Galactic Hydrogen

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Abstract

Hydrogen (21cm) spectral scans were taken at a range of longitudes along the galactic plane of the Milky Way Galaxy. From these spectra, velocities of hydrogen clouds were obtained to plot the rotation curve, which was the main objective of this experiment. The telescope used was the '7m' radio telescope at Jodrell Bank Observatory, Manchester, UK which was operated remotely using the JBiO website. The beamwidth - or resolution - (θ_s) of a 6.4m radio telescope was calculated using the full width at half maximum (FWHM) of temperature against sky-position scans for strong radio sources outside of the Milky Way Galaxy. The weighted mean value for different sources was calculated to be $\theta_s = 2.143^\circ \pm 0.006^\circ$. Also, the maximum power of the several strong radio sources was obtained. The best result was calculated for the Cygnus-A source, being 1450 ± 10 Jy.

1. Introduction

Radio telescopes observe objects in the radio wave region which is the most expansive region of the electromagnetic spectrum. Unlike optical telescopes, they can be operated both night and day at the sea level, because radio waves are not absorbed by the atmosphere. The '7m' telescope at Jodrell Bank Observatory, Manchester, UK (which is 6.4m in diameter) was originally built in 1970 [1] and can be operated to take power scans of strong radio sources and to obtain 21cm hydrogen spectra. This experiment involved measuring the beam width of this telescope using signals from distant radio sources and measuring the velocity of hydrogen clouds at different radial distances from the galactic centre. The rotation curve produced in the latter half of this experiment has important interpretations. For example, it implies the existence of dark matter in our universe. Since the curve produced levels off, instead of dropping with distance (expected due to Keplerian rotation) this suggests the presence of a significant mass far from the Galactic Centre, emitting no light of any wavelength but with gravitational pull strong enough to maintain the velocities of these stars [2].

2. Theory

3.1 Estimating the Beam Width of the Telescope

Telescopes produce an image which is a convolution of the signal received from a source and the response from the telescope beam. Strong distant sources can be modelled as delta functions, with infinite power at one single point and zero everywhere else. Combining this with the telescope response will give a Gaussian curve used to find the beamwidth. The actual graph plotted is of brightness temperature across the sky against the scan offset. This is because the energy of a blackbody is directly proportional to its surface temperature. Brightness temperature is the temperature a blackbody would have to produce the observed intensity of the radiation. By modelling the telescope as being surrounded by a blackbody with such brightness temperature, an antenna temperature can be defined [3]. This can be calculated from the power scans taken of some strong sources, assuming it is equal to the full width at half maximum (FWHM) of the graph plotted from the scan. The FWHM is taken as the distance between the two successive points at the y-value = ½ maximum y-value.

The actual value of the beam width is given by:

$$\theta_s = k \, \frac{\lambda}{d} \tag{1}$$

where θ_s is a beam width, λ is the wavelength of light and d is a telescope diameter. k is a constant specific to the telescope used. This is the Raleigh criterion developed by Lord Raleigh in the 19th century [4].

The formula to convert the maximum temperature from the Gaussian plots to a flux density S_v, where k, Ω_s and T are the Boltzmann constant, solid angle, and temperature of the source, respectively, is given by

$$S_v = \frac{2k\Omega_s}{\lambda^2} T. \tag{2}$$

The final equation for flux density can be obtained by substituting the expression for the solid angle into the original formula (2).

$$\Omega_s = \frac{4\theta_s}{\pi d^2} , \tag{3}$$

$$S_v = \frac{8k\theta_s}{\pi\lambda^2 d^2} . \tag{4}$$

S_v is normally measured in W m^{-2} Hz^{-1}, but for very small values, the Jansky (Jy) unit is often used. 1 Jy = 10^{-26} W m^{-2} Hz^{-1}. Using Equation 5, the conversion between 1 Kelvin and 1 Jy is calculated as 1 K = (6.90 x 10^{-4}) Jy.

3.1 Obtaining the Rotation Curve

Hydrogen emits radiation by undergoing a spin-flip transition, which has a low energy difference, so the emitted photons have a relatively long wavelength of 21 cm [5]. As a result of different relative velocities between us as an observer and hydrogen clouds along the line of sight, emitted photons experience redshift, which then results in emission spectra obtained instead of single lines at 21 cm. Based on the formula for redshift

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c} , \tag{5}$$

velocities v of the hydrogen relative to earth can be found. In equation (5), z represents the redshift, c denotes the speed of light. λ and λ_0 are observed and emitted wavelengths, respectively.

