Measuring the Rotation of TW Hydrae

George J. Bendo, Adam Avison, and Rebecca Freestone
Jodrell Bank Centre for Astrophysics, The University of Manchester
19 June 2019

Overview

TW Hydrae is a protostellar object that is in the process of absorbing gas from a surrounding gas disc to become a hydrogen-burning main sequence star. The goal of this experiment is to use the DS9 astronomical image viewing tool to display and perform spectroscopic measurements on an image of TW Hydrae from the Atacama Large Millimeter/submillimetre Array (ALMA). The Doppler shifting of spectral lines in the image can be used to determine the velocity at which gas is rotating around the protostar, which in turn can be used to determine the mass of the protostar.
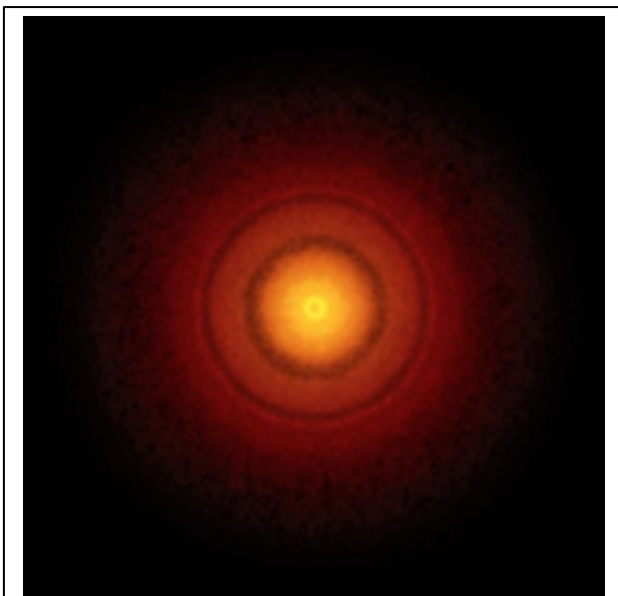

Figure 1:An ALMA image of the thermal emission from the dust in the gas disc surrounding TW Hydrae. (Different ALMA data with a coarser resolution are used in this experiment.) Image credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO).

General Astronomy Concepts

Stars form out of dense clouds of interstellar dust and gas. Typically, the gas pressure within these clouds prevents them from collapsing under their own gravity, but a shock wave, such as from a supernova or from the gravitational waves in spiral galaxies' arms, can cause the clouds to collapse. When this happens, the gas density increases as material falls inwards. The falling material retains its angular momentum and forms a circumstellar disc with a protostar at its centre. This disc feeds material into the forming star and can also potentially form planets.

TW Hydrae is a type of protostellar object known as a T Tauri star. It has become dense enough that it is recognisable as a star but not so dense that the core has begun fusing hydrogen into helium. Instead, the primary source of energy for the protostar is the energy lost as the star contracts and becomes denser. Unlike main sequence stars, which produce visible light, TW Hydrae produces infrared and millimetre radiation.

This experiment is based on using an image of TW Hydrae taken using ALMA, a millimetre/submillimetre telescope in the Atacama Desert in Chile. The image covers spectral line emission from carbon monoxide (CO), which traces molecular gas in the protostellar disc. Measurements of the Doppler shifting of the spectral line from its central frequency (345.7960 GHz) can be used to determine the rotational velocity of the gas in the disc. Using these results and Kepler's Third Law, it will be possible to estimate the mass of the central object.

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[1]. 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 (Δv) that can be collected over a telescope area (ΔA), or

$$f_v = \frac{\Delta E}{\Delta t\, \Delta A\, \Delta v}$$

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

$$I_v = \frac{f_v}{\Delta\Omega} = \frac{\Delta E}{\Delta t\, \Delta A\, \Delta v\, \Delta\Omega}$$

**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. The ALMA data used in this experiment have a beam that is equivalent to a circle with a radius of 0.85 arcsec.

