The mass and hydrogen content of M31

Aude Alapini

Dept. of Physics and Astronomy
The University of Manchester

Third Year Laboratory Report

Oct. 2004

This experiment was performed in collaboration with C. Janes.

Andromeda galaxy, also called either M31 or NGC224

Abstract

The neutral hydrogen mass and the total mass of M31 were calculated using spectra taken on the Lovell radio telescope at Jodrell Bank (Manchester, UK). The obtained values are $2.05.10^9$ solar masses for the mass of neutral hydrogen and $3.62.10^{11}$ solar masses for the total mass of M31. These values are lower than the amount expected. The lack of mass should come from the methods used for our calculations. The software, Drawspec, was used to calibrate and analyse the spectra. The contour map, drawn with this PC based package, shows us the presence of two spiral arms. The rotation curve, deduced from the analysis, shows that the centre of

M31 behaves like a solid body. It also gives the proof of the presence of dark matter outside this galaxy.

1. Introduction

Andromeda is a spiral galaxy part of our galaxy cluster. It is composed of a lot of different chemical elements, including neutral hydrogen which is found in the interstellar medium. This chemical element can be detected at a frequency of 1420 MHz. This frequency corresponds to the 21-cm neutral hydrogen line, formed by a transition between the two hyperfine levels of the ground state of hydrogen.

This report explains how the mass and the radial velocities of the neutral hydrogen in M31 were calculated, using a PC based package Drawspec [1]. It gives the deduced 2-D velocity field and the rotation curve of the neutral hydrogen in Andromeda. As M31 is coming toward the Milky Way, the velocities measured in this experiment are negative.

We used 59 spectra of M31, taken on the Lovell (250ft) radio telescope at Jodrell Bank.

2. Correction to the spectra

This is an example of a source spectrum (fig 1) and the corrected one (fig 2):

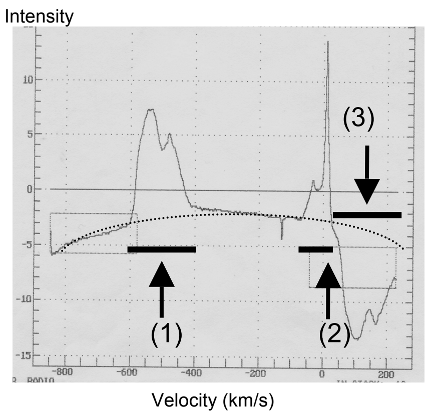

fig 1. Source spectrum [1]

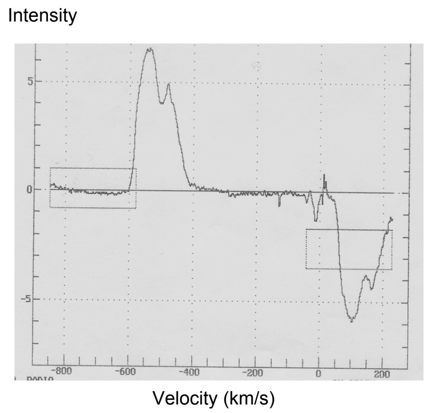

fig 2. Corrected spectrum [1]

The range (1) is the range of velocity of the neutral hydrogen in M31. The range (2) is the one of the local hydrogen (i.e. the neutral hydrogen of our galaxy in the line of sight). The range (3) is a mirror image of the signal from M31. It is a consequence of the technique of frequency switching used to improve the transmission of the signal in the electronic device.

The source spectra can’t be analysed directly and need to be corrected by different parameters first.

2.1. Baseline removal

As we can see on fig 1, the spectrum is superimposed on a non-linear baseline (curved dash line). The electronic device, used for the data acquisition, has a waveband of efficiency. The baseline is a consequence of this electronic feature.

We wanted to know the intensity of the signal from M31 for each velocity. Therefore this curved baseline was removed for each spectrum, using the polynomial fit function of Drawspec.

2.2. Gain elevation

The elevation is the angle between the pointing direction of the antenna and ground. The telescope gain ($\frac{T_b}{T_b(90)}$) depends on the elevation (*el*), according to the equation (1) where T_b is the brightness temperature.

$$T_b = T_b(90)e^{0.0076(\frac{1}{\sin(el)}-1)} \tag{1}$$

The accuracy of the radio telescope is 1%. Therefore, for a correction factor more than 0.01, we need to correct the signal. The spectra with elevation less than 20° had been multiplied by the associated value of the exponential term.
To multiply a spectrum by a number we use the “a”djust function of Drawspec.

