NEUTRAL HYDROGEN AND DYNAMICAL MASS OF M31

William Cooper
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School of Physics and Astronomy,
University of Manchester
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The analysis of neutral hydrogen spectra obtained from a grid of positions across the M31 galaxy was used to calculate the mass of neutral hydrogen and the dynamical mass of M31, $(3.00 \pm 0.31)\times10^9 M_\odot$ and $(6.91 \pm 2.1)\times10^{11} M_\odot$ respectively. The zeroth moments of the spectra were used to evaluate the mass of neutral hydrogen, and the dynamical mass was calculated by plotting a rotation curve of M31 using the Doppler shift from the neutral hydrogen emission. The rotational curve produced can also validate the existence of dark matter.

I. INTRODUCTION

This paper is concerned with the neutral and dynamical mass of M31 and the method used to estimate these values. The HI 21cm emission line spectra were obtained in 1990, over three days, by the Lovell Radio Telescope at Jodrell Bank Observatory.

M31 or Messier 31 is also known as the Andromeda galaxy, the closest galaxy to the milky way at 780 ± 40 kiloparsecs (kpc) away[2]. It is a spiral galaxy with twice as many stars as the milky way, and in this experiment, we investigate the dynamics of the galaxy and calculate the area of M31.

Spectra analysis was done using the software package DRAWSPEC. This program allowed each individual spectra to be calibrated and corrected, for example, removing non-linear baseline, gain elevation and brightness temperature calibration. Then collectively, create zeroth and first-moment contour maps.

II. THEORY

Neutral hydrogen is found in the interstellar medium of a galaxy and emits energy at a wavelength of 21cm due to the spin-flip transition. This wavelength is not in the visible spectrum and can only be observed via radio observations which we have only had equipment precise enough to measure for the last 70 years[1]. A neutral hydrogen atom is an electron and a proton, so the mass can be assumed to be the dominant mass of the proton. Neutral hydrogen is used because it is not absorbed or strongly scattered by interstellar medium[5].

DRAWSPEC can calculate the nth moments for each spectra automatically. The intensity-weighted zeroth moment is effectively the line integral of the spectra to get the area under the M31 neutral hydrogen peak, alternatively known as the total flux. The first moment is the integral weighted by the velocity.

When the zeroth moment (total flux) of each spectra has been calculated, it can be further used to create a contour map of flux as a function of position in right ascension and declination. Zeroth moment(μ_o) equation:

$$\mu_o = \sum_{i=0}^{n} I_i, \tag{1}$$

$$I_i = T_b \Delta v. \tag{2}$$

I_i is the intensity within channel i, which has a channel width of Δv(km/s), and T_b is the brightness temperature(Kelvin). The zeroth moment is the sum of intensity over all n channels.

The M31 hydrogen peaks are approximately Gaussian, thus a moments analysis can be useful to find the Doppler shifted velocity centroid. The first moment(μ_1) or intensity weighted mean velocity is given by:

$$\mu_1 = \frac{\sum_{i=0}^{n} I_i v_i}{\sum_{i=0}^{n} I_i}, \tag{3}$$

where v_i is the velocity of the n^{th} channel and I_i is the same as equation (2).

The column density is in the units of atoms per cm squared; in this experiment, the number of hydrogen atoms per cm squared.

$$N_h(\alpha, \delta) = 3.848 \times 10^1 4 \int T_b(\alpha, \delta, v)\Delta v. \tag{4}$$

N_h is the column density along the direction right ascension(α) and declination (δ). T_b is brightness temperature(kelvin) and v is the frequency (Hz). The mean zeroth moment, equation (1), is used to calculate the brightness temperature.

