

# Dark Matter in M81

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## Overview

The presence of dark matter within galaxies can be identified by comparing the mass of the stars and interstellar gas within galaxies to the mass inferred from the velocities of the gas and stars as they orbit within the galaxy. This experiment uses data from the Spitzer Space Telescope and Jansky Very Large Array to identify the presence of dark matter within the spiral galaxy M81.

## General Astronomy Concepts

In typical galaxies, a small fraction of the matter consists of stars and interstellar gas. A larger fraction of the matter consists of dark matter. In some galaxies, up to 90% of the matter may be dark matter.

Stars can be identified by the production of visible light as well as ultraviolet and near-infrared light, and interstellar gas can be identified by emission across the electromagnetic spectrum, but dark matter itself neither emits nor absorbs electromagnetic radiation. Instead, the presence of dark matter is usually identified by determining the mass needed to produce

observed phenomena related to the gravitational forces present in any galaxy (or groups of galaxies) and comparing this to the mass of the stars and gas seen in the galaxy.

One of the observed phenomena related to gravitational forces is the velocity of orbiting objects. When a small object is in orbit around a much larger object, such as a star or a gas cloud around a galaxy, the force  $F_C$  needed to keep it in orbit is

$$F_C = \frac{mv^2}{r}$$

where  $m$  is the mass of the object in orbit,  $v$  is the velocity, and  $r$  is the radius of the orbit. This force will equal the gravitational force  $F_G$  given by

$$F_G = \frac{GMm}{r^2}$$

where  $M$  is the mass of the larger object and  $G$  is the gravitational constant. Setting these two forces equal to each other and performing some algebra gives

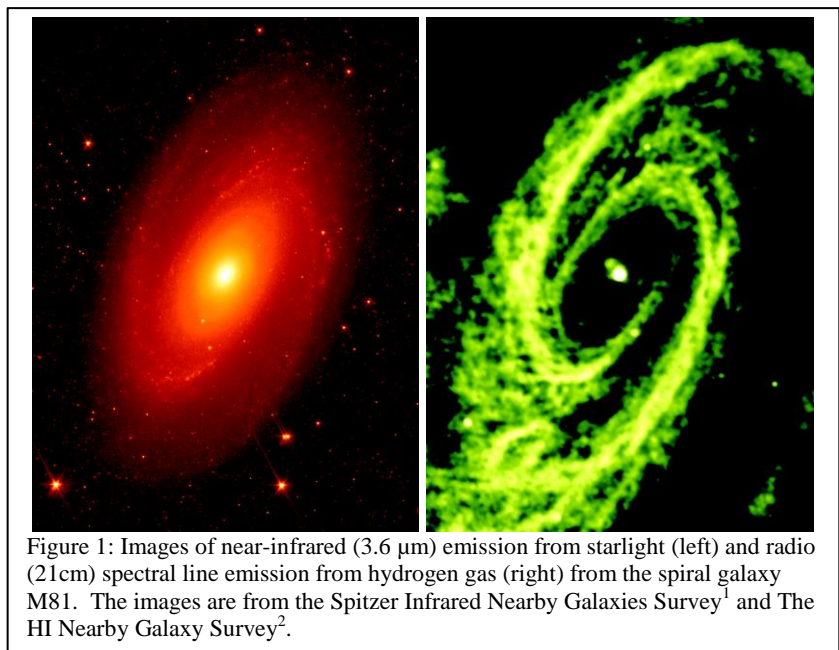


Figure 1: Images of near-infrared (3.6  $\mu\text{m}$ ) emission from starlight (left) and radio (21cm) spectral line emission from hydrogen gas (right) from the spiral galaxy M81. The images are from the Spitzer Infrared Nearby Galaxies Survey<sup>1</sup> and The HI Nearby Galaxy Survey<sup>2</sup>.

$$M = \frac{v^2 r}{G}$$

Using measurements of  $v$  and  $r$ , it is possible to calculate  $M$ . The values for  $r$  can be calculated using distances to the galaxies and trigonometry. The velocities can be calculated by measuring the Doppler shifting of spectral line emission from either stars or gas within galaxies.

This experiment is based on an analysis of optical and radio data of the spiral galaxy M81. Optical and radio images of the galaxy are shown in Figure 1. The stellar mass can be calculated using observations of starlight; this experiment uses measurements at the near-infrared wavelength of 3.6  $\mu\text{m}$ . Most of the mass of the interstellar gas in most galaxies is found in hydrogen gas. In M81, the hydrogen spectral line emission observed at the radio wavelength of 21 cm (or a frequency of 1.420 GHz) can be used to measure the mass of the gas. The Doppler shift of the hydrogen line emission can be used to measure the rotational velocity of the galaxy. By comparing the measurements of the stellar and gas masses to the dynamical masses, it is possible to identify the presence of dark matter in galaxies.

### Additional Information: Units for Measuring Light

The analysis in this experiment is based on data with units of Janskys (Jy). One Jy is equal to  $10^{-26} \text{ W/m}^2/\text{Hz}^1$ . This is a measurement of a quantity referred to as flux density ( $f_\nu$ ), which represents the amount of energy ( $\Delta E$ ) per time ( $\Delta t$ ) observed within a given frequency range ( $\Delta \nu$ ) that can be collected over a telescope area ( $\Delta A$ ), or

$$f_\nu = \frac{\Delta E}{\Delta t \Delta A \Delta \nu}$$

Sometimes measurements are reported as surface brightness ( $I_\nu$ ), which is the flux density spread over an area of the sky ( $\Delta \Omega$ ). This is given by the equation

$$I_\nu = \frac{f_\nu}{\Delta \Omega} = \frac{\Delta E}{\Delta t \Delta A \Delta \nu \Delta \Omega}$$

### Additional Information: Coordinate Systems

Astronomers use a coordinate system similar to the latitude and longitude system applied to Earth. The astronomical equivalent coordinates are called right ascension and declination. Right ascension is equivalent to longitude, and it is often measured in hours, minutes, and seconds with a range from 0 to 24 hours, with 60 minutes in an hour, and with 60 seconds in a minute. Sometimes, however, right ascension is measured in degrees instead (with 1 hour equivalent to 15 degrees). Declination is equivalent to latitude, and it is measured in degrees, minutes, and seconds, with 60 minutes in a degree and 60 seconds in a minute. Declination ranges from +90:00:00 (at the point directly above the Earth's North Pole) through 00:00:00 (the location directly above the Earth's equator) to -90:00:00 (at the point directly above the Earth's South Pole). See Figure 2 for an example of this coordinate system overlaid on the constellation Orion.

