Measuring Distances to Galaxies using the Tully-Fisher Relation

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Overview

The Tully-Fisher relation is a relation between the luminosity of a galaxy and the velocity at which it rotates, which can be used to measure distances to galaxies. This experiment uses data from the Spitzer Space Telescope and Jansky Very Large Array to derive this relation for a set of galaxies where the distances have been determined using other methods. After this, the relation is used to derive the distances to other galaxies. These distances along with measurements of the mean velocities of the galaxies can then be used to determine the Hubble constant.

General Astronomy Concepts

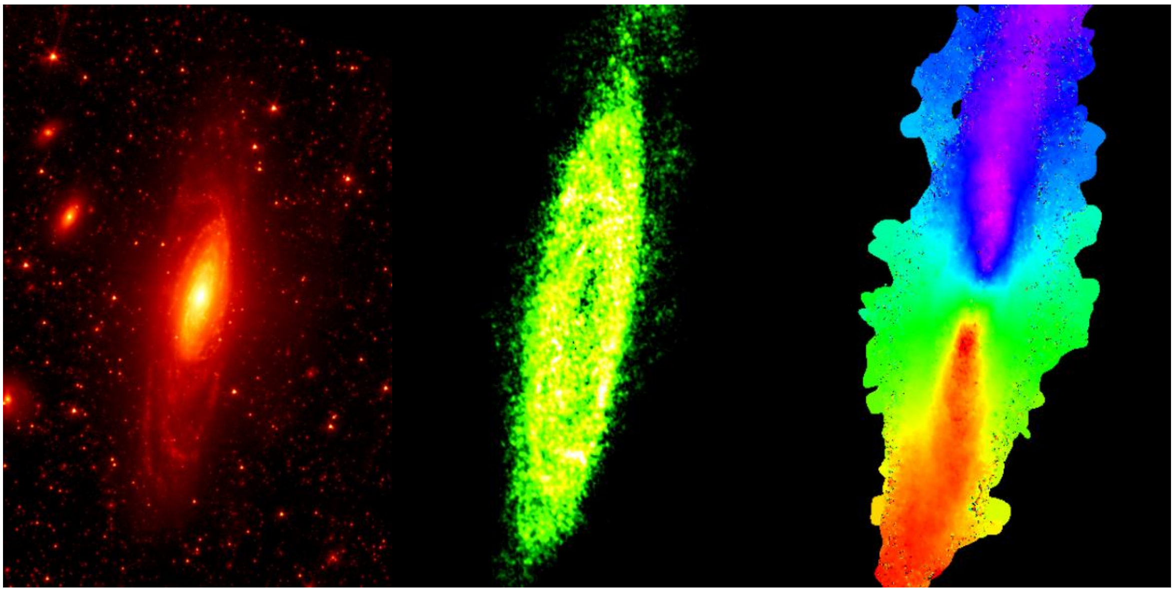

Figure 1:Images of near-infrared (3.6 μm) emission from starlight (left), radio (21cm) spectral line emission from hydrogen gas (centre), and the rotational velocity of the hydrogen gas (right) for the spiral galaxy NGC 7331. The images are from the Spitzer Infrared Nearby Galaxies Survey[3] and The HI Nearby Galaxy Survey[4].

Edwin Hubble first identified first that most galaxies were moving away from the Earth (based on the Doppler shifting of their spectra) and second that the galaxies that were further away appeared to be moving away faster than galaxies that are closer to the Earth[1]. The equation for this is given by

$$v_{mean} = H_0 D$$

where v_{mean} is the mean velocity of the galaxy, D is the distance, and H_0 is a scalar term called the Hubble constant. These observations established that the Universe was expanding and led to the Big Bang theory.

