These include a constant density and perfectly spherical shape of the bulge. The flat portion of the rotation curve points to the existence of non-luminous matter within the milky way, as the sun travels much faster than it should for its distance from the GC.

References

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