Lengths and distances in the sky are often measured in degrees, arcminutes, and arcseconds, with 60 arcminutes in 1 degree and 60 arcseconds in 1 arcminute. Arcminutes and arcseconds are often abbreviated as arcmin and arcsec. For reference, the Sun and Moon are both 0.5 degrees (or 30 arcmin) across. The Andromeda Galaxy, which is the nearest spiral galaxy, and the Pleiades cluster of stars are both 3 degrees across.

Areas are often described as square versions of the angular measurements, such as square degrees ( $\text{deg}^2$ ), square arcseconds ( $\text{arcsec}^2$ ), and square radians or steradians (sr). Areas in radio data are often described in

terms of the beam of telescope, which is the angular area that light from a point source is spread over in the final images. The JVLA data used in this experiment have a beam area of  $181.6 \text{ arcsec}^2$ .

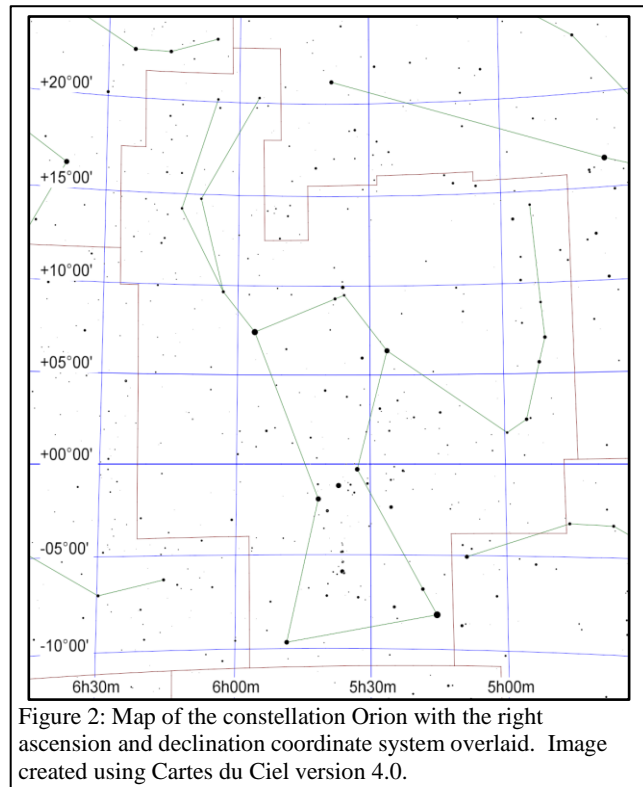


Figure 2: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

### Preparation Procedure

1. Download and install the beta release of DS9 (version 8.1b1) from <http://ds9.si.edu/site/Beta.html> . This software is available for Windows, Mac, and Linux. (This experiment will not work on some computers with version 8.0.1 of DS9, which is the version available from the main download page.)
2. Download the following images from the NASA/IPAC Extragalactic Database (NED), a general astronomy image and data repository at <http://ned.ipac.caltech.edu/> .
  - a. Download the Spitzer Space Telescope near-infrared image from [http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC\\_3031:I:IRAC\\_3.6:kab2003](http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3031:I:IRAC_3.6:kab2003) .
  - b. Download the Very Large Array radio image of the total hydrogen line emission from [http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC\\_3031\\_NA\\_MOM0:I:HI:wbb2008](http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3031_NA_MOM0:I:HI:wbb2008) .
  - c. Download the Very Large Array radio image cube of the hydrogen line emission from [http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC\\_3031\\_NA\\_CUBE:I:HI:wbb2008](http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3031_NA_CUBE:I:HI:wbb2008) . **WARNING: This image is 3.2 GB in size. For computers on slow internet connections, it may be necessary to download the images the day before performing the experiment.**
3. Move all of the images to the same directory.
4. If any of the downloaded images do not end in ".fits", add this to the end of the filenames.

## Measurement Procedure (Near-Infrared Image)

1. Start DS9.
2. Under "File" in either the menu or the button bar, click on "Open". In the new window that appears, select the near-infrared image (NGC\_3031:I:IRAC\_3.6:kab2003.fits).
3. Under "Scale", click on "Log". This will change the way that the image values are displayed on the computer screen.
4. Middle-click on the image (or go to "Edit", select "Pan", and then left click in the image) to re-centre the image. Try to re-centre the image on the centre of the galaxy, which will be the brightest point in a smooth, extended source.
5. To zoom in or out, either use the scroll wheel on the mouse or go to "Zoom" in the menu or button bar and select one of the options. Zoom out until the entire galaxy is visible.
6. To change the brightness and contrast of the image so that the galaxy is easier to see, first move the cursor to the image window, then hold down the right mouse button (or, on a Mac laptop, hold down the mouse button and the cmd key at the same time), and then move the cursor either up and down or side to side in the window. Do this until both spiral arms are visible but without making them look completely white. See Figure 3 for an example of what the image should look like after this step.
7. As an additional option, change the colours by clicking on an alternate scheme under "Color" in the menu or button bar. (It may be necessary to repeat step 6 after doing this.)
8. Under "Edit" in either the menu or button bar, click on "pointer" or, if that is not listed, "region".
9. Under "Region" in the menu bar, click on "Shape" and then click on "Ellipse".
10. Left click on the image to draw an ellipse. When this region is selected, it will have four small squares around it. Move the ellipse so that it is located near the centre of the galaxy. This can be done by clicking on the ellipse with the left mouse button and, while holding the left mouse button down, dragging the ellipse