Distances can be determined by measuring the amount of light from objects with known brightnesses. The total amount of energy (in the form of light or electromagnetic radiation) produced over time by any astronomical object is called its luminosity, which is labelled L. As that energy propagates through space, it is spread over a sphere with a surface area of $4\pi D^2$. Telescopes actually measure the flux of energy, f, which is given by the equation

$$f = \frac{L}{4\pi D^2}$$

Hubble used Cepheid stars to measure the distances to galaxies. Cepheids are a class of bright stars where their pulsation period is directly related to their luminosities, which are first calibrated for objects in the Milky Way using reliable distance measurements (for example, parallax) as well as flux measurements. The luminosities derived from the observed pulsation periods as well as flux measurements of the Cepheids yield distances to other galaxies containing Cepheids. Other stars, such as the brightest red supergiants, can be used in the same way to determine distances as long as the expected luminosities are known. However, these methods rely upon being able to see (or resolve) the individual stars within other galaxies. Except for the closest galaxies, the stars in other galaxies appear to blur together unless a telescope like the Hubble Space Telescope is used, and even that telescope has limitations.

The Tully-Fisher relation was developed as a way to determine the distances to galaxies where it is not possible to identify the individual stars. This method, which can be applied solely to spiral galaxies, depends on the assumption that the luminosity of the whole galaxy is related to the maximum rotation velocity v_{rot} as given by the equation

$$L = A v_{rot}^{\beta}$$

This is based on the idea that galaxies which have more mass will be brighter and will also rotate more quickly[2].

This experiment consists of deriving the Tully-Fisher relation for a set of nearby galaxies where the distances have been measured using Cepheids and then applying this relation to measure the distances to other galaxies. After this, the distances as well as measurements of the mean velocities are used to derive the Hubble constant. The fluxes are measured using near-infrared images of starlight from the Spitzer Space Telescope, while the rotational velocities are measured from hydrogen line spectral observations from the Jansky Very Large Array. Examples of the infrared and radio data used in this experiment are shown in Figure 1. The rotation of the disc causes the hydrogen line to be Doppler shifted as given by the equation

$$f_{obs} = f_{rest} \sqrt{\frac{\left(1 - \frac{v}{c}\right)}{\left(1 + \frac{v}{c}\right)}}$$

where f_{obs} is the observed frequency of the line emission from the gas, f_{rest} is the frequency of the line emission when the gas is not moving, v is the velocity of the gas, and c is the speed of light. In the data used in this experiment, this equation has already been applied to convert the observed frequencies to velocities. An example of the velocities measured from Doppler-shifted radio line emission is shown on the right in Figure 1.

Basic data about the two sets of galaxies used in this experiment are listed in the two tables on the next page.

Galaxy with Known Distance	Central Position[a] (J2000 coordinates)		Optical Disc[b]			Inclination[c] (deg)	Distance[d] (Mpc)
	Right Ascension	Declination	Semimajor Axis (arcmin)	Semiminor Axis (arcmin)	Position Angle (deg)		
NGC 925	02:27:16.9	+33:34:45	5.4	2.9	17	66	9.2
NGC 2403	07:36:51.4	+65:36:09	10.0	5.0	36	63	3.2
NGC 2841	09:22:02.6	+50:58:35	5.2	2.7	60	74	14.1
NGC 3031	09:55:33.2	+69:03:55	13.5	7.8	65	59	3.6
NGC 3351	10:43:57.7	+11:42:14	4.2	3.1	101	41	10.0
NGC 3621	11:18:16.5	-32:48:51	4.9	2.0	71	65	6.6
NGC 3627	11:20:15.0	+12:59:30	6.3	3.8	72	62	10.1
NGC 7331	22:37:04.0	+34:24:56	4.7	1.9	80	76	14.7
NGC 7793	23:57:49.8	-32:35:28	5.4	3.5	10	50	3.4

[a] The positions are from from the NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu/).
[b] The optical disc data for NGC 3031, NGC 3351, NGC 3627, and NGC 7793 are from the Spitzer Survey of Stellar Structure in Galaxies[5]. The optical disc data for NGC 925, NGC 2403, NGC 3621, and NGC 7331 are from the HyperLeda website (http://leda.univ-lyon1.fr/). The position angle is expressed as degrees from west through north (which is non-standard but practical for this experiment).
[c] The inclinations of the galaxy discs are from The HI Nearby Galaxy Survey[4]. 0° corresponds to face-on, and 90° corresponds to edge-on.
[d] The distances are in megaparsecs, where one megaparsec equals 3.086×10^{22} meters. All measurements are based on Cepheid data analysed by the Hubble Space Telescope Key Project to Measure the Hubble Constant[6] except for three galaxies observed in other studies[7,8].

