Determining the mass and dynamics of H1 in the M31 galaxy

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This experiment was performed in collaboration with Ben Dodson.

Abstract

The mass of neutral hydrogen (H1) in the Andromeda galaxy and the galaxies total dynamical mass were estimated using 21-cm line spectra, emitted from interstellar gas and measured by the Lovell telescope. Hydrogen mass was calculated from integrals of the spectra peaks and the dynamical mass was obtained from a velocity curve. Uncertainty of estimating the galactic area and the radius of points within the galaxy limited the accuracy of the H1 and dynamical mass measurements respectively. We found the H1 mass to be $(1.24 \pm 0.14) \times 10^9$ M_{\odot} and the dynamical mass to be $(1.70 \pm 0.26) \times 10^{11}$ M_{\odot}.

1. Introduction

This experiment involved radio observation of the Andromeda galaxy, also known as Messier 31 (M31). It is a spiral galaxy like our own Milky Way galaxy, the largest galaxy in the local group and only 2.5 million light-years away from us [1]. Spectra of M31 were collected by the 76m Lovell telescope from Jodrell Bank. Data was then analysed using the software package DRAWSPEC.

Spectra were taken observing the 21-cm line radiating from neutral hydrogen gas within the galaxy. This radiation results from the hyperfine effect of the Hydrogen's

electron moving from a parallel to an antiparallel spin state and the subsequent energy difference between the two states. The 21-cm line is the most important line in astronomy as it is the only spectral line that can be emitted under normal interstellar conditions. Measurement of this 21-cm line then allows a calculation of the neutral hydrogen mass and also the velocities of the hydrogen atoms can be found from the Doppler shifting of the line. [2]

Indeed, probing of this unique line in the 1970's lead to large hints of galaxies matter being significantly more than directly observable, ordinary matter and the suggestion of galaxies being surrounded by a dark matter halo. Formally, beginning the study of dark matter. [3]

2. Theory

2.1. Moments analysis

DRAWSPEC has a moment's analysis tool that is useful for this experiment. In particular, use of the 0^{th} and 1^{st} order moments. The 0^{th} moment calculation is given by,

$$Mom0 = \sum T_b \Delta v, \qquad (1)$$

where T_b is the brightness temperature of a channel with velocity width Δv . Effectively, this integrates spectra over all the channels they were observed with. The 1st order moment calculation is given by,

$$Mom1 = \frac{\sum_{i} T_{b} \Delta v. v_{i}}{\sum_{i} T_{b} \Delta v},$$
(2)

where v_i is the velocity of the *i*th channel. This calculation is now weighted by velocity.

2.2. Density of H1

The probability of observing a 21-cm spin transition is related to the number of H1 atoms being observed. This means the line integral of a spectra is directly related to the H1 density by,

$$\rho = 3.848.10^{14} \int T_b df , \qquad (3)$$

where ρ is the number of H1 atoms per cm² and df is a frequency width.

2.3. Estimating galactic area

To convert this density into the number of H1 atoms an estimate of M31's galactic area must be made. Figure 1 shows the geometric setup for a single spectrum observation.



Figure 1. The circle of observation, radius r, formed by a telescope at a distance D_{M31} from the M31 galaxy and with an angular beam width, θ .

When the beam width is small, the small angle approximation can be used for the tangent function, when calculating the radius of an observation. For this experiment, 57 spectra were taken. Therefore, the total area of our observations is approximately given by,

$$A = 57A_{circle} = \frac{57}{4} \pi D_{M31}^{2} \theta^{2}, \qquad (4)$$

where D_{M31} is known to be (780 ± 40) kpc and the beam width of the Lovell telescope is 12 arcminutes.

2.4. Keplerian motion of H1 gas

As an approximation the H1 gas atoms are in Keplerian motion, this allows a centripetal force to be equated with a gravitational force and gives a limit on the dynamical mass within a radius,

$$M_r = \frac{v^2 r}{G},\tag{5}$$

where G is the gravitational constant and M_r is the dynamical mass causing a rotation at radius r of velocity v.

3. Experimental Method and Results

3.1. Cleanup and calibration of spectra

A polynomial fit was subtracted from each of the spectra to remove baseline noise and prevent a systematic zero error when performing a moment's calculation. Telescope gain elevation and subsequently the equivalent brightness temperature varies as a function of elevation given by,

$$T_{b} = T_{b}(90^{\circ})\exp(0.0076\cos ec(el) - 1), \qquad (6)$$

where *el* is the elevation of the measurement and $T_b(90^\circ)$ is a constant temperature value for 90° elevation. This function was plotted, as shown in Figure 2.



Figure 2. A plot of the percentage difference of T_b from $T_b(90^\circ)$ for a range of elevation angles.