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.)
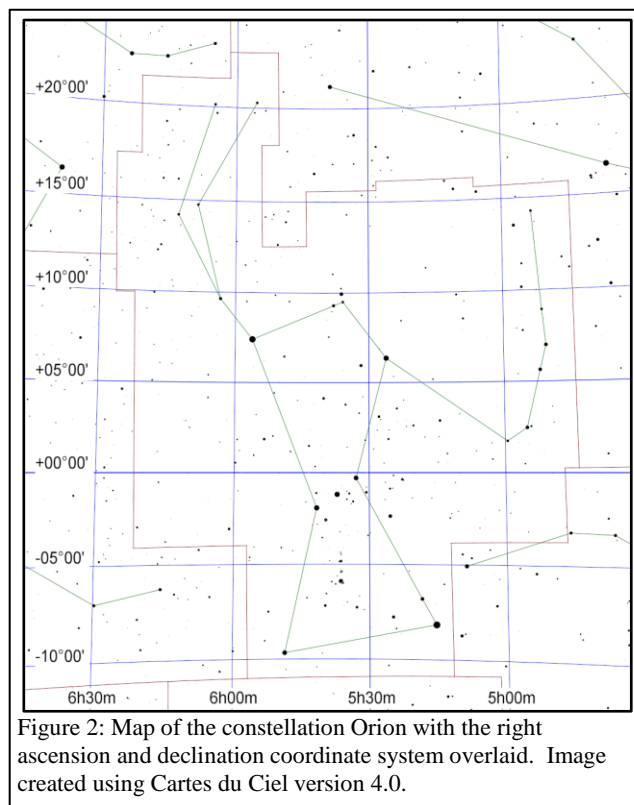
2. Download the ALMA data from https://almascience.nrao.edu/almadata/sciver/TWHya/TWHYA_BAND7_ReferenceImages.tgz . If that does not work, go to https://almascience.nrao.edu/almadata/sciver/TWHya/ and download TWHYA_BAND7_ReferenceImages.tgz. This is a file format called a gzipped tar file. It is a compressed file format that contains multiple files.

3. Follow one of the procedures below to extract the image from the tgz file.
   a. On Windows computers, follow these steps.
      i. Install either PeaZip (http://www.peazip.org/) or 7-Zip (http://www.7-zip.org/).
      ii. Open the TWHYA_BAND7_ReferenceImages.tgz file using PeaZip or 7-Zip. Extract the files from the tgz file. This should produce a new file named TWHYA_BAND7_ReferenceImages.tar. If the new file does not end in ".tar", add this to the end of the filename.
      iii. Open TWHYA_BAND7_ReferenceImages.tar in PeaZip or 7-Zip and extract the contents again.
      iv. The above steps should have created a folder named TWHYA_BAND7_ReferenceImages. Copy the file named TWHydra_CO3_2line.image.fits to a folder where it is possible to save analysis results.
   b. On Mac computers, double-click on the downloaded tgz file to open it. Find the file named TWHydra_CO3_2line.image.fits and copy this to a folder where it is possible to save analysis results.

Measurement Procedure

1. Start DS9.

2. Under "File" in either the menu or the button bar, click on "Open". Find and then open the FITS image (TWHydra_CO3_2line.image.fits). The data are three dimensional; two dimensions represent spatial dimensions on the plane of the sky, while the third dimension represents frequency. The main DS9 window will display the data as seen on the plane of the sky at a given frequency, while a second window labelled "Cube" can be used to select the frequency.

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

4. 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 increases the size of the image so that it fills the DS9 display window.

Figure 3: The CO spectral line image displayed in DS9 after setting the scale to log, adjusting the zoom, and changing the frequency so that the emission from the centre of the disc is visible.