Galaxy with Unknown Distance	Central Position[a] (J2000 coordinates)		Optical Disc[b]			Inclination[c] (deg)
	Right Ascension	Declination	Semimajor Axis (arcmin)	Semiminor Axis (arcmin)	Position Angle (deg)	
NGC 628	01:36:41.7	+15:47:01	5.8	4.8	28	7
NGC 2903	09:32:10.1	+21:30:03	6.1	3.0	109	65
NGC 3184	10:18:16.9	+41:25:27	4.1	3.5	48	16
NGC 3521	11:05:48.6	-00:02:09	6.9	3.9	71	73
NGC 4826	12:56:43.6	+21:40:59	5.8	3.2	26	65
NGC 5055	13:15:49.3	+42:01:45	8.6	5.2	17	59

[a] The positions are from from the NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu/).
[b] The optical disc data are from the Spitzer Survey of Stellar Structure in Galaxies[5]. The position angle is expressed as degrees from west through north (which is non-standard but practical for this experiment).
[c] The inclinations of the galaxy discs are from The HI Nearby Galaxy Survey[4]. 0° corresponds to face-on, and 90° corresponds to edge-on.

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} W/m^2/Hz. This is a measurement of a quantity referred to as flux density (f_ν), which represents the amount of energy (ΔE) per time (Δt) observed within a given frequency range ($\Delta \nu$) that can be collected over a telescope area (ΔA), or

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

Sometimes measurements are reported as surface brightness (I_ν), 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.

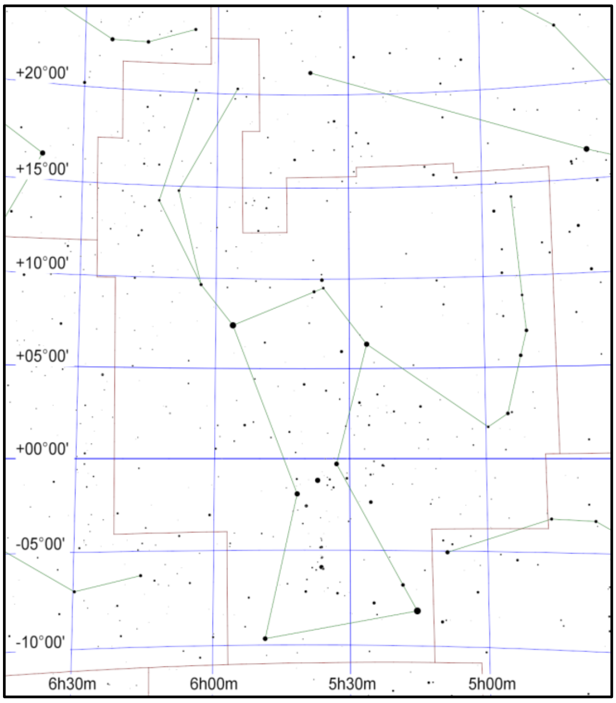

Figure 2: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

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. For reference, the Sun and Moon are both 0.5 degrees (or 30 arcminutes) 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 (deg^2), square arcseconds (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.

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 files from the NASA/IPAC Extragalctic Database (NED), a general astronomy image and data repository at http://ned.ipac.caltech.edu/ . The near-infrared images, which trace the starlight within the galaxies, contain "IRAC_3.6" in their names; this refers to the instrument used for the observation (IRAC) and the wavelength of the data (3.6 μm). The radio data, which trace the hydrogen gas in the galaxies and which can be used to measure the rotational velocities, contain "HI" in their names.

