Investigating the mass distribution and dynamics of M31 using 21-cm neutral hydrogen emission

Neil Power
Department of Physics and Astronomy, University of Manchester (10623021)
Experiment performed in collaboration with Oliver Smedt (10742907)
(Dated: May 5, 2023)

21-cm emission spectra obtained using the Lovell telescope were used to estimate the total mass of neutral hydrogen in the M31 galaxy. Data from 57 spectra were sampled across the span of the galaxy and corrected to remove background and local hydrogen emission. A neutral hydrogen mass of $(3.1 \pm 0.1)\times10^9$ solar masses was found by integrating over these spectra. The distribution of neutral hydrogen throughout M31 was investigated, and the mass and velocity distributions found. The total mass of M31 was estimated to be $(6.7 \pm 1.2)\times10^{11}$ solar masses. The M31 galaxy is therefore $(0.5 \pm 0.1)\%$ neutral hydrogen by mass.

I. INTRODUCTION

First observed in 1951 by Harold Ewen and Edward Purcell at Harvard University, the 21-cm spectral emission line results from the 'spin-flip' transition of hydrogen [1]. These 21-cm radio waves can penetrate dust clouds and most other obstacles, and so can be clearly observed by radio telescopes. This 'spin-flip' transition is rare, but the large masses of hydrogen in galaxies mean the emission is easily observable. This experiment uses 21-cm observations from the Lovell telescope of the Messier-31 ('Andromeda') galaxy.

II. THEORETICAL BACKGROUND

A. Radio Astronomy

Radio telescopes measure signal as a system noise temperature in Kelvin. As well as signal from the source, there is noise from the neighbouring sky, noise from ground-based interference, and noise from the electrical components of the telescope itself [2]. Methods such as frequency switching (taking two measurements a small frequency difference apart and subtracting the two measurements) are used to reduce background and noise. The final result consists of a system noise temperature from the observed source, with a small background baseline. The 21-cm peak will be redshifted depending on the velocity of the part of M31 measured, and the thermal motion of the hydrogen gas will broaden the signal.

Due to its size and weight, the Lovell telescope deforms slightly at certain elevations, affecting the collecting area and observed temperature observed

$$T(90^\circ) = T(\angle)\exp\left[0.0076(\mathrm{cosec}\,(\angle) - 1)\right] \tag{1}$$

where T(90°) is the measurement that would be obtained at the zenith, and $T(\angle)$ is the actual measurement at elevation $\angle$ [3].

B. 21-cm Hydrogen Line

The average HI column density, N_h is related to the area under a 21-cm spectral line graph by

$$N_h = 14064 \int T_B(\alpha, \delta, v)dv \tag{2}$$

where $T_B(\alpha, \delta, v)$ is the brightness temperature, measured in K, as a function of right ascension α, declination δ and velocity v. N_h has units of solar masses per kiloparsec [4].

The integral in Equation 2 is the zeroth moment,

$$\mu_0 = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} T_b \Delta v \tag{3}$$

where I_i is the intensity of channel i, which has frequency width $\Delta\nu$ and brightness temperature T_b [5].

C. Galactic Dynamics

To investigate the dynamics of M31, the intensity weighted mean velocity of the neutral hydrogen can be calculated using the first moment [5],

$$\mu_1 = \frac{\sum_{i=1}^{n} I_i v_i}{\sum_{i=1}^{n} I_i} \tag{4}$$

where v_i is the velocity of channel i.

The observed velocity $V_0(r)$ for a spiral galaxy rotating with circular velocity $V_r(r)$ is given by

$$V_0(r) = V_r(r)\sin\theta_i \cos\theta_{az} \tag{5}$$

where θ_i is the inclination angle of the galaxy and θ_{az} is the angle of the point to the semi-major axis in the plane of the galaxy [6].

Assuming a spherically symmetric galaxy, the mass $M(r)$ enclosed at a radius r can be found by

$$M(r) = \frac{v^2 r}{G} \tag{6}$$

where v is the velocity at radius r and G is the gravitational constant.

III. EXPERIMENTAL METHOD

57 different spectra were used in this experiment, sampled at values of right ascension and declination varying from (8, 39) to (12, 43.6) degrees in order to span the majority of the visible portion of M31.

A. Calibration and Correction of Spectra

Spectra taken using the Lovell telescope have a parabolic curved 'baseline' that varies from spectra to spectra, as shown in Figure 1. To remove this, signal due to emission were identified and removed, and a polynomial of degree 3-6 was fitted to the remaining background data. This polynomial was then subtracted from the spectra to leave only the actual hydrogen measurements. An elevation correction using Equation 1 was also applied.