5. In the "Cube" window, move through frequencies (either by moving the slider or my using the "Previous", "Stop", "Play", and "Next" buttons) until the source is visible and appears the most elongated. This should occur at slice 58 or a frequency of 3.45793×10^{11} Hz. See Figures 3 and 4 for examples.
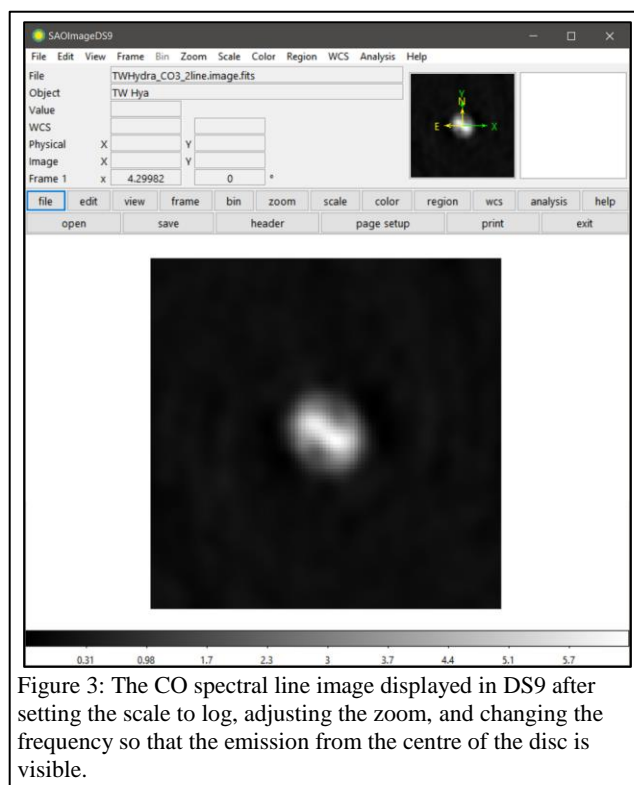
6. If it is necessary to change the brightness and contrast of the image to see the stars better, first move the cursor to the image window, then hold down the right mouse button (or, on a Mac laptop, hold down the mouse button and the cmd key at the same time), and then move the cursor either up and down or side to side in the window. Do this until the background is either dark grey or black and the disc is either light grey or white.

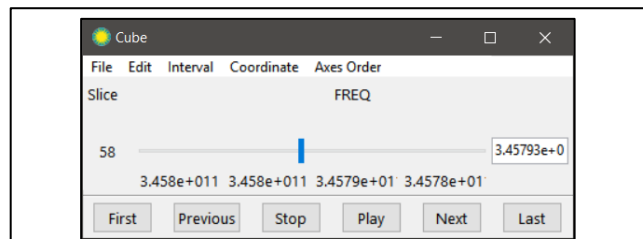

Figure 4: The Cube window showing the frequency and slice (third dimension) of the image cube displayed in the main DS9 display seen in Figure 2.
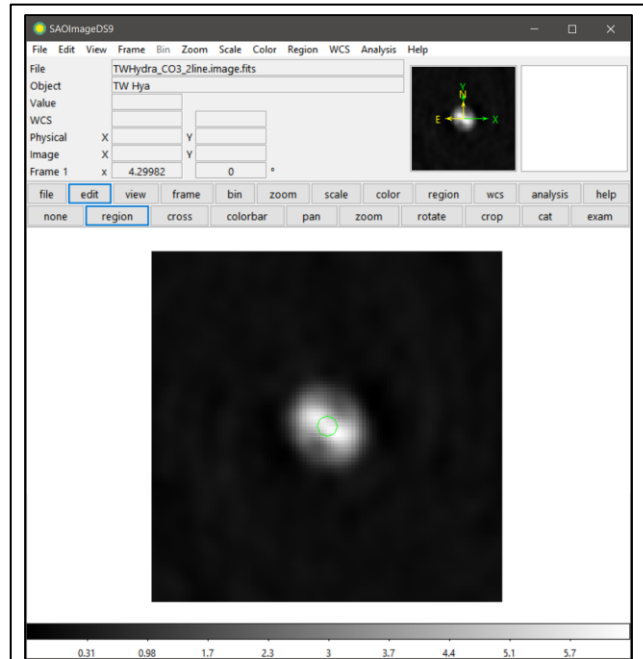
7. As an additional option, change the colours by clicking on an alternate scheme under "Color" in the menu or button bar. (It may be necessary to repeat step 6 after doing this.)