The area of M31 from the line of sight of the telescope is used to multiply with the column density to get the total number of neutral hydrogen atoms observed from M31. One spectra is a part of a set of 57 that make up the shape of the M31. Each spectra is a 'box' that has a width in right ascension units and a height in declination, as shown in figure 1. These can be converted to radians and further into units of kilo parsecs using:

$$X_{\alpha/\delta} = \theta D, \tag{5}$$

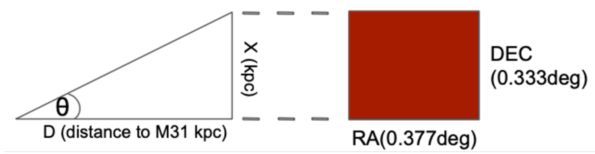

FIG. 1. Diagram of the method to calculate area, the spectra (orange box) is from the zeroth moment contour map in figure 3(a).

where X is the width/height in kpc, θ is the angle subtending the spectra, and D is the distance to M31. Small angle approximation is used. Height $\times$ width gives the area of one spectra box. Multiply by 57 to get the total area of M31. Note M31 has an average declination of 41^o from the equator; therefore, this had to be taken into consideration, and the right ascension was multiplied by $cos(41)$.

Using Kepler's third law and assuming the galaxy is circular, an equation for the total dynamical mass of M31 (M_{M31}) can be constructed:

$$M_{M31} = \frac{v_{edge}^2 r_{M31}}{G}, \tag{6}$$

where v_{edge}^2 is the velocity at the edge of the galaxy at the radius r_{M31} and G is the gravitational constant $= 6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$. The velocity at the edge is the velocity at the radius, as we want the mass inside the radius of the galaxy, which is the total mass. The edge velocity is a circular velocity, not the observed velocity directly from the spectra. This had to be deprojected into the plane of the galaxy to get the true circular velocity using the equation:

$$v(r) = \frac{v_o(r)}{sin(i)cos(\theta)}, \tag{7}$$

where $v(r)$ is circular velocity, v_o is the observed velocity, i is the inclination angle of the galaxy (75.5^o), and θ is the azimuthal angle, the angle subtended for each spectra from the major axis of M31. The observed velocity is the Doppler shift of the HI emission line from the galaxy.

III. EXPERIMENTAL METHOD AND RESULTS

Each of the 57 spectra had an explicit non-linear baseline with a reoccurring local hydrogen peak from the milky way, and the Doppler shifted M31 hydrogen peaks which ranged from zero to two peaks. Spectra have velocity(km/s) on the x-axis, and the centre of the local hydrogen peak is 0km/s relative to Earth. The y-axis at first is an arbitrary unit of flux. This can be seen in figure 2(a).

By placing three boxes on the baseline trend, the area without peaks, a polynomial could be fitted in the order 1-6. The aim was to get the polynomial to fit as close to the baseline as possible, and this could be achieved by using the provided root-mean-squared(rms) values of each polynomial degree. The average degree was around 3 or 4; after this, the rms did not change significantly.

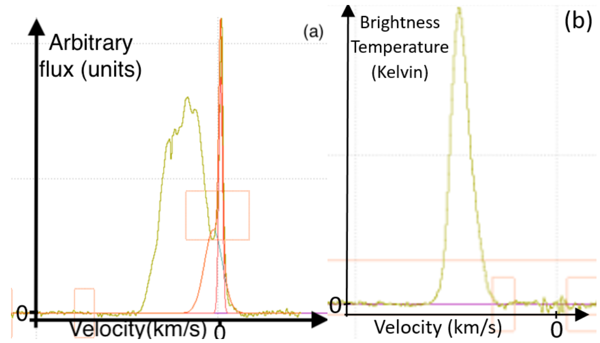

FIG. 2. Before(a) and after(b), the spectra have been calibrated for brightness temperature and corrected for the baseline and local hydrogen removal. The Doppler shift from 0km/s can be observed here.

The sensitivity of the radio telescope used is dependant on the direction of observation. This is because the telescope's dish is warped due to gravity. However, further investigation of this showed the scale factor of this effect is in the order of 10^{-3} for the observations made in this experiment and, therefore can be ignored.