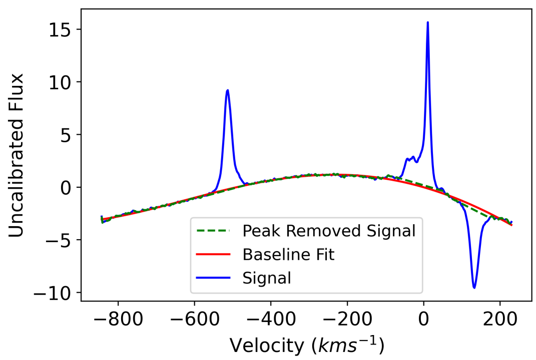

FIG. 1. This figure shows the spectra at (10, 41) degrees, with the M31 peak (left), local hydrogen peak (right, positive) and a mirror peak (right, negative). A 4th degree polynomial (red) was fitted to the background signal (green).

The units of flux calculated from the spectra are arbitrary. For flux in Kelvin, the S8 supernova remnant (with total flux of 850 K kms^{-1} [7]) was used to find a scale factor of 0.65 $\pm$ 0.01 to apply to the M31 spectra.

Finally, the data still contains local hydrogen from the Milky Way and other sources. For most spectra, the local hydrogen at approximately 0 kms^{-1} is clearly distinct from the redshifted M31 emission, whereas for others the peaks overlap. The size and shape of the local hydrogen emission peak was found by averaging the values in the local peak range (0 to 50 kms^{-1}) for spectra with no peak overlap. This average peak could then be subtracted from all of the spectra to leave only M31 emission.

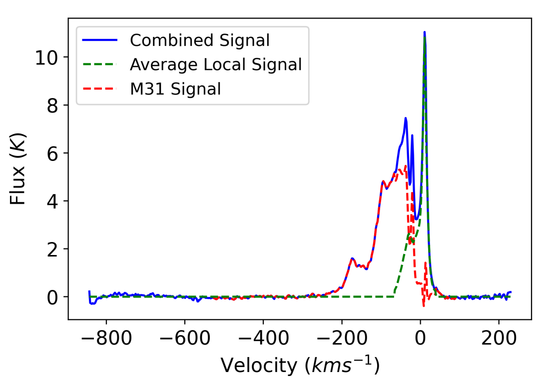

FIG. 2. This figure shows the corrected spectra (blue) at (11, 41.6) degrees, where the M31 and local hydrogen peaks overlap. The average local hydrogen peak is plotted (green), and subtracted to show the purely M31 signal (red).

Equation 3 was then used to integrate over each spectrum, and then Equation 2 used to calculate the density of neutral hydrogen. M31 was divided into 57 rectangles of equal area, each centred at the position of an observation. These were multiplied by their densities to find the total neutral hydrogen mass of M31. This is a slight underestimate as the edges of M31 may be neglected, but most mass will be located centrally.

B. Calculating velocity and mass distribution

Equation 4 was used to calculate observed velocities for each spectra. for each spectra. Velocities relative to the centre were found by subtracting the central bulk motion of M31, 290 $\pm$ 5 kms^{-1}. Equation 5 was then used to convert from radial speed to orbital speed. The inclination angle, i, was calculated using the ratio of the semi-major and semi-minor axes found from the mass contour plot. The galaxy was deprojected using a rotation matrix of i and α (where α is the angle of the semi-major axis to the right ascension axis). With the basis axes changed to the semi-major and semi-minor axes in units of kiloparsec, the radius and θ of a point could be calculated with simple geometry of a circle.

IV. EXPERIMENTAL RESULTS & DISCUSSION

A. Neutral hydrogen content of M31

The neutral hydrogen content of M31 was found to be (3.1 $\pm$ 0.1)$\times 10^9$ solar masses, less than a DRAO array study that found 4.7 $\times 10^9$ solar masses [6]. Noise left after the baseline subtraction contributed a random error, estimated by integrating over the areas with no signal, typically of order 1%. The systematic error introduced when subtracting the average local hydrogen was estimated by integrating over the local peak on spectra with no overlap, also of order 1%. A distance to M31 of (752 $\pm$ 27) kpc [8] was used, and these errors combined for the final value. Using the individual densities of each of the 57 spectra, Figure 3 shows the density of neutral hydrogen measured throughout M31.

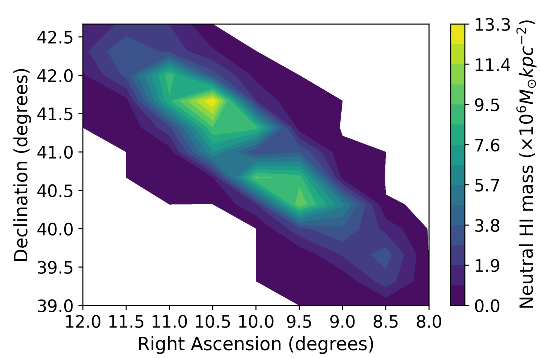

FIG. 3. This figure shows a contour of the neutral hydrogen column density across M31 from the observed spectra, where densities decreasing radially from the centre.

