

# Measuring the Rotation of TW Hydrae

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## 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 measure the rotational velocity of the gas disc so as to measure the mass of the star. The DS9 astronomical image viewing tool will be used to display an image of TW Hydrae from the Atacama Large Millimeter/submillimetre Array (ALMA) and to measure Doppler shifting of the gas emission detected by the telescope.