2.3. Brightness temperature calibration

The brightness temperature that can be measured from the spectra is not really the one of the object we are looking at. Indeed, the data captured take also in account the temperature of the device (antenna, electronics …). Although our data had already been corrected with reference to the temperature of the antenna, in practice the units are arbitrary.

To correct this effect, we used a spectrum of a standard region S8, taken in the same conditions as our M31 spectra. The theoretical brightness integral of S8 is 850K.km.s^{-1}. Using a range of velocity without including the range (2) (see fig 1), the experimental brightness temperature of S8 was measured. Then each of our M31 spectra was multiplied by the correction factor of 0.661 that we found.

2.4. Removal of local hydrogen (range (2) of fig 1)

In figure 1, the hydrogen of M31 and the local hydrogen can easily be identified. Nevertheless, for some spectra, the velocity of the neutral hydrogen in M31 is so close to 0 km.s^{-1} that we can’t make the difference between the both. Therefore, if we want to integrate over all the velocities of the hydrogen in M31, we have to remove the local hydrogen.

Using the “C”ombine function of Drawspec, we subtracted to each spectrum, which contains peak(s) of hydrogen of M31, the nearest blank one (i.e. the nearest one which has only local hydrogen). The “C”ombine function adds two spectra and divides the result by two. Therefore, the resulting spectra were multiplied by two.

3. Neutral hydrogen mass in M31 (8)

For a given position (α,δ), the number of hydrogen atoms per cubic centimetre is given by the formula:

$$N_h(\alpha,\delta) = 3.848.10^{14}\int T_b(\alpha,\delta,\upsilon)d\upsilon \qquad (2)$$

υ is the frequency in Hz, α is the right ascension and δ is the declination.

The integral $\int T_b(\alpha,\delta,\upsilon)d\upsilon$ is determined by using the 0th moment (3) analysis of Drawspec.

$$mom0(\alpha,\delta) = \sum_i^n I_i(\alpha,\delta) \qquad (3)$$

I_i is the intensity of the signal for a given channel i. n is the total number of channel in the selected range (from -674 to -1.8 km.s^{-1}).

Then the $mom0$ was plotted as a function of position (α,δ) (fig 3) using the contour "@" facility of Drawspec.

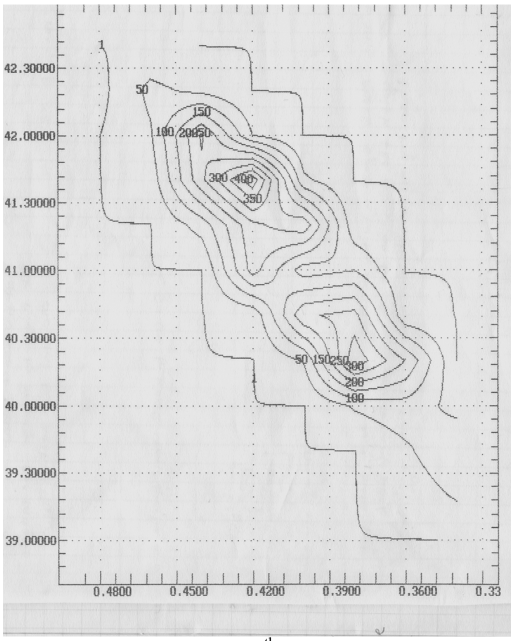

fig 3. Contour map of 0th moment analysis [1]

The total number of hydrogen atoms is given by:

$$N_h = 3.848.10^{14} \times mean \times 4.74.10^3 \times area(in\ cm) \qquad (4)$$

The *mean* value is 92.35 km.s^{-1} and it is obtained with the "I"mstat function of Drawspec using a box around the contour map.
The factor 4.74.10^3 is used to convert the km.s^{-1} in Hz.

Calculation of the *area* (6)

We should take in account that M31 is at an average declination of 41°. Therefore, $\Delta\alpha$ is equal to $\dfrac{\Delta\alpha_{box}}{\cos(41°)}$.

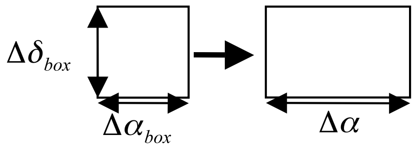

fig 4. variation of $\Delta\alpha$ with regard to the declination

$\Delta\delta_{box} = 3.66°$.
$\Delta\alpha_{box} = 0.144h = 2.16°$

To convert an angle in degrees to a distance in meters we use the formula:

$$d(in\ m) = \tan(angle(in\ °)) \times d_{MK-M31}(in\ m) \quad (5)$$

The distance to M31 (d_{MK-M31}) is equal to $690.10^3 \times 3.086.10^{16}$ m [2].