As already stated, the y-axis of spectra is in arbitrary flux units. In radio astronomy, it is useful for flux to be in brightness temperature T_b as the intensity at radio wavelengths is proportional to T_b. To calibrate our data in terms of T_b, we can use a spectra with a known flux. Dividing this by the integral of the calibration peak gives the brightness temperature scale factor of 0.670, which can be applied to the y-axis, figure 2(b).

It is known that neutral hydrogen emission can be found by integrating over the spectra; however, the local hydrogen peaks are still present, and this would provide a systematic error in all values of the emission. To remove the local hydrogen peak, a Gaussian(s) can be fitted to it and then subtracted. This is done for every spectra.

Our data is now fully calibrated and corrected, figure 2(b). A contour map showing the flux as a function of position in α and δ can now be created via DRAWSPEC taking the zeroth moment of each spectra using equation (1).

The mean zeroth moment or total flux of all 57 spectra is $155.26 km/s$ calculated by DRAWSPEC. Using equation (4) and the fact a velocity channel width of 1km/s = 4.47kHz frequency channel width Δv, the column density(N_h) is calculated in units of atoms per cm squared. Using equation (5) the total area is $1.26 \times 10^{46} cm^2$. Multiplying column density by area gives the total number of neutral hydrogen atoms, multiplying this by the mass of a proton ($1.627 \times 10^{-27} kg$) and dividing by the solar mass ($1.989 \times 10^{30} kg$) produces a neutral hydrogen mass of $(3.00 \pm 0.31) \times 10^9 M_\odot$.

The individual spectra are approximately Gaussian in shape, therefore moments analysis using equation (3) gave information on the Doppler shifted centroid velocity and the velocity dispersion of each observed spectrum. This is represented in the spider diagram, figure 3(b).

The contours on the first-moment plot show areas of constant rotational velocity before it was deprojected. The spider diagram shows the different rotational velocities of points