Galaxy with Known Distance	Files
NGC 925	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_0925:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_925_NA_CUBE:I:HI:wbb2008
NGC 2403	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_2403:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_2403_NA_CUBE:I:HI:wbb2008
NGC 2841	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_2841:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_2841_NA_CUBE:I:HI:wbb2008
NGC 3031	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/2008AJ....136.2563W/NGC_3031_NA_CUBE:I:HI:wbb2008
NGC 3351	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3351:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3351_NA_CUBE:I:HI:wbb2008
NGC 3621	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3621:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3621_NA_CUBE:I:HI:wbb2008
NGC 3627	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3627:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3627_NA_CUBE:I:HI:wbb2008
NGC 7331	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_7331:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_7331_NA_CUBE:I:HI:wbb2008
NGC 7793	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_7793:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_7793_NA_CUBE:I:HI:wbb2008

Galaxy with Unknown Distance	Files
NGC 628	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_0628:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_628_NA_CUBE:I:HI:wbb2008
NGC 2903	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2009ApJ...703..517D/NGC_2903:I:IRAC_3.6:d2009 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_2903_NA_CUBE:I:HI:wbb2008
NGC 3184	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3184:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3184_NA_CUBE:I:HI:wbb2008
NGC 3521	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_3521:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_3521_NA_CUBE:I:HI:wbb2008
NGC 4826	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_4826:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_4826_NA_CUBE:I:HI:wbb2008
NGC 5055	http://ned.ipac.caltech.edu/uri/NED::Image/fits/2003PASP..115..928K/NGC_5055:I:IRAC_3.6:kab2003 http://ned.ipac.caltech.edu/uri/NED::Image/fits/2008AJ....136.2563W/NGC_5055_NA_CUBE:I:HI:wbb2008

3. If necessary, rename each downloaded FITS file so that it ends in ".fits".

Measurement Procedure (Near-Infrared Data)

1. Start DS9.

2. Under "File" in either the menu or the button bar, click on "Open". Find and then open the near-infrared FITS image (with "IRAC_3.6" in its name) for one of the galaxies with a known distance.

3. Under "Scale", select "log". This will change the way the image values are displayed on the computer screen.

4. If it is necessary to change the brightness and contrast of the image to see the galaxy better, 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 the entire galaxy is visible. The result should look similar to Figure 3.

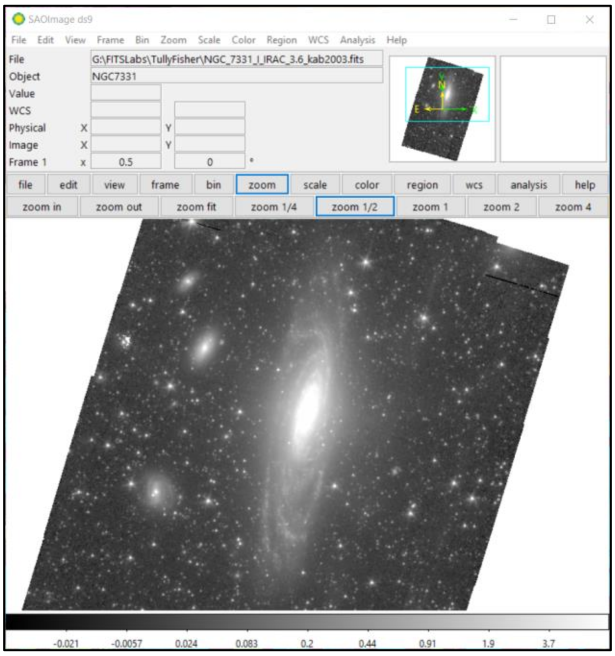

Figure 3: The near-infrared (3.6 µm) image of NGC 7331 as it appears in DS9 after applying steps 1-6 in the measurement procedure for the near-infrared data.

5. To re-center the image, middle click on the image. Alternately, go to "Edit", select "pan", and then left click on the image.

6. 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. Select a zoom factor that changes the size of the image so that the entire galaxy as well as a margin around the galaxy is visible in the DS9 display window.

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 4 after doing this.)

8. Under "Edit" in either the menu or button bar, click on "region".

9. Under "Region" in the menu bar, select "Shape" and then "Ellipse".

10. Left click on the image to draw an ellipse. When this region is selected, it will have four small squares around it.

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 doing this, type in the right ascension and declination for the centre of the galaxy as listed in the table at the end of the introduction.