According to the figure 4,

$$area(cm^2) = \Delta\alpha(cm) \times \Delta\delta_{box}(cm) \quad (6)$$

The mass of neutral hydrogen (HI) in M31 is given by:

$$M_{HI(M31)} = N_h \times M_H \quad (7)$$

$M_H = 1.67.10^{-27} kg$.
$M_\Theta = 1.989.10^{30} kg$.

Using (7) and (4) we obtained **$M_{HI(M31)} = 2.05.10^9\ M_\Theta$** **(8)**

This value is a quarter of the $7.6.10^9\ M_\Theta$ expected [3; p337].

4. Dynamics of neutral hydrogen in M31

There are different ways to investigate the dynamics of the neutral hydrogen. The 1st moment analysis can be used. This method gives the mean velocity for each spectrum. However, sometimes there are more than one velocity component because of the inclination (i) of the plan of M31 to the line of sight. It these cases the 1st moment method has few physical meaning. Therefore, it is better to use the least squared method where each peak of the signal are fitted by a gaussian. The "g"aussian function of Drawspec gives us the value of the velocity for each peak.

Only the highest velocity component was kept for each spectrum as it is the one which is the most perpendicular to the line of sight. Then, the value of the velocity of the spectrum in the centre of M31 was subtracted to the velocity of the other spectrum. This gave us the observed velocity V_{obs} for each spectrum.

The radial velocity $V(r)$ of each spectrum is calculated according to the formula:

$$V(r) = \frac{V_{obs}}{\sin(i)\cos(\theta)} \quad (9)$$

θ is the angle between the major axis and the position of the spectrum in M31.
i is 75.5 °, calculated according to $i = \cos^{-1}(\frac{b}{a})$ (see fig 5 for the definition of a and b).

Using the values of $V(r)$, a 2-D velocity field (fig 5, each cross represent the position of a spectrum) and the rotation curve (fig 6) were built.

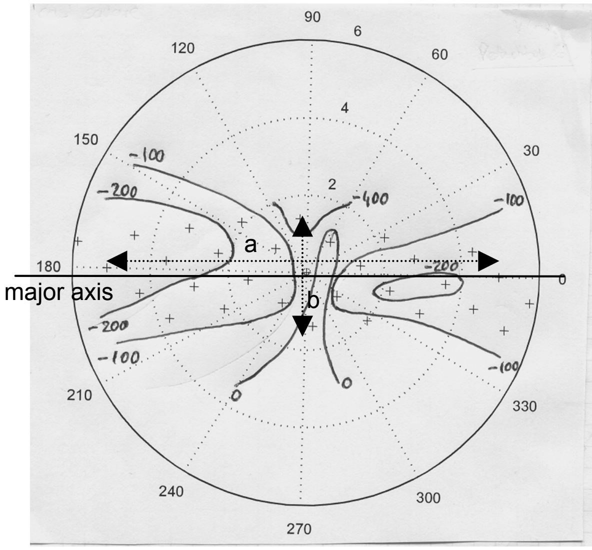

fig 5. velocity dispersion in M31 [4]