We decided less than a percent difference was an acceptable variation and therefore all spectra under a 30° elevation were corrected by a scale factor using (6). The y-axis for all spectra was then calibrated from arbitrary flux units to a Kelvin temperature scale. This was done by comparison with two single peak spectra from our galaxy of known integral value. The local hydrogen line was then subtracted by subtraction of multiple Gaussian fits. Figure 3 shows the overall effect of this clean up and calibration on one of the spectra.



Figure 3. Spectra M31P64 in its raw form on the left and after clean up and calibration on the right. Notice the two peaks on the raw data: a peak from M31 and a local hydrogen peak around zero velocity.

3.2. H1 mass calculation

The 0th order moments analysis, given by (1), was performed on the 57 calibrated spectra. A contour plot of the HI density was made, using the moment's data, as shown in Figure 4. The plot clearly shows two regions with large amounts of HI and a lack of HI in the centre, presumably where it has been used to produce stars.



Figure 4. A contour plot of the H1 density within the M31 galaxy.

The moment's analysis gave a mean value of 163.05 K km/s. This value was then converted to a HI density using (3) and the fact that a velocity channel of 1 km/s corresponds to a frequency channel of 4.74 kHz. Multiplication of this density by the area given by (4) calculated the total number of H1 atoms. Multiplication by the proton rest mass gave a value for the total H1 mass in M31. The dominant source of error for the calculation comes from the uncertainty in the area of the galaxy as a result of uncertainty on the distance to the galaxy and there is also a smaller error from the noise fluctuation remaining on the spectra. Propagation of these errors gave a final H1 mass value of $(1.24 \pm 0.14) \times 10^9$ M_☉.

3.3. H1 dynamics

The 1st order moments analysis, given by (2), was performed on the spectra and a velocity contour plot, shown in Figure 5, was produced. The plot shows a general clockwise rotation of the galaxy as well as a central velocity of -300km/s indicating movement of the galaxy towards us. The contours show solid body rotation in the centre of the galaxy transitioning to a disk rotation at the edge. Velocities of the spectra peaks were also recorded manually, to prevent the issue of DRAWSPEC misinterpreting double peaks in its moment's calculations. A 2-D velocity plot was manually constructed, as shown in Figure 6. This is consistent with the rotation pattern shown by Figure 5.



Figure 6. A 2-D velocity field of the H1 gas within the M31 galaxy.

The observed velocity was converted to a circular velocity by the equation,

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

where *i* is the inclination of the M31 galaxy and θ is the angle from the galaxies major axis about the galaxies centre. Contour points along the major axis were recorded. The velocities were converted using (7) and subtracting the galaxies central velocity. A velocity curve was plotted, as shown in Figure 7. This also seems to follow the pattern of a solid body transitioning into a disk.



Figure 7. A velocity curve of the H1 gas within the M31 galaxy. Note the linear relation up to 10kpc and then either a dip or flattening of the curve beyond 10kpc.

Using (5) and the final point of the curve from Figure 6, a limit on the total dynamical mass of the galaxy can be calculated for a radius of 25kpc. A linear relation between the error in calculating the radius and the error in velocity has been used with an extra two percent added on for radii greater than 10kpc as this is where the linear relation clearly breaks down. This gave a dynamical mass, up to a radius of 25kpc, of $(1.70 \pm 0.26) \times 10^{11} M_{\odot}$.

4. Conclusion

The final value obtained for the total H1 mass is far from being within 3 standard deviations of high-sensitivity studies results of $(3.86 \pm 0.19) \times 10^9 M_{\odot}$ [4]. However, it is within the same order of magnitude which indicates our mass value could be acceptable as a rough estimate but it has been severely underestimated. Errors are about 10-15% of the calculated values, which seems realistic for our method of calculation. The main problem is we have only taken 57 spectra from M31 and could do with taking more spectra in the area between our circles of observation to get a more complete estimate on mass. Our area estimate has also been underestimated because no correction has been made for the gaps between our circles of observation. This could perhaps be scaled up using known values of area for the M31 galaxy.

Our H1 mass estimate can be used to estimate the total mass of ordinary matter within M31. Hydrogen is the most abundant element in the universe and constitutes about 75% of ordinary matter [5]. The mass of stars within M31 is estimated as 1.3×10^{10} M_{\odot} [6]. Adding this to our value for the mass of interstellar gas gives an ordinary mass estimate of 1.47×10^{10} M_{\odot}. Our ordinary matter estimate only accounts for 8.5% of our calculated dynamical mass. This indicates that a significant portion of the galaxy's mass is not detectable from radiation emission. Indeed, Figure 7 also supports the theory of additional matter if the curve is interpreted as flattening out. As observed luminous matter would imply a curve that dropped off with increasing radius. The curve shows a constant velocity with increasing radius, suggesting additional mass in between the measuring point and the galactic centre. These two

pieces of evidence point towards the M31 galaxy being surrounded by a spherical halo of matter that doesn't emit any radiation, commonly known as dark matter.

References

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