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

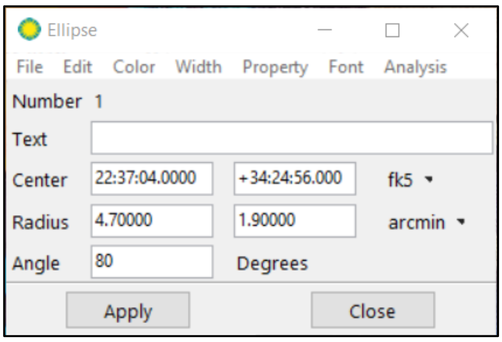

Figure 4: The window with the ellipse coordinate and dimension information.

"ArcMin", click on these options. After this, set the radii of the galaxy to those listed in the table at the end of the introduction.

14. In the row labelled "Angle", type in the position angle of the major axis of the ellipse as listed in the table in the introduction. (The position angles are in degrees from west through north or, in these specific images, in degrees from the x-axis clockwise through the y-axis.) See Figure 5 for an example of what the image looks like with an ellipse overlaid on it 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 µm) emission from the galaxy. Also record the number of pixels in the region listed under npix.

16. Under "Region" in the menu bar of the main DS9 window, select "Shape" and then "Circle".

17. 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.)

18. Double click on the circle to open a new window labelled "Circle".

19. 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 20 arcseconds.

20. Under "Analysis" in the menu, select "Statistics". Record the number listed in the new window under median. This is a measurement of the background signal in the image.

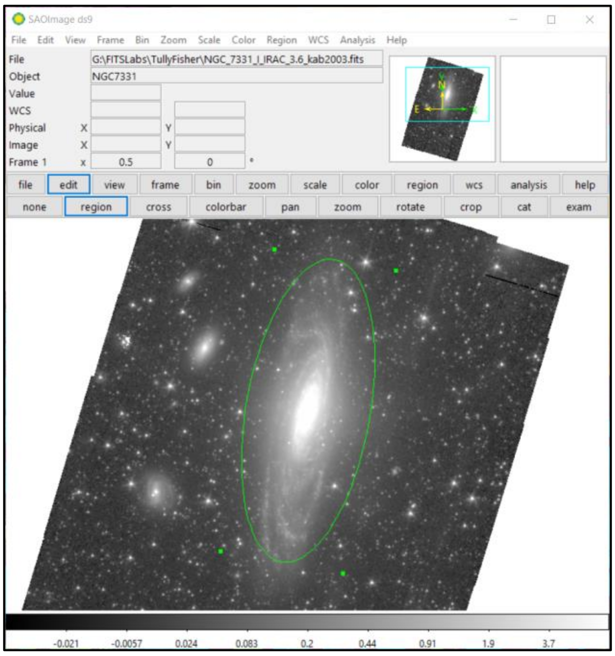

Figure 5: The same image as in Figure 3 but with an ellipse drawn over the galaxy.

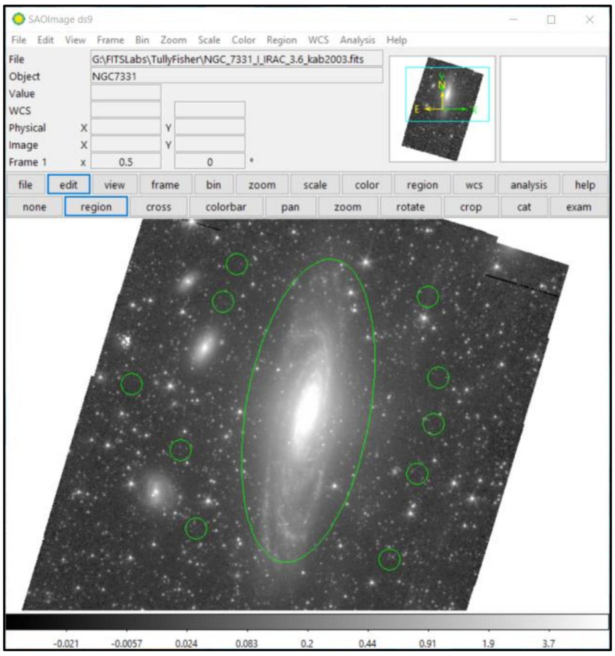

Figure 6: The same image as in Figure 3 but with an ellipse drawn over the galaxy and with 10 circles drawn in background regions around the galaxy.