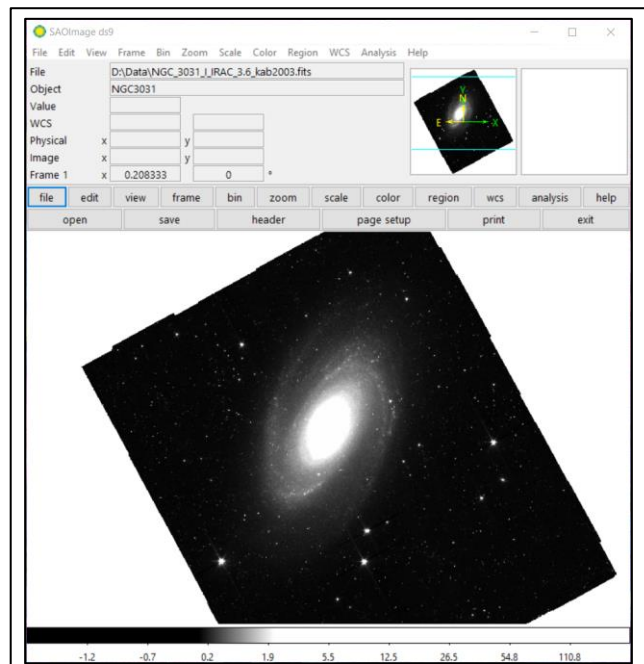


Figure 3: The near-infrared (3.6  $\mu\text{m}$ ) image of M81 as it appears in DS9 after applying steps 1-6 in the measurement procedure for the near-infrared data.

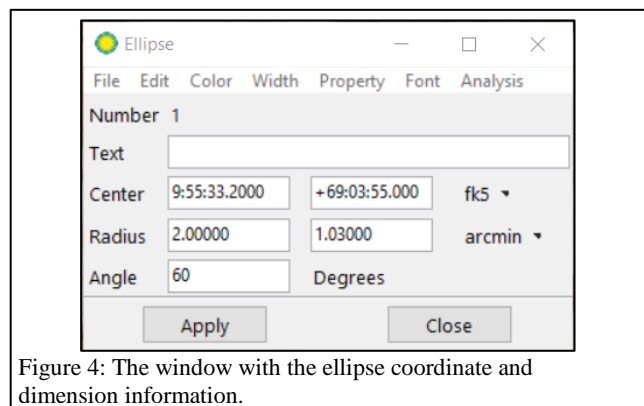


Figure 4: The window with the ellipse coordinate and dimension information.

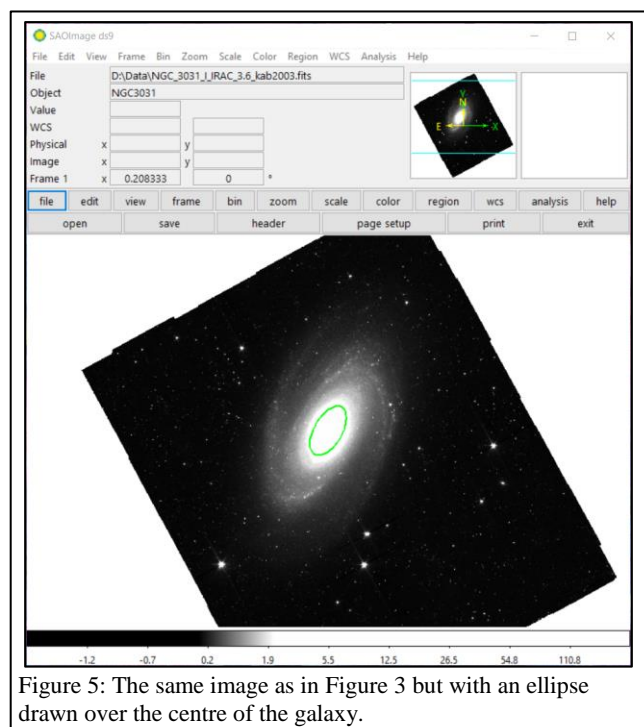


Figure 5: The same image as in Figure 3 but with an ellipse drawn over the centre of the galaxy.

across the image. Alternately, use the arrow keys.

11. Double click on the ellipse, which will open a new window labelled "Ellipse". See Figure 4 for an example.
12. Click on the drop-down menu to the right of the row of boxes listing the centre of the ellipse. If check marks are not visible next to "WCS" and "fk5", click on these options. After this, type in the right ascension and declination for the centre of the galaxy, which are 09:55:33.2 and +69:03:55 according to NED.
13. Click on the drop-down menu to the right of the row of boxes listing the radii of the ellipse. If check marks are not visible next to "WCS" and "ArcMin", click on these options. After this, set the first radii of the galaxy to 2.00 arcmin and set the smaller radii to 1.03 arcmin. (These relative dimensions match the ellipse to the inclination of the disc of the galaxy according to The HI Nearby Galaxy Survey<sup>2</sup>.)