Some data artefacts were initially visible, for example where the baseline had been over-subtracted giving a negative total flux. These spectra were then corrected, usually by changing the width of the signal areas excluded when fitting the baseline polynomial. As expected, the areas with highest neutral hydrogen density are located in the centre of the galaxy, where the majority of the galaxy's mass is located. There is an area of lower hydrogen density at the very centre of the galaxy - possibly a result of the hydrogen there being used up for star formation.

B. Dynamics of M31

Taking the measured orbital velocities and plotting them against their distance to the galactic centre produces the rotation curve shown in Figure 4. These are several areas at the edge of the galaxy where very little flux is measured, leading disproportionately high or low velocities from purely noise. The sources of uncertainty for the mass density were combined with the uncertainties in i and α, both calculated from the uncertainty in determining the major and minor axis from Figure 3. The curve features a sharp initial rise followed by a gentle plateau. This differs from a theoretical Keplerian rotation curve [5], which predicts a sharp initial rise then more gradual decline to the edge of the galaxy.

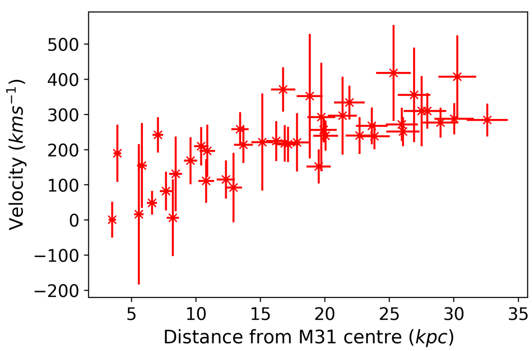

FIG. 4. This figure shows the orbital velocity of hydrogen in M31 at increasing radii. Several >1000kms^{-1} outliers from edge regions of the galaxy were removed.

The mass curve is shown in Figure 5. An overall trend of mass scaling with distance is seen. Figure 5 shows a continual increase in enclosed mass, corresponding to the plateauing velocity in 4, even beyond the visible mass limit of 25 kpc [6], indicating that more mass than the visible mass is present. This curve can be used to estimate the total mass of M31, by taking the enclosed mass value at the furthest point measured. This was found to be $(6.7 \pm 1.2)\times10^{11}$ solar masses at a distance of (32.5 ± 2.8) kpc from the galactic centre. A 2009 DRAO study using the same method found a total mass of the same order of magnitude, with $(4.7 \pm 0.5)\times10^{11}$ solar masses at 38 kpc [6].

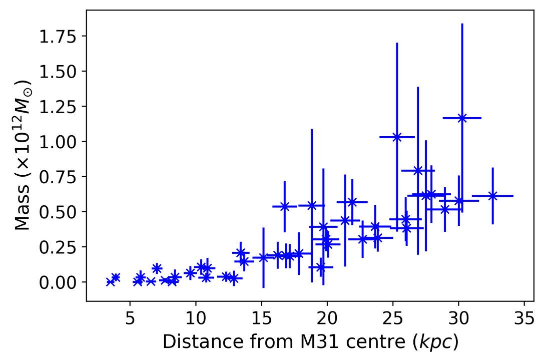

FIG. 5. This figure shows the enclosed mass calculated from rotational velocity at increasing radii.

V. CONCLUSION

By measuring 21-cm hydrogen spectra taken at intervals across the M31 galaxy, the neutral hydrogen content of M31 was found to be $(3.1 \pm 0.1)\times10^9$ solar masses. A contour plot of the mass density distribution was produced, clearly showing the shape of the galaxy. The velocity and mass curves deviated from the expected curves for visible mass, indicating the presence of non-luminous matter contributing to the mass of M31 beyond 25 kpc. The total mass at (32.5 ± 2.8) kpc was estimated to be $(6.7 \pm 1.2)\times10^{11}$ solar masses, and therefore M31 is (0.5 ± 0.1) % neutral hydrogen by mass.

[1] K. Stephan, How Ewen and Purcell discovered the 21-cm interstellar hydrogen line, IEEE Antennas and Propagation Magazine (1999).
[2] F. G.-S. Bernard Burke, *An Introduction to Radio Astronomy* (Cambridge University Press, 2009).
[3] R. Davies, L. Staveley-Smith, and J. Murray, Neutral hydrogen observations of southern galaxies, Royal Astronomical Society (1989).
[4] J. Condon and S. Ransom, *Essential Radio Astronomy* (Princeton University Press, 2016).
[5] Y. Sofue and V. Rubin, Rotation Curves of Spiral Galaxies, Annual Review of Astronomy and Astrophysics (2001).
[6] L. Chemin, C. Carignan, and T. Foster, HI kinematics and dynamics of M31, American Astronomical Society (2009).
[7] P. Kalberla, U. Mebold, and K. Reif, Brightness temperature calibration for 21-cm line observations, Astronomy and Astrophysics (1982).
[8] A. Riess, J. Fliri, and D. Valls-Gabaud, Cepheid Period-Luminosity Relations in the Near-infrared and the Distance to M31 from the HST Wide Field Camera 3, American Physical Journal (2012).