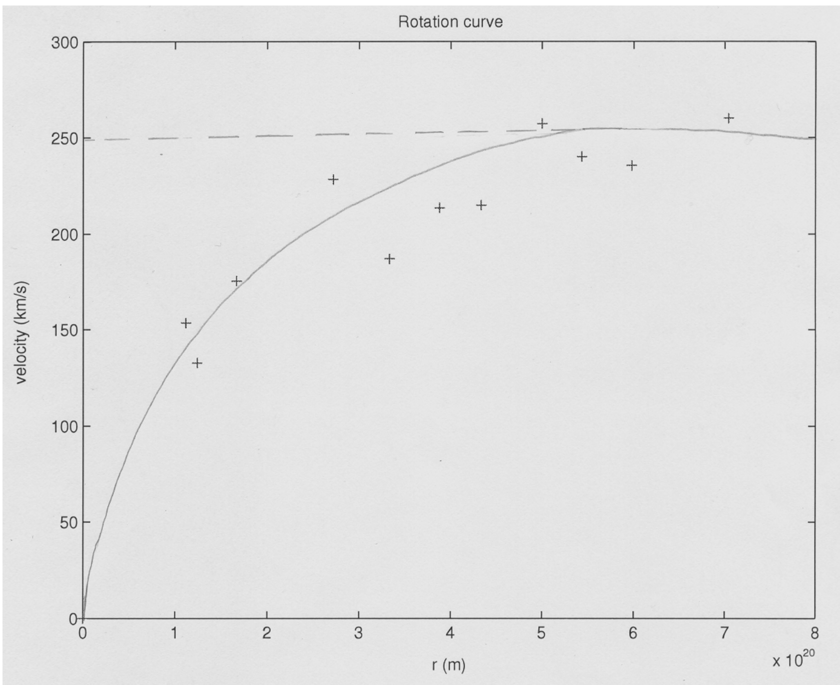

fig 6. rotation curve of M31 [4]

Assuming a Keplerian motion for the hydrogen and knowing that the gravitational force and the centrifugal force balance each other, for an object of mass *m* at the edge of M31, we can write:

$$\frac{V^2(r)\times m}{r} = \frac{G\times M_{T(M31)}\times m}{r^2} \qquad (10)$$

The gravitational constant G is equal to $6.67.10^{-11}\mathrm{m^3kg^{-1}s^{-2}}$.
Therefore, the total mass of M31 is given by:

$$M_{T(M31)} = \frac{V^2(r)\times r_{edge}}{G} \qquad (11)$$

According to fig 6, $r_{edge} = 8.10^{20}$ m and $V(r_{edge}) = 245$ km.s^{-1}.

The total mass of M31 is $\mathbf{M_{T(M31)} = 3.62.10^{11}\, M_\Theta}$ **(12)**

This is half the 7-10 x $10^{11}\, M_\Theta$ estimated by Evans *et al.* [5]**.**

According to our measurement (8), 0.57 % of the total mass of M31 is neutral hydrogen.

5. Conclusion and Discussion

The calculated mass of neutral hydrogen and the total mass of M31 are less than the values expected. The lack of mass should come from the fact that:

a) We assumed that the local hydrogen peak was not different between a spectrum and its nearest blank one. This was not exact and we were obliged to take a range of velocities until -1.8 km.s^{-1} and not until 0 km.s^{-1}, so we should have missed some mass.
b) We had data only for 59 regions of M31 but not for the whole galaxy. Therefore we used two moment analyses to investigate the whole galaxy, which had involved some approximations.

0.57 % of the total mass is neutral hydrogen. The rest of the mass is shared between all the other chemical components (i.e. ionised hydrogen, helium …). To calculate the real mass of M31 we should investigate the dynamics of the dwarf companions of M31 (see two of them on the picture of Andromeda, front page) [5].

The contour map (fig 3) represents the repartition of the mass in M31. The two regions of high amount of mass are the two spiral arms of M31.

The linear behaviour of the rotation curve (fig 6) at short distance from the centre of M31 is a feature of a solid body. Therefore the centre of M31 is a bulb which behaves like a solid body.

At long distance from the centre of the galaxy, we expect the velocity of the neutral hydrogen to drop down. Indeed according to (11), if the attractive mass ($M_{T(M31)}$) is constant and the distance to the centre increases, the radial velocity decreases. This isn't what happens. In reality, the velocity remains constant while the radial distance continues to increase. Therefore, there is additional mass even outside the galaxy itself. M31 and its dark matter region constitute the halo of Andromeda galaxy.

Acknowledgments

I would like to thank Christopher Janes, my lab partner, for his patience, his friendship and his good mood, which had made this laboratory so pleasant.

Also, I would like to thank our demonstrators Alan Pedlar and Duncan Lorimer for their help to understand the physics behind this experiment, and for their patience to repeat the explanation until I understand correctly.

References

[1] Drawspec © 1994, H. S. Liszt

[2] *The mass and Hydrogen content of M31*, lab script, third year laboratory.

[3] Morton S. Robert, *Radio Observations of Neutral Hydrogen in Galaxies*. Stars and Stellar Systems, Vol. IX, page 309.

[4] MATLAB, Version 6.5.0, The MathWorks, Inc.

[5] Evans, N. W., Wilkinson, M.I, Guhathakurta, P., Grebel, E.K., Vogt, S.S *Dynamical mass estimates for the halo of M31 from Keck spectroscopy*. ApJ, 540:L9-12, 2000 September.

Length and Date

The number of words in this document is 1933 .

This document was printed on 14/04/2010 at 15:39.