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

9. Left click on the image to draw a circle. When this region is selected, it will have four small squares around it. Move the circle until it is located in the centre of the source. This can be done by clicking on the circle with the left mouse button and, while holding the left mouse button down, dragging the circle across the image. Alternately, use the arrow keys. See Figure 5 for an example. (In this step or the next one, a plot of the counts average versus frequency may appear automatically. Close this for now; the window will be re-opened later in step 21.)

Figure 5: The same image as in Figure 3 but with a green circular region drawn in the centre.

10. Double click on the circle, which will open a new window labelled "Circle". See Figure 6 for an example. (A plot of the counts average versus frequency may appear automatically. Close this for now; the window will be re-opened later in step 21.)

11. 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 0.85 arcseconds.

Figure 6: The window with the circle coordinate and dimension information.

12. In the "Cube" window, click "Next" two times. This will show the light emitting from a part of the disc moving at a different velocity relative to the centre, and the line emission will be at a lower frequency.

13. Repeat steps 9-11 to draw a circle with a radius of 0.85 arcsec around the brightest emission at this frequency.

14. In the "Cube" window, click "Previous" four times. This will show the light emitting from the opposite side of the disc, and the line emission will be at a higher frequency.

15. Repeat steps 9-11 to draw a circle with a radius of 0.85 arcsec around the brightest emission at this frequency.

16. Shift the central region so that it lies as close as possible to the midpoint between the other two regions. The three circles should lie along a straight line.

17. Repeat steps 9-11 to draw two more circles above the first three circles. Place the circles so that they lie in a straight line with the first three circles and so that the circles are just barely touching each other.

18. Repeat steps 9-11 to draw two more circles below the other circles. Place the circles so that they lie in a straight line with the other circles and so that the circles are just barely touching each other. The end result should look like Figure 7.

19. Double click on one of the circles. This will open the "Circle" window.

20. The row labelled "Center" contains the coordinates for the center of the circle. Go to the drop-down menu on the right side of this row and select "image". After this, record the coordinates of the circle, which will be in terms of image pixels. After doing this, go to the drop-down menu to the right of the coordinates and select "WCS".

21. In the "Circle" window, click on "Analysis" and select "Plot3D". This should open the plot of the average CO line surface brightness (labelled "Counts Average" but actually in units of Jy/beam) versus frequency. See Figure 8. In a typical plot, the line intensity peaks near the central frequency. The peak will be located at different locations for the different circles drawn on the image; this shows how the CO line emission is Doppler shifted by the rotation of the gas disc around TW Hya.

22. Under "File", click on "List Data". This will open a new window labelled "Data". See Figure 9.

23. The "Data" window contains two columns of data: the frequency in Hz on the left, and the surface brightness in Jy/beam on the right. Find the frequency that corresponds to the maximum surface brightness and record the values from both columns. (If the plot shows two peaks, choose the frequency between these two peaks.) Also record the frequencies and surface brightnesses for the two data points above and the two data points below this
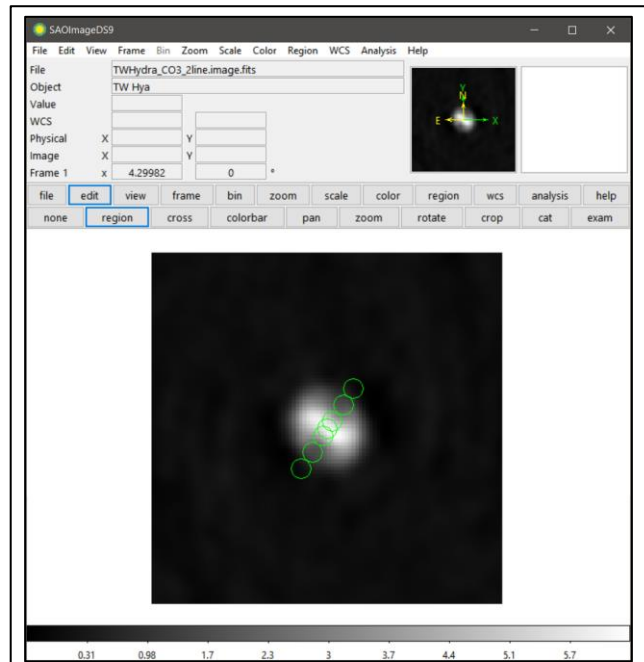