21. Repeat steps 17-20 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 6.

22. 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 a name based on the name of the galaxy 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".

23. Repeat all of the steps in this section for the galaxies with known distances.

24. Repeat all of the steps in this section for one or more galaxies with unknown distances.

Measurement Procedure (Radio Data)

1. Under "File" in either the menu or the button bar, click on "Open". Find and then open the FITS image of hydrogen spectral line emission at radio wavelengths (with "HI" in its name) for one of the galaxies with a known distance. 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 7 for an example of the "Cube" window.

2. Under "Scale", select "log".

3. Under "Region" in the main DS9 window, click on "Load Regions". Load the region file that was saved in step 22 of the measurement procedure for the near-infrared image of the galaxy. (If a dialogue box appears, just click "OK".)

4. In the "Cube" window, move through frequencies (either by moving the slider or by using the "Previous", "Stop", "Play", and "Next" buttons) until the galaxy is visible. Because the hydrogen emission comes from a rotating disc, the emission will appear at different locations in the image when different velocities are selected. Find a velocity where the emission comes from the centre of the galaxy. See Figure 8 for an example.

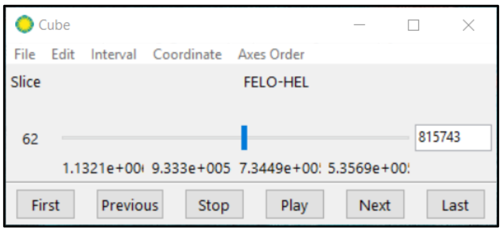

Figure 7: The Cube window showing the velocity and slice (third dimension) of the image cube displayed in the main DS9 display seen in Figure 8.

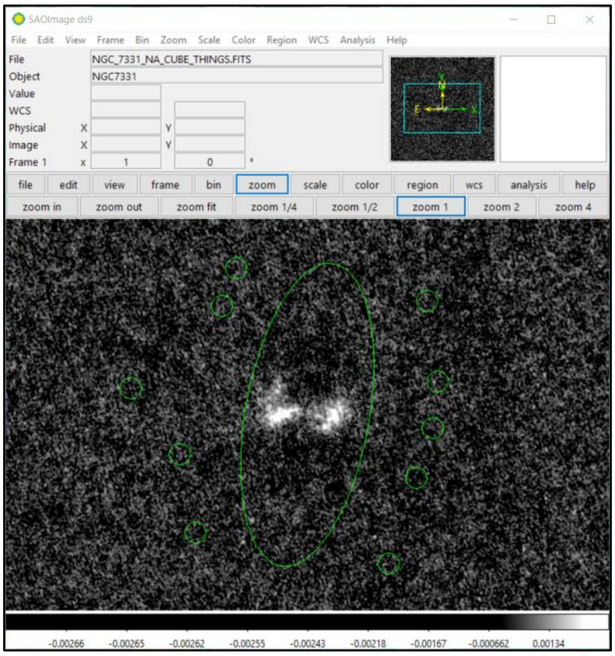

Figure 8: The radio (21 cm) image cube of the spectral line emission from hydrogen gas in NGC 7331as it appears in DS9 after applying steps 1-7 in the measurement procedure for the radio data.

5. Follow steps 4-7 from the near-infrared measurement procedure to adjust the display of the data if necessary.

6. Double click on the ellipse, which will open a new window labelled "Ellipse".

7. Under "Analysis" in the "Ellipse" window, select "Plot3D". This will display a plot of the average hydrogen line surface brightness within the ellipse (labelled "Counts Average" but actually in units of Jy/beam) versus the velocity of the gas (given in m/s). See Figure 9 for an example.

8. Under "File" in the menu for the plot, select "List Data". This will open a new window labelled "Data". See Figure 10 for an example.