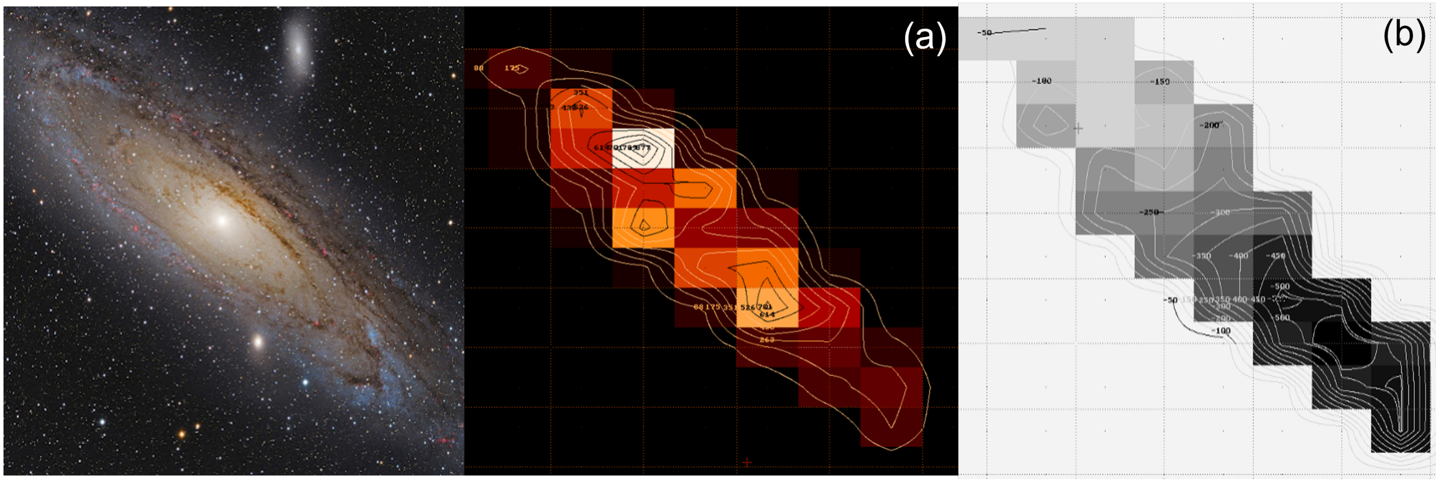

FIG. 3. Contour plots of zeroth (a) and first moment (b) of 57 HI spectra across the M31 galaxy shown in left visible light plot.

on the plane of the galaxy, with the right-most darker regions rotating towards and the left-most, lighter regions moving away from us, all relative to the bulk motion of the galaxy, which is $300km/s$ towards the milky way. This plot was used to deproject the velocity values by calculating the distances between the centre of the galaxy and then working out the azimuthal angle between two spectra. Equation (7) was then used to produce a rotation curve of M31, figure 4.

Using equation (6), the dynamical mass can be calculated $(6.91 \pm 2.1)\times 10^{11} M_{\odot}$ by reading off the values at the edge of the rotation curve. This equation assumes the galaxy is entirely circular, and that the rotation follows the model shown by the red dashed line on the rotation curve.

The data trend fits the SBR prediction for the bulk of the galaxy but does not follow the Keplerian prediction; the galaxy at the edges is spinning much greater than expected. This observation can be explained as a large distribution of dark matter throughout the galaxy which does not produce electromagnetic radiation. The gravity of this dark matter keeps the galaxy together at these rotational speeds.

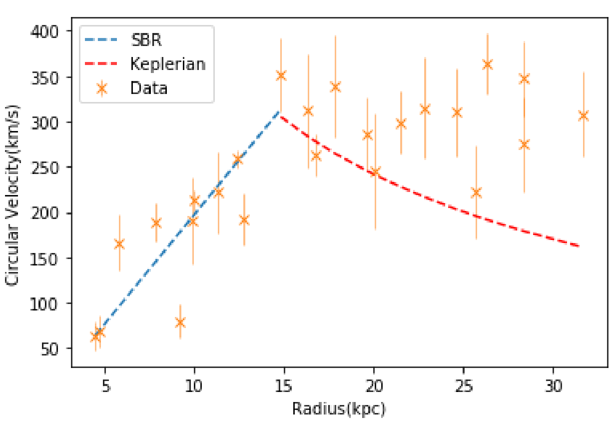

FIG. 4. Rotation curve of M31, circular velocity(km/s) vs radius(kpc) with a fit for Solid Body Rotation(SBR) and Keplerian motion as a prediction.

IV. CONCLUSION

The neutral hydrogen mass has an error of around 10 percent and is within three standard deviations of a precise study of $3.7 \times 10^{9} M_{\odot}$[4], suggesting our method produces a reasonable result. Our error for hydrogen mass was a propagation from our dominant error of the distance to M31 $(780 \pm 40kpc)$, which was propagated by quadrature in the area uncertainty.

Dynamical mass had a greater uncertainty at 30 percent, which shows an overestimation of errors. This large uncertainty stems from the uncertainty of the circular velocity, as visibly seen in figure 4 by the error bars. This circular velocity is calculated using equation (7) and contains the azimuthal angle which is derived from the main source of uncertainty yielding this large value. Our errors were combined in quadrature. Our dynamical mass is within three standard deviations of a precise study $2.2 \times 10^{11} M_{\odot}$[4]. Errors could be improved by taking more spectra between existing ones.

This data can be used as evidence that dark matter exists as the rotation flattens off at large radii contrasting the Keplerian prediction suggesting there is significantly more mass than what we can observe as Mass is proportional to velocity squared in Kepler's third law and a higher velocity is observed. If we can't observe this mass, it must not produce electromagnetic radiation, and this is known as dark matter[3].

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