Figure 7: The same image as in Figure 3 but with multiple green circular regions drawn along the major axis of the disc.
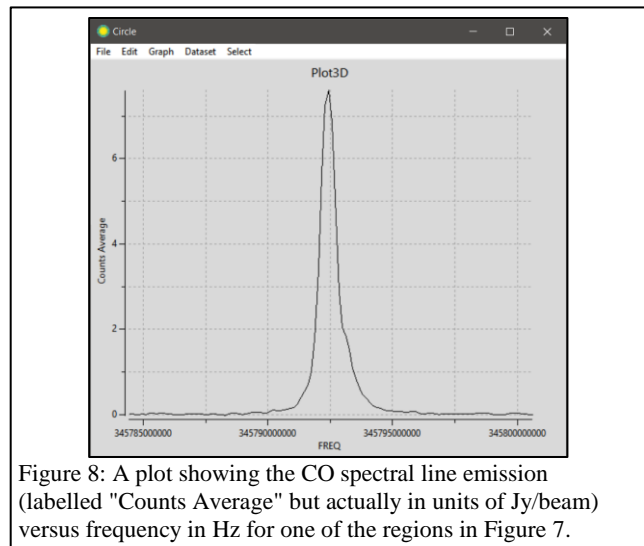

Figure 8: A plot showing the CO spectral line emission (labelled "Counts Average" but actually in units of Jy/beam) versus frequency in Hz for one of the regions in Figure 7.

Figure 9: The window with numerical data used to create the plot of surface brightness versus frequency that is seen in Figure 7.

central frequency. The frequencies should be recorded to 7 significant figures, but the surface brightnesses only need to be recorded to 2 significant figures.
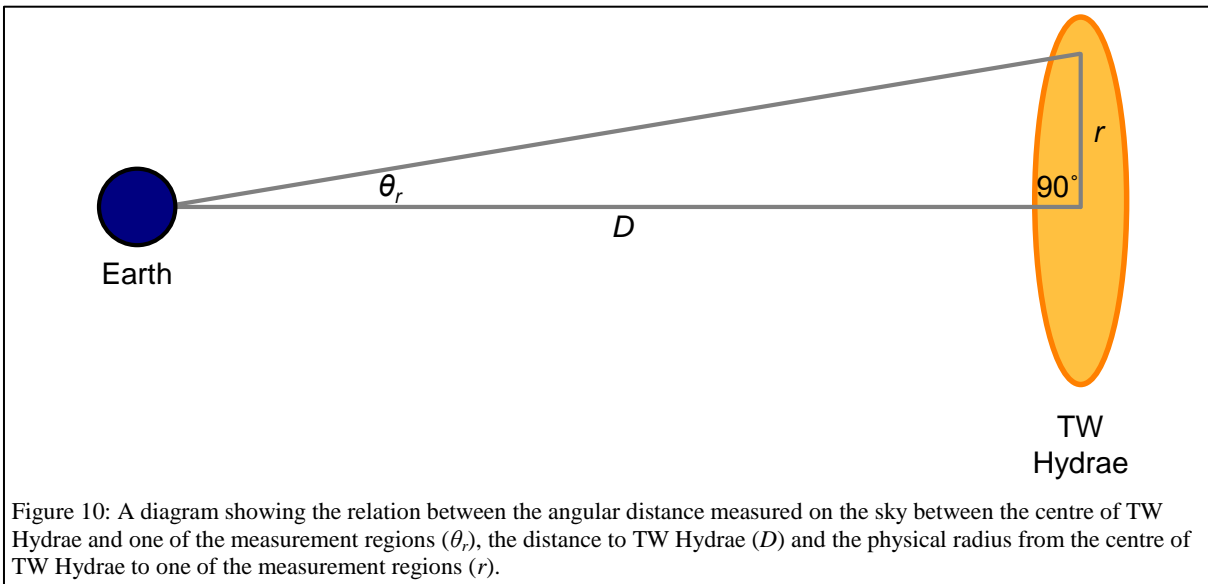
24. Repeat steps 19-23 for all of the circles.