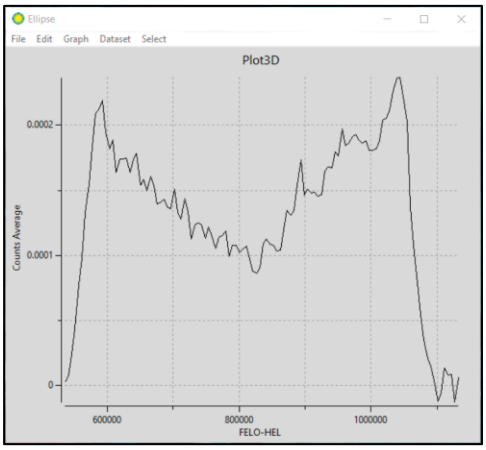

Figure 9: A plot showing the hydrogen spectral line emission (labelled "Counts Average" but actually in units of Jy/beam) versus velocity (labelled "FELO-HEL" in this example but actually in m/s) for the ellipse in Figure 8.

9. The "Data" window contains two columns of data: the velocity of the gas in m/s on the left, and the surface brightness in Jy/beam on the right. Use the graph and the list of numbers to find the peak surface brightness value. (If the plot has two or more peaks like in Figure 9, use the higher value.)

10. Find the velocities that corresponds to half of the peak surface brightness value at both the high velocity end and the low velocity end of the graph.

11. Repeat all of the steps in this section for the galaxies where measurements were made from the near-infrared data.

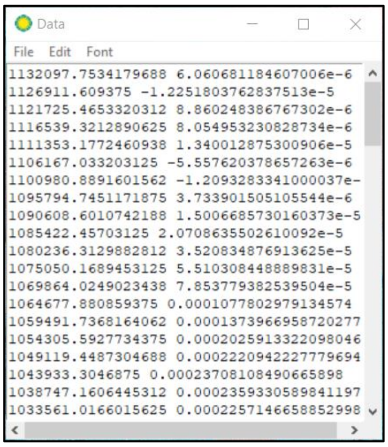

Figure 10: The window with numerical data used to create the plot of surface brightness versus frequency that is seen in Figure 9.

Numerical Analysis Procedure

1. For each near-infrared image, calculate the mean of the measurements within the background regions.

2. For each near-infrared image, multiply the mean background value by the number of pixels within the galaxy disc. After doing this, subtract this value from the sum of the pixel values for the galaxy disc. This number represents the signal from the galaxy.

3. The near-infrared data are in units of megaJanskys per steradian (MJy/sr), and the pixel are normally 0.75 arcseconds (or 3.64×10^{-6} radians) wide. Convert the near-infrared measurements to Janskys by multiplying by 1.32×10^{-5}.

4. The flux densities in Janskys should be converted into units of W/m^2/Hz by multiplying by 10^{-26}.

5. For the galaxies with known distances, the flux densities should be converted to luminosity densities L_ν with units of W/Hz. This can be done using

$$L_\nu = 4\pi D^2 f_\nu$$

which is a variant on the equation relating luminosity and flux given in the introduction. Use the distances given in megaparsecs (Mpc) in the table in the introduction and convert these to meters; one megaparsec is equivalent to 3.086×10^{22} meters.

6. The units of the velocities in the radio data are in m/s. Convert these data to units of km/s.

7. For each set of velocity measurements from each radio image, calculate the average velocity. This corresponds to the velocity with which the galaxy is moving from the Earth.

8. For each set of velocity measurements from each radio image, calculate the difference between the velocity values. This is a measurement of the rotational velocity of the galaxy.

9. Each rotational velocity needs to be corrected for the inclination of the galaxy. See Figure 11 for a diagram depicting this projection effect. To correct for this, use

$$v_{rot} = \frac{v_{rot\ (obs)}}{\sin\theta_i}$$

where $v_{rot(obs)}$ is the observed rotation velocity, v_{rot} is the actual rotation velocity, and θ_i is the inclination given in the tables in the introduction.