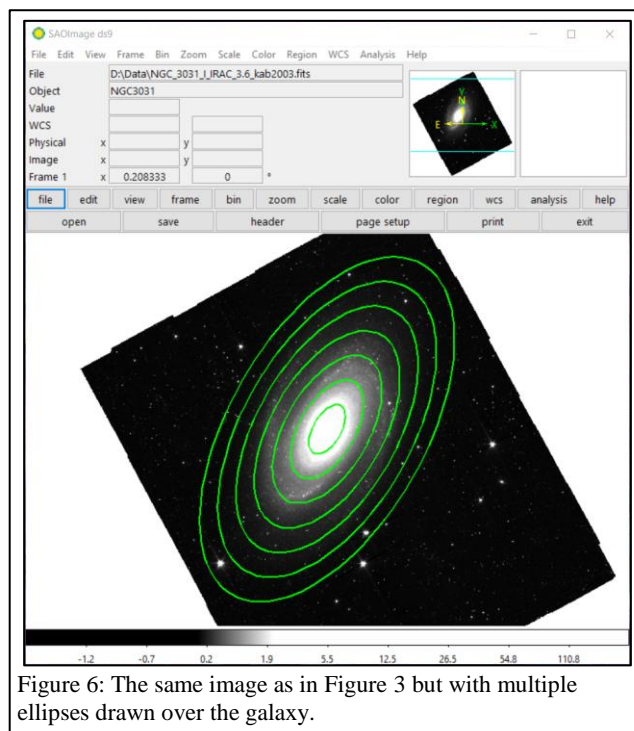


Figure 6: The same image as in Figure 3 but with multiple ellipses drawn over the galaxy.

14. In the row labelled "Angle", type in 60 degrees, which is the position angle of the major axis of the ellipse in degrees from west through north given by The HI Nearby Galaxy Survey<sup>2</sup>. See Figure 5 for an example of what the image should look like after performing these steps.
15. Under "Analysis" in the menu of the "Ellipse" window, select "Statistics". This will open a new window. Record the number listed under sum as the near-infrared (or 3.6  $\mu\text{m}$ ) emission from the galaxy. Also record the number of pixels in the region listed under npix.
16. Repeat steps 10-15 to draw ellipses with axis dimensions that are 2, 3, 4, 5, 6, and 7 times the size of the first ellipse and to measure the near-infrared emission and number of pixels within each ellipse. Figure 6 shows what the image should look like after this step.
17. Under "Region" in the menu bar of the main DS9 window, select "Shape" and then "Circle".
18. Left click on the image to draw a circle. Move the circle to a location outside the ellipse without any bright stars or other sources of strong emission. (It is acceptable if the circle covers a region with faint stars.)
19. Double click on the circle to open a new window labelled "Circle".
20. Click on the drop-down menu to the right of the row of boxes listing the radius of the circle. If check marks are not visible next to "WCS" and "ArcSec", click on these options. After this, set the radius of the circle to 60 arcsec.
21. Under "Analysis" in the menu, select "Statistics". Record the number listed in the new window under median. This is a

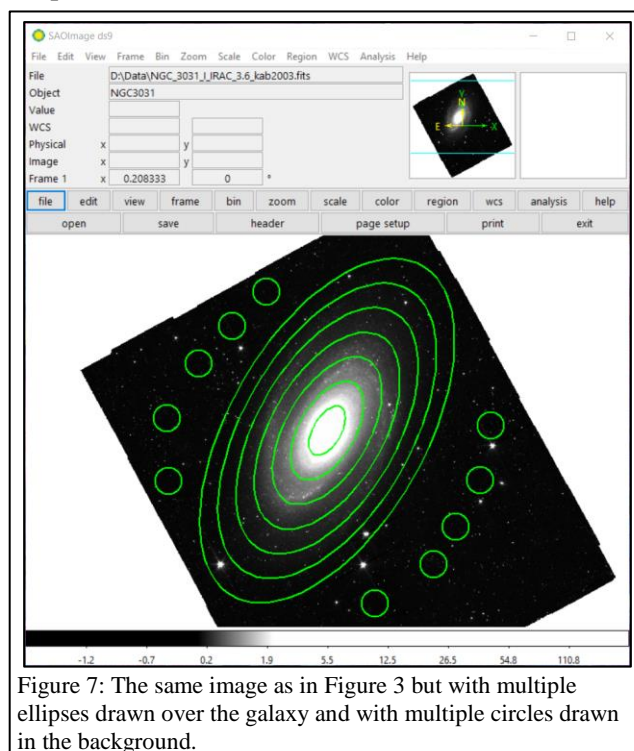


Figure 7: The same image as in Figure 3 but with multiple ellipses drawn over the galaxy and with multiple circles drawn in the background.

measurement of the background signal in the image.

22. Repeat steps 18-21 to measure the background in a total of 10 circles covering relatively blank locations around the galaxy. The distribution of the circles should look like Figure 7.
23. Under "Region" in either the menu or button bar of the main DS9 window, click on "Save Regions". In the next dialog window that appears, give the region file an appropriate name and click "Save". In the second dialog window that appears, make sure that the format is set to "ds9" and the coordinate system is set to "fk5" and click "OK".

### Measurement Procedure (Total Hydrogen 21cm Radio Line Emission Image)

1. Under "File" in either the menu or the button bar, click on "Open". Open the image of the total hydrogen line radio emission (NGC\_3031\_NA\_MOM0:I:HI:wbb2008e.fits).
2. Follow steps 3-7 from the near-infrared measurement procedure to adjust the display of the data if necessary.
3. Under "Region" in the main DS9 window, click on "Load Regions". Load the region file that was saved in step 23 of the measurement procedure for the near-infrared image of the galaxy. (If a dialogue box appears, just click "OK".) The display should look like Figure 8.
4. Double-click on each ellipse to open the "Ellipse" window, and then click on "Statistics" to open the statistics windows. Record the number listed under the sum as the total hydrogen line (or 21 cm) emission from the ellipse.