Numerical Analysis Procedure

1. Calculate the distances from the centre of the central circle to the centres of the other circles in terms of pixels. These will be the radii from the centre of the disc. Multiply the radii by the pixel scale, which is 0.3 arcsec/pixel, to get the angular distance between the circles. This angular distance will be labelled θ_r.

2. The angular distances should be converted to physical distances using

$$r = D \tan \theta_r$$

where θ is the angular distance, r is the radius in physical units, and D is the distance from Earth to T Hydrae, which is 59.5 pc [1]. For reference, 1 pc is equal to 3.086×10^{16} m. Figure 10 shows the geometry of the disc as seen from the Earth.

Figure 10: A diagram showing the relation between the angular distance measured on the sky between the centre of TW Hydrae and one of the measurement regions (θ_r), the distance to TW Hydrae (D) and the physical radius from the centre of TW Hydrae to one of the measurement regions (r).

3. Calculate the weighted mean frequency $\bar{f}$ of the spectral line emission in each circle using

$$\bar{f} = \frac{\sum_i I_i f_i}{\sum_i I_i}$$

where I_i is the surface brightness measured at each frequency f_i in the circle.

4. Calculate the velocity v_{los} along the line of sight of the gas in each circle using
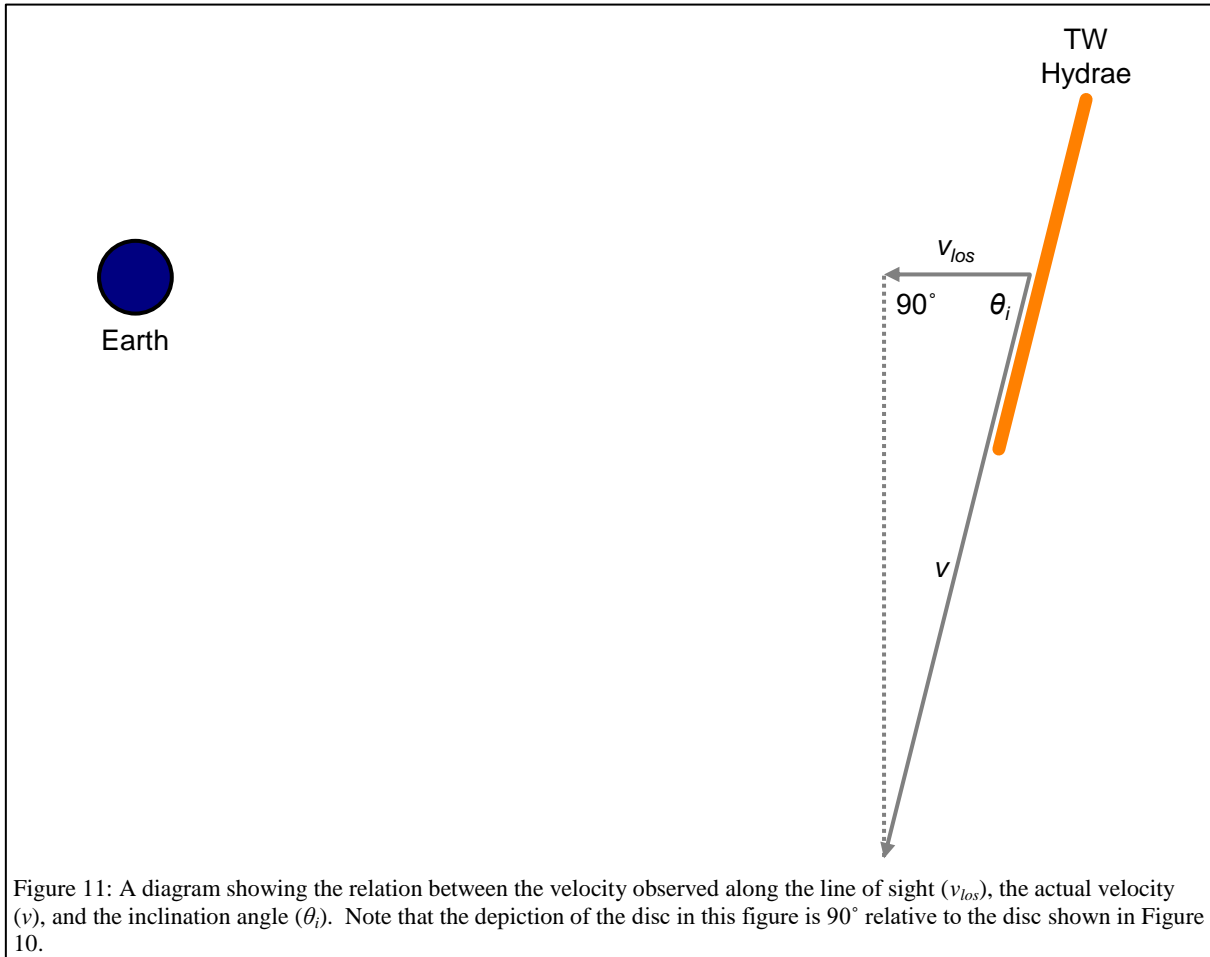
$$v_{los} = (3.00 \times 10^8 \text{ m/s}) \left(1 - \frac{\bar{f}}{345.7960 \text{ GHz}} \right)$$

which is based on special relativity. After doing this, subtract the velocity for the central circle from the velocities for the other circles.