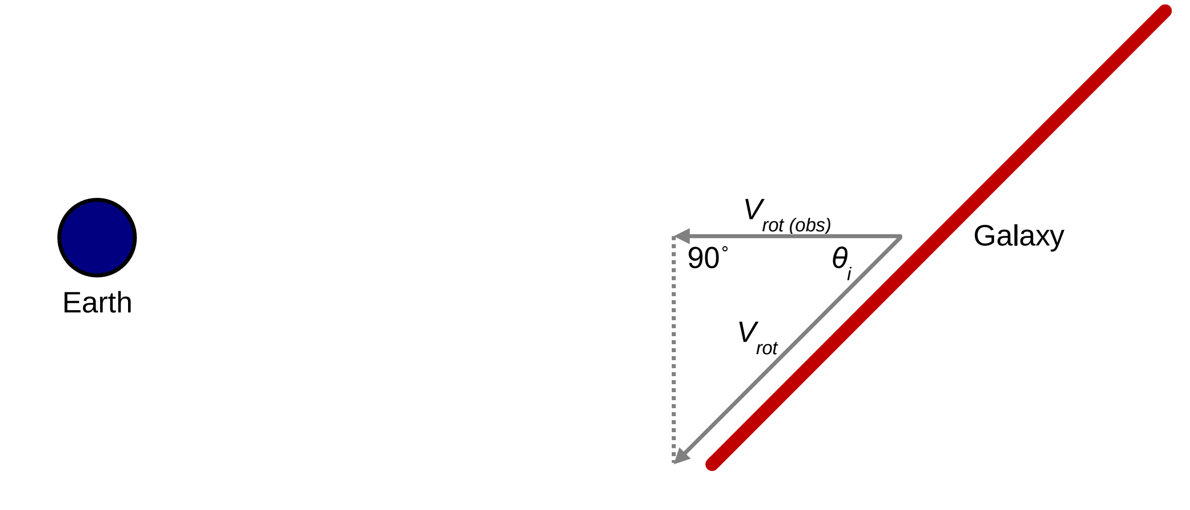

Figure 11: A diagram showing the relation between the velocity observed along the line of sight (v_{los}), the actual velocity (v), and the inclination angle (θ_i). The galaxy would appear halfway between face-on and edge-on as seen from Earth in this diagram.

10. For the galaxies with known distances, create a plot with $\ln(L_v)$ on the y-axis and $\ln(v_{rot})$ on the x-axis. This is the Tully-Fisher relation. Find the best-fitting line for the relation.

11. For the galaxies with unknown distances, use the best-fitting line from step 10 and the v_{rot} measurements to derive the L_v values. After doing this, use the calculated L_v values and the measured f_v to determine the distances. Convert these distances to megaparsecs.

12. Optionally, create a plot with the measured v_{mean} on the y-axis and the D (in megaparsecs) on the x-axis. This is the Hubble relation. Find the slope of the line that best fits this relation; this will be the Hubble constant H_0. Alternately, calculate v_{mean} /D for each galaxy and then average the values together to find the Hubble constant.

Discussion Questions

1. Some of the spectra for the radio data are very smooth, while others have a lot of spikes caused by noise in the data. How does the noise affect determining the velocities at half the peak velocity?

2. Try to identify the galaxy with a known distance that deviates the most from the relation between $\ln(L_v)$ and $\ln(v_{rot})$. Does this galaxy have any peculiar properties that make it different from the other galaxies?

3. While galaxies generally appear to be moving away from the Earth because of the expansion of the universe, the galaxies also move randomly relative to this expansion. Based on the Hubble relation created in this experiment, how large is this random component? Do all galaxies actually appear to be moving away from the Earth?

4. How do the plot of the Hubble relation and the value of the Hubble constant change when galaxies with distances from the Tully-Fisher relation are used compared to when these galaxies are not used?

5. A combination of observations of Cepheids from the Hubble Space Telescope and Gaia spacecraft[9] have been used to calculate the value of the Hubble constant as 73.2 km/s/Mpc, while data on the cosmic

microwave background radiation observed by the Planck spacecraft[10] gave a value of 66.9 km/s/Mpc. How do these values compare to the results from the relation in this experiment?

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