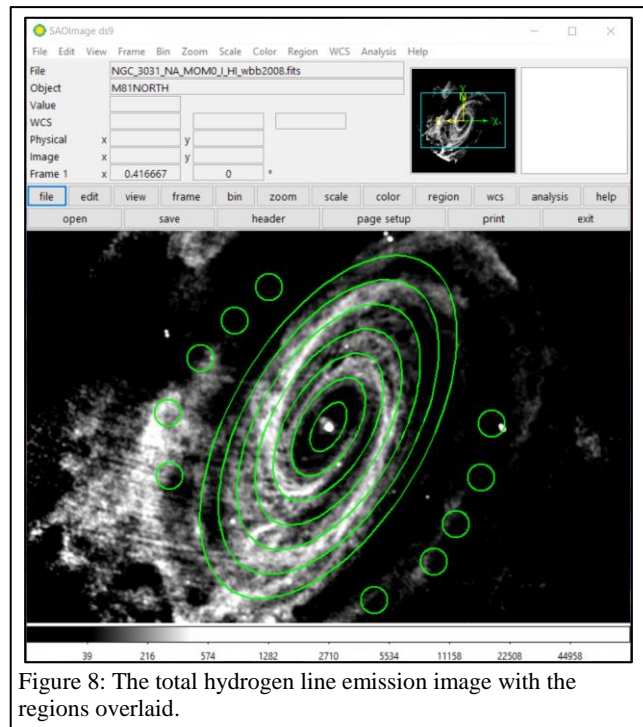


Figure 8: The total hydrogen line emission image with the regions overlaid.

### Measurement Procedure (Hydrogen 21cm Radio Line Image Cubes)

1. Under "File" in either the menu or the button bar, click on "Open". Open the image cube of 21 cm hydrogen radio spectral line emission (NGC\_3031\_NA\_CUBE:I:HI:wbb2008.fits). The data are three dimensional; two dimensions represent spatial dimensions on the plane of the sky, while the third dimension represents the velocity of the gas producing the hydrogen emission (which was calculated from the frequency using the equation for the Doppler shifting of light). The main DS9 window will display the data as seen on the plane of the sky at a given velocity, while a second window labelled "Cube" can be used to select the velocity. See Figure 9 for an example of the "Cube" window.
2. Under "Scale", select "log".
3. In the "Cube" window, move through frequencies (either by moving the slider or by using the "Previous", "Stop", "Play", and "Next" buttons) until emission from outside the galaxy's nucleus appears to trace a relatively straight diagonal line through the nucleus (instead of a U shape). See Figure 10 for an

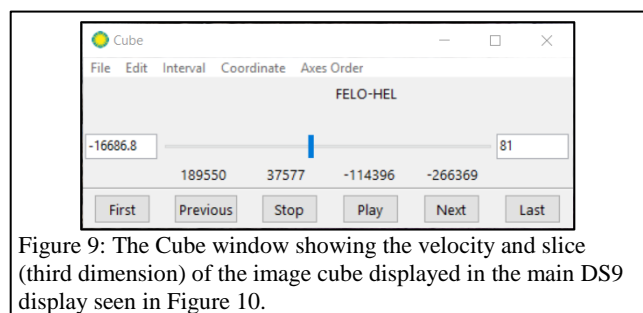


Figure 9: The Cube window showing the velocity and slice (third dimension) of the image cube displayed in the main DS9 display seen in Figure 10.

example. Because the hydrogen emission comes from a rotating disc, the emission will appear at different locations in the image when different velocities are selected.

4. Follow steps 4-7 from the near-infrared measurement procedure to adjust the display of the data if necessary.
5. Move the cursor around the image until you identify the pixel that corresponds to the peak at the centre of the galaxy. The coordinates for the cursor location (in both astronomical coordinates and pixel coordinates) are displayed at the top of DS9. When the centre of the peak emission is found, record the pixel coordinates.
6. Under "Edit" in the menu bar, click on "region".
7. Left click on the image to draw a circle.
8. Double-click on the circle to open the "Circle" window.

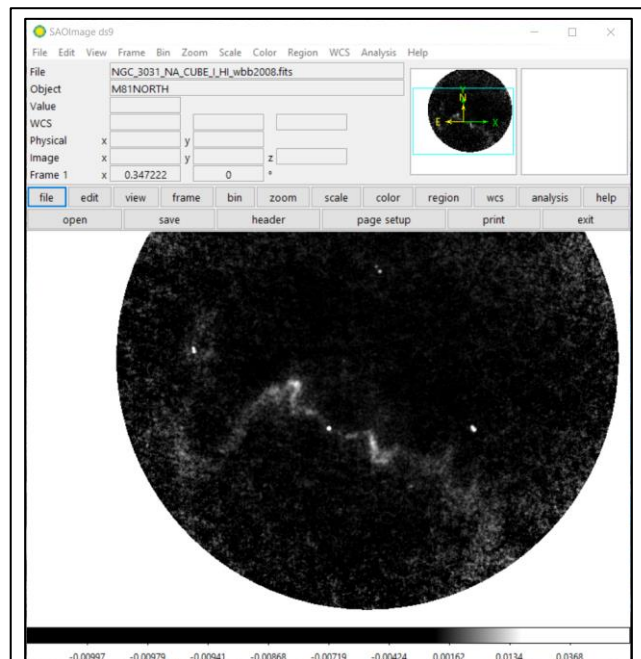


Figure 10: The image cube of the 21 cm radio spectral line emission from M81 as it appears in DS9 after applying steps 1-4 in the measurement procedure for these data.