5. The actual velocities include a component perpendicular to the line of sight, as seen in Figure 11. As seen from Earth, the disc of TW Hydrae is inclined at an angle θ_i of $7°$ [2,3]. The line of sight velocities can therefore be converted to the actual rotational velocity of the gas in the disc using

$$v = \frac{v_{los}}{\sin \theta_i}$$

See Figure 11 to see a diagram depicting this projection effect.

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). Note that the depiction of the disc in this figure is $90°$ relative to the disc shown in Figure 10.

6. Use the equation

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

to calculate the mass of the star based on the measurements from each circle. In this equation, G is the gravitational constant, which is 6.67×10^{-11} m^3 kg^{-1} s^{-1}. After doing this, average all of the mass measurements and then convert the mass to units of solar masses $M_\odot$ by dividing by 1.99×10^{30} kg/$M_\odot$. This is the final result of the analysis.

Discussion Questions

1. How does the mass measurement compare with the mass of the sun? Given this, what type of star appears to be forming in the centre of TW Hydrae?

2. Create a plot with radius on the x-axis and velocity on the y-axis. What shape is the function?

3. Do you get the same or similar mass measurement from all of the measurement regions? If not, what could have affected the measurements?

4. If the inclination was changed by 1˚, how would the estimated mass change?

References

[1] Gaia Collaboration et al., *Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties*, 2016, *Astronomy & Astrophysics*, 595A, 2

[2] Qi C. et al., *Imaging the Disk Around TW Hydrae with the Submillimeter Array*, 2004, *Astrophysical Journal*, 616, L11

[3] Andrews S. A. et al., *Ringed Substructure and a gap at 1 au in the Nearest Protoplanetary Disk*, 2016, *Astrophysical Journal*, 820, L40