Under the assumption that all parts of the galaxy are moving at a similar velocity, the maximum velocity v_{max} some general line of sight (LOS) obtained from the spectra will correspond to the velocity of the hydrogen at the point P, shown in Figure 1. This is because, in other places on the line of sight, only some components of velocities are observed. Using simple geometry, equations for r and v can be obtained as follows,

$$r = \sin L , \tag{6}$$

$$v = v_{max} + v_0 \sin L . \tag{7}$$

R_0 and r represent the distance of the Sun and point P from the galactic centre; v_0 and v are their respective radial velocities. L is the longitude of the LOS. Values for R_0 and v_0 were taken to be 7.94 ± 0.42 kpc [6] and 235 ± 20 kms$^{-1,}$ respectively [7]. The last equation takes in consideration the velocity of the Sun about the galactic centre because the hydrogen spectra give the relative velocities only, while the actual velocity of the gas at point P needed to obtain the rotation curve.

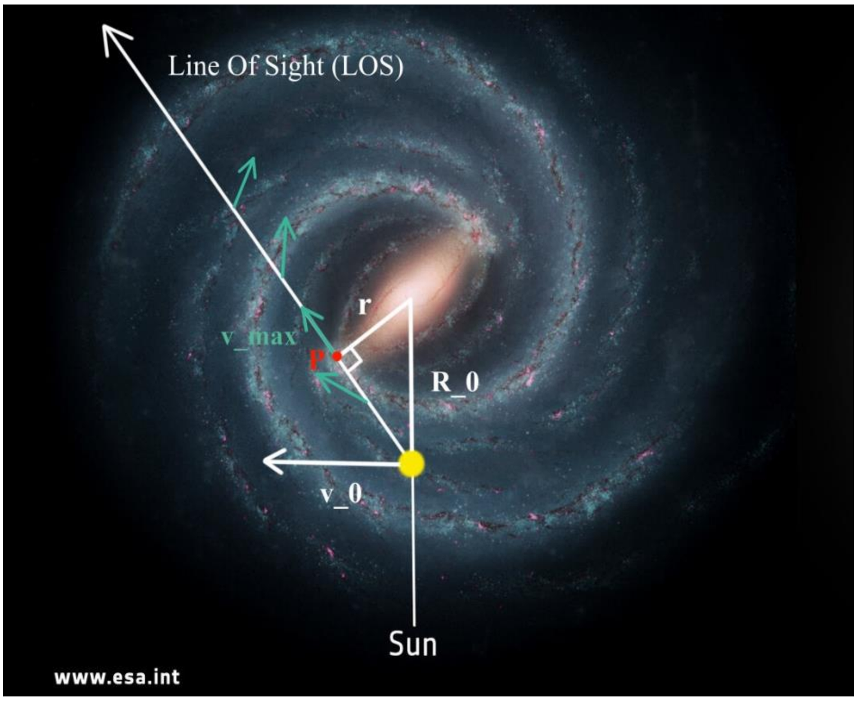

Figure 1: The diagram of our galaxy with the specific line of sight seen from the Solar System and used to relate the velocities obtained from the hydrogen spectra to the quantities needed for the rotation curve. A specific line of site is chosen as an example [Adapted from reference [8] with additional original modifications].

One more critical consideration is the correction to the Local Standard of Rest (LSR). All velocities should be adjusted so that the hydrogen is at rest in the close surroundings on the Solar System. This can be achieved by subtracting the dot product on the LOS vector dotted with the vectorially added Earth's and Sun's velocities relative to the LSR from the velocities given by analysing the spectra.

3. Experimental approach

Using the Jodrell Bank Internet Observatory (JBiO) website, we scheduled radio source scans at specific times to obtain the resolution of the telescope used. First, the 'Source Track' feature was used to check when the best times were for observing specific sources. After the scan completed, data for brightness temperature and scan offset from the chosen source position was acquired. The background level was subtracted automatically. A Gaussian curve for the data on the theoretical beam profile was then fitted to the data. Parameters of the fit gave the values for FWHM and maximum value for each source. Maxima values were then converted to Jansky as described in section 1 to compare with the known values for the specific sources. Standard deviation of the fitted curve was also considered as an uncertainty in the further calculation of the velocity and position of the hydrogen clouds.