9. Click on the drop-down menu to the right of the row of boxes listing the centre of the ellipse. If a check mark is not visible next to "image", click on this options. After this, calculate a location that is 2 arcmin (or 120 arcsec or 80 pixels since each pixel is 1.5 arcsec in size) away from the centre of the galaxy on the major axis of the galaxy (which is oriented at an angle 60 degrees counterclockwise from the x-axis towards the y-axis in this image). Type those pixel coordinates in as the centre of the circle. Note that one of the possible two locations is above and to the right of the centre of the galaxy and the other is located below and to the left; Figure 11 shows the location below and to the left.
10. Click on the drop-down menu to the right of the row of boxes listing the radius of the circle. If check marks are not visible next to "WCS" and "ArcMin", click on these options. After this, set the radius of the circle to 1 arcmin. See Figure 11 for what the image should look like after these steps.

11. Under "Analysis" in the "Circle" window, select "Plot3D". This will display a plot of the average hydrogen line surface brightness within the ellipse (labelled "JY/BEAM Average") versus the velocity of the gas (labelled "FELO-HEL" but actually in m/s). See Figure 12 for an example.
12. Under "File" in the window with the plot of the spectrum, click on "List Data". This will open a new window labelled "Data". See Figure 13. The "Data" window contains two columns of data: the velocity (related to frequency) in m/s on the left, and the surface brightness in Jy/beam on the right.
13. Use both the plot of the spectrum and the list of the numerical data to find the velocity that corresponds to the maximum hydrogen line emission (but ignore any spikes near velocities

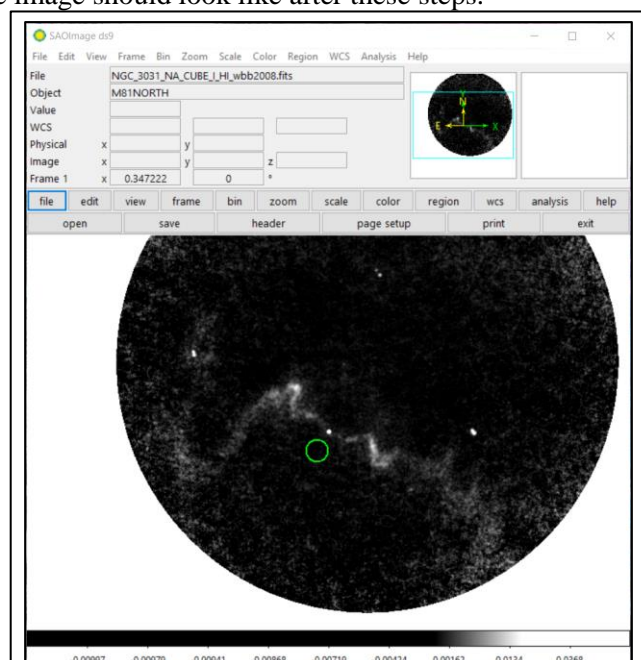


Figure 11: The same as Figure 10 but with a circle placed 2 arcmin from the centre of the galaxy on the major axis.

of 0 m/s). Record this number and also the distance of the centre of this circle from the centre of the galaxy in arcmin.

14. Repeat steps 7-13 for circles that are located 2, 4, 6, 8, 10, 12, and 14 arcminutes away from the centre of the galaxy on both sides of the centre. See Figure 14 for what the image should look like when all of the regions have been created.
15. Under "Region" in either the menu or button bar of the main DS9 window, click on "Save Regions". In the next dialog window that appears, give the region file an appropriate name and click "Save". In the second dialog window that appears, make sure that the format is set to "ds9" and the coordinate system is set to "fk5" and click "OK".

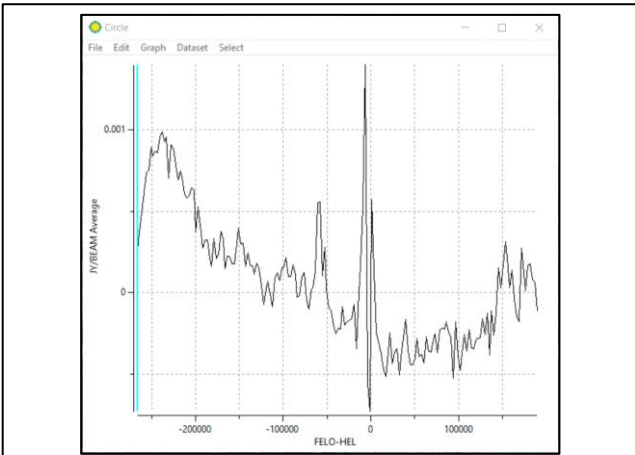


Figure 12: A plot showing the hydrogen spectral line emission (labelled "JY/BEAM Average" but actually in units of Jy/beam) versus velocity (labelled "FELO-HEL" but actually in m/s) for the ellipse in Figure 11.

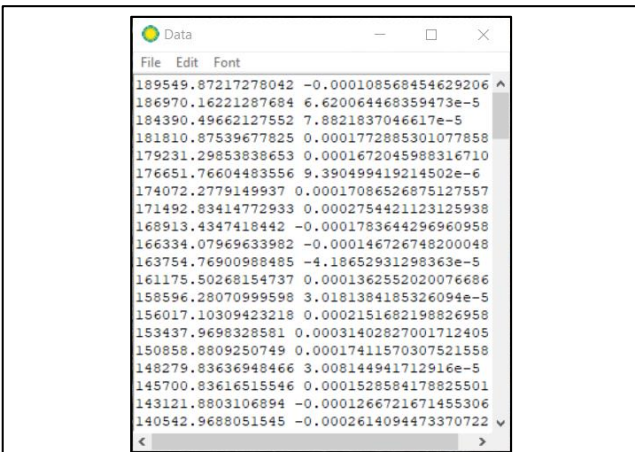


Figure 13: The window with numerical data used to create the plot of surface brightness versus frequency that is seen in Figure 12.

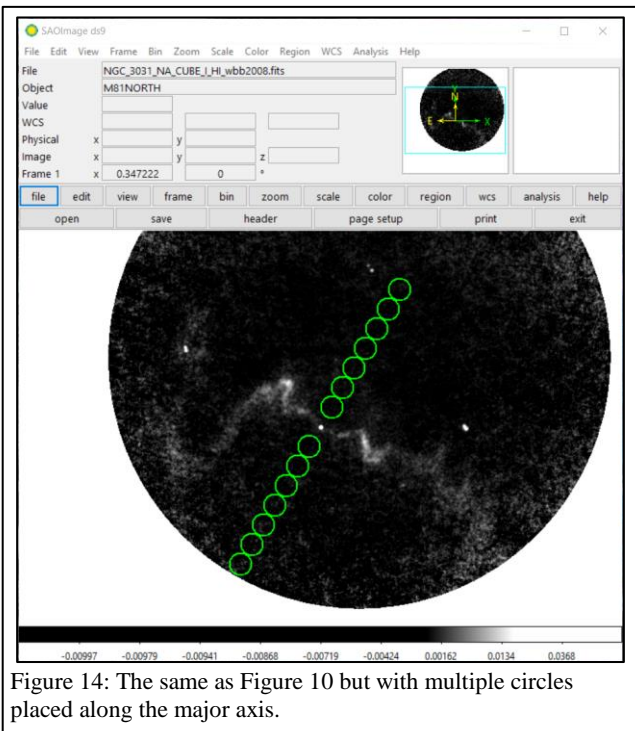


Figure 14: The same as Figure 10 but with multiple circles placed along the major axis.



## Numerical Analysis Procedure

1. The semi-major axes for each elliptical region used to measure fluxes of the stellar and atomic gas emission should be converted to physical distances using

$$r = D \sin \theta_r$$

where  $\theta_r$  is the angular distance from the centre of the galaxy,  $r$  is the radius from the centre of the galaxy in physical units, and  $D$  is the distance from Earth to the galaxy, which is given by the Cosmicflows-2 survey<sup>3</sup> as 3.61 Mpc. For reference, 1 Mpc is equal to  $3.086 \times 10^{22}$  m. See Figure 15 to see the geometry of an inclined galaxy disc as seen from the Earth. The results from these calculations will also be equivalent to the distance from the centre of the galaxy to the position of the circular regions used to measure the Doppler shifted frequency of the hydrogen line emission.

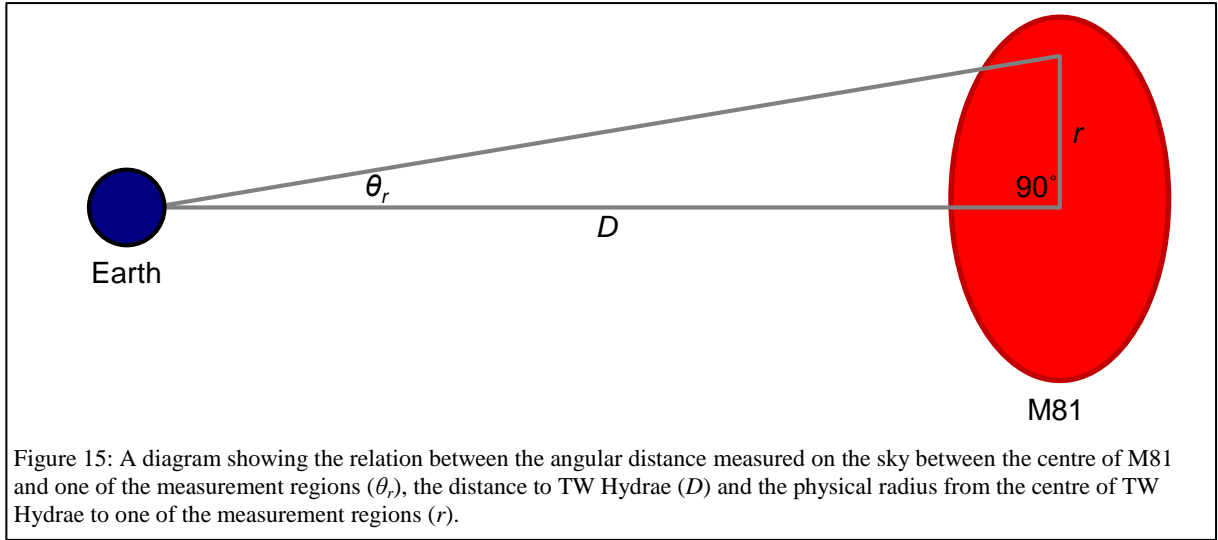


Figure 15: A diagram showing the relation between the angular distance measured on the sky between the centre of M81 and one of the measurement regions ( $\theta_r$ ), the distance to TW Hydrae ( $D$ ) and the physical radius from the centre of TW Hydrae to one of the measurement regions ( $r$ ).

2. Calculate the mean of the measurements within the background regions in the near-infrared image.
3. Multiply the mean background value in the near-infrared image by the number of pixels within each ellipse. After doing this, subtract this value from the sum of the pixel values for each ellipse. This number represents the near-infrared signal from each ellipse.
4. The near-infrared data are in units of megaJanskys per steradian (MJy/sr), and the pixel are 0.75 arcsec (or  $3.64 \times 10^{-6}$  radians) wide. Convert the near-infrared measurements to Janskys by multiplying by  $1.32 \times 10^{-5}$ .
5. The stellar mass  $M_{stars}$  for each elliptical region can be calculated from the flux densities  $f_\nu$  of the near-infrared data using

$$\frac{M_{stars}}{M_\odot} = 3.73 \times 10^8 \left( \frac{f_\nu}{\text{Jy}} \right) \left( \frac{D}{\text{Mpc}} \right)^2$$

which was derived specifically for  $3.6 \mu\text{m}$  data<sup>4</sup>. The units of  $M$  are in solar masses (with  $1 M_\odot = 1.99 \times 10^{30}$  kg).

6. The data units for the individual pixels in the total hydrogen 21 cm line maps are in (Jy m/s)/beam. The sums for the data need to be converted to units of Jy m/s. This can be done by first dividing the data by the beam area, which is  $181.6 \text{ arcsec}^2$ , and then multiplying by the area of a pixel, which is  $2.25 \text{ arcsec}^2$ .
7. The total atomic gas mass  $M_{gas}$  within each ellipse can be calculated from the flux  $f$  from the hydrogen 21cm line in Jy/(m/s) using

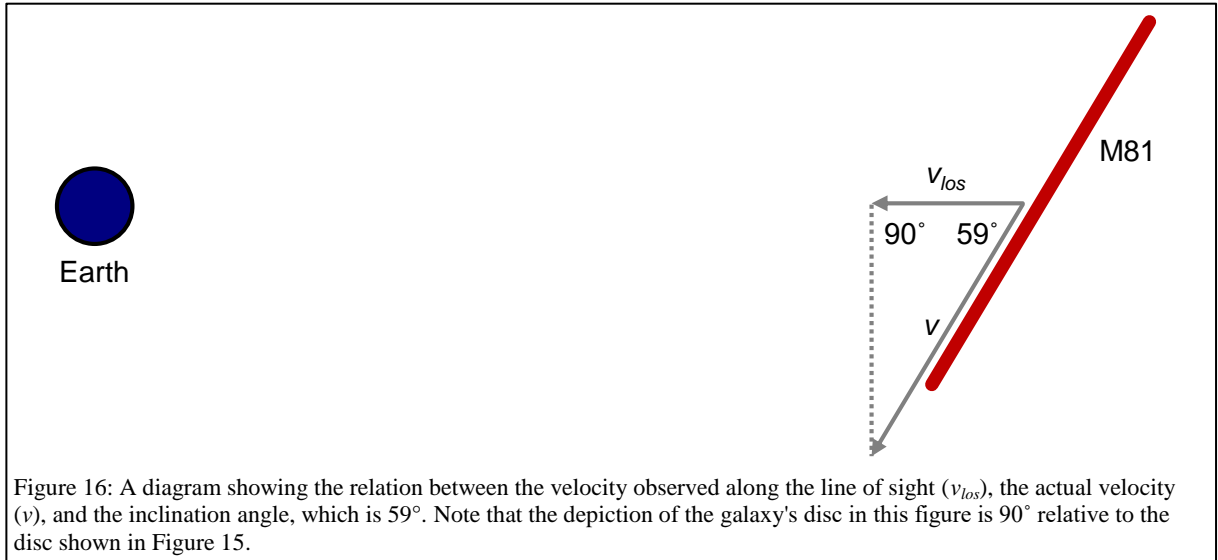
$$\frac{M_{gas}}{M_{\odot}} = 236 \left( \frac{f}{\text{Jy m/s}} \right) \left( \frac{D}{\text{Mpc}} \right)^2$$

which is the conversion used by the survey that acquired the radio data<sup>2</sup>.

8. Find the average of the atomic gas velocities in all circles. Subtract this value from each velocity measured in each circular region.
9. For each set of velocities measured at the same distance from the centre of the galaxy, calculate the average of the absolute values.
10. The actual velocities include a component perpendicular to the line of sight, as seen in Figure 16. The measured velocities are actually called line of sight velocities or  $v_{los}$ . The  $v_{los}$  values from the previous step should be converted to the actual rotational velocities  $v$  using

$$v = \frac{v_{los}}{\sin 59^{\circ}}$$

where 59 degrees is the inclination of the galaxy<sup>2</sup>.



11. Use the equation

$$M_{dyn} = \frac{v^2 r}{G}$$

to calculate the mass  $M_{dyn}$  enclosed within each radius from step 1 using each velocity measurement from step 10. This is called the dynamical mass because it is the mass measured using the laws of gravity. In this equation,  $G$  is the gravitational constant, which is  $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ . After doing this, convert the masses to units of solar masses  $M_{\odot}$  by dividing by  $1.99 \times 10^{30} \text{ kg}/M_{\odot}$ .

12. Plot the sums of the stellar and atomic gas masses within each ellipse (from steps 5 and 7) as a function of the semi-major axis of the ellipse (from step 1) in kpc. (1 kpc is equal to  $3.086 \times 10^{19} \text{ m}$ .) In the same graph, plot the dynamical masses (from step 11) as a function of the radius from the centre of the galaxy to each pair of circles in kpc. This is the final result of the analysis.

## Discussion Questions

1. Based on the results from the analysis, is dark matter present in the galaxy analysed? If so, how is the dark matter distributed as a function of radius?
2. If dark matter was found, how is it distributed compared to the stars and the gas in the galaxy?
3. How do the distributions of the gas and stars compare to each other?
4. The measurements in this experiment are based on the assumption that the galaxy is flat. This is a good approximation for the gas but not the stars. Explain why.
5. Explain the limitations of this analysis in identifying the location of dark matter within the galaxy.

## References

- <sup>1</sup> Kennicutt R. C. Jr. et al., *SINGS: The SIRTf Nearby Galaxies Survey*, 2003, *Publications of the Astronomical Society of the Pacific*, 115, 810
- <sup>2</sup> Walter F. et al., *THINGS: The HI Nearby Galaxy Survey*, 2008, *Astronomical Journal*, 136, 2563
- <sup>3</sup> Tully R. B. et al., *Cosmicflows-2: The Data*, 2013, *Astronomical Journal*, 146, 86
- <sup>4</sup> Eskew M. et al., *Converting from 3.6 and 4.5  $\mu\text{m}$  Fluxes to Stellar Mass*, 2012, *Astronomical Journal*, 143, 139