The rotation curve, which is a plot of velocities of different parts of the galaxy against their distances from the galactic centre, was created using a similar procedure. The velocities were obtained by taking emission spectra of the neutral hydrogen in the interstellar gas of the Milky Way. A software of the telescope was automatically making the calculations for the redshift and correcting for the LSR. Output data as the set of velocities and their corresponding intensities at the chosen LOS, which was then plotted with the velocities on the horizontal axis. The rightmost velocity was determined to be the value of v_{max} for each of the spectra produced. The maximum velocity with its uncertainty was judged by eye. Only the longitudes in a range of 0 to 90 degrees on the galactic plate (latitude of 0) were chosen to be examined due to the limitations of the theory used in the analysis.

4. Results

One of the power scans obtained for Taurus A is shown in Figure 3.

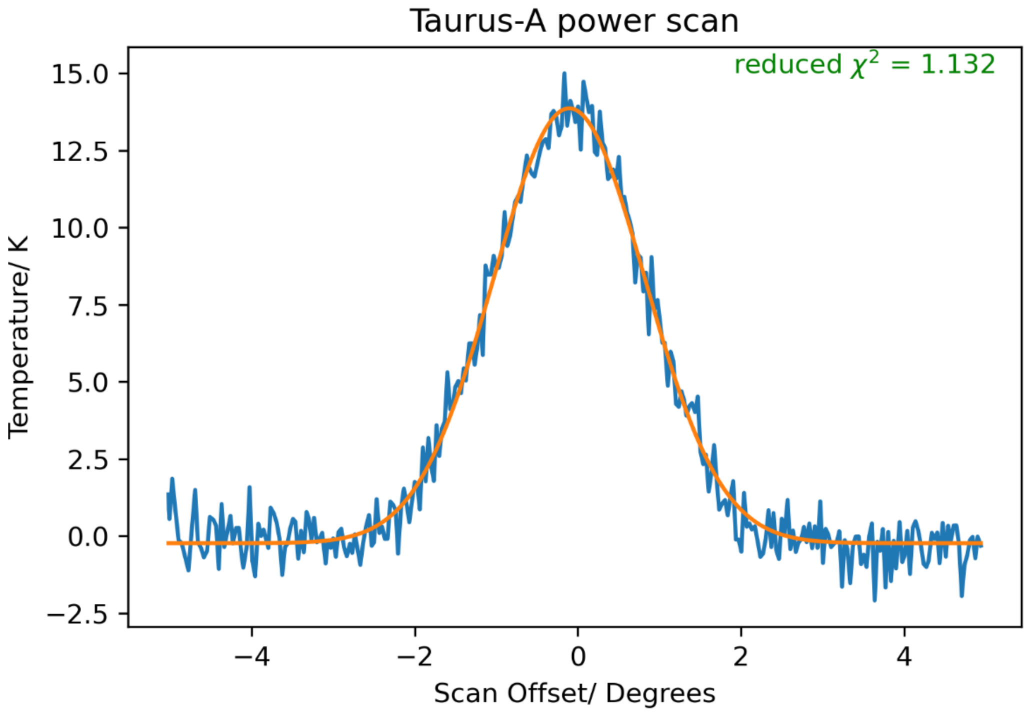

Figure 2: Power scan of the strong radio source Taurus-A. Gaussian curve was fitted with a χ_R^2 = 1.13. FWHM has a value of 2.19° ± 0.02°.

A total of four power scans were taken, and the values on each together with their associated uncertainties were combined in a weighted mean. Uncertainties for each value were propagated from an uncertainty in standard deviation parameter of gaussian, obtained from the covariance matrix of each fit. Mean beamwidth represented by FWHM was calculated to be 2.143° ± 0.006°. The coefficient for the beamwidth formula was found to be 1.14 ± 0.03. The coefficient is unique for different telescopes so that no comparison can be made with previous work.

The maximum power results for each of the sources studied are presented in Table 1.

Source	Maximum Power/ Jy
Cygnus-A	1450 ± 10
Taurus-A	1030 ± 10
Virgo-A	330 ± 10
Cassiopeia-A	2120 ± 30

Table 1: Maximum power values for each of the examined sources with their respective uncertainties in the units of Jansky.

Values calculated are not consistent with the previously known results within the suggested uncertainty [9] and are generally lower than expected, except for Virgo-A which had the noisiest curve. The unknown systematic uncertainty related to how measurements are taken and processed in the telescope is most likely to have a major effect. It should be considered first to improve the results.

The rotation curve obtained by using the hydrogen spectra is presented in figure 4.

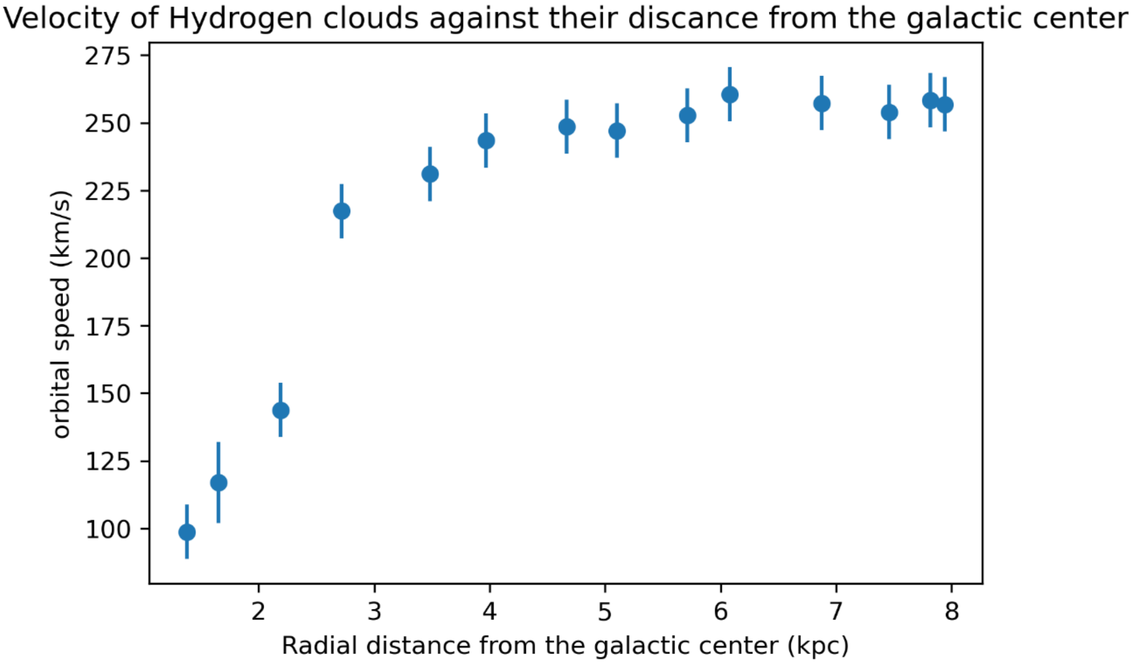

Figure 3: Plot of orbital speeds of different parts of the Milky Way about the galactic centre against their distance from it. This is known as the rotation curve of the galaxy.

The rotation curve showed constant velocities in the region of $(3 < r < 8)$ kpc within the error bars, which fits the assumption stated in section 3. Closer to the galactic centre, obtained velocities are much smaller, so this region should be investigated without assuming constant velocities. The main contributors for the uncertainty for this plot were uncertainties in the Sun's velocity and position. However, these errors, together with a beamwidth obtained for the telescope contributing to the uncertainty in the longitude, are all systematic errors. They would only affect the vertical or horizontal shift of the plot, but not the general pattern which we are interested in. The only random error associated with the uncertainty for the maximum velocity of the hydrogen obtained from the spectra was estimated to be in a range of 10-15 kms-1 and shown in error bars in Figure 4. Our rotation curve is compatible with the previously known data in terms of velocities being similar for the region between 3 kpc and 8 kpc. Although the average velocities in that region obtained are generally bigger than previously known by about 40 kms-1 [10]. This could be due to the large systematic uncertainty in the value for the velocity of the Sun, but it is still not sufficient to cover the difference. It is then suggested again that there could be another significant source of systematic uncertainty in the procedure of taking the velocity data. Also, the uncertainties on the velocities might be underestimated, considering that normally big uncertainties occur in most of the astrophysical experiments.

5. Conclusions

One of the best values of the maximum power was obtained for the Cygnus-A source, which was 1450 ± 10 Jy. The rotation curve obtained with this experiment showed constant velocities except close to the galactic centre. This result fits a previously known curve [10] with a deviation of the value of the velocity due to significant systematic uncertainty in a key parameter, namely the radial velocity of the Sun, and possibly some unknown additional error. The beamwidth of the telescope used to take the hydrogen spectra has a value of $2.143^\circ \pm 0.006^\circ$. Velocities of parts of the galaxy with a radial distance $r < 3$ kpc cannot be claimed to be certain under the assumption used in the calculations and should be investigated further. The suggested improvement is fitting the hydrogen spectra computationally in a similar pattern as was done for the power scans. This would result in more definite values for velocities in the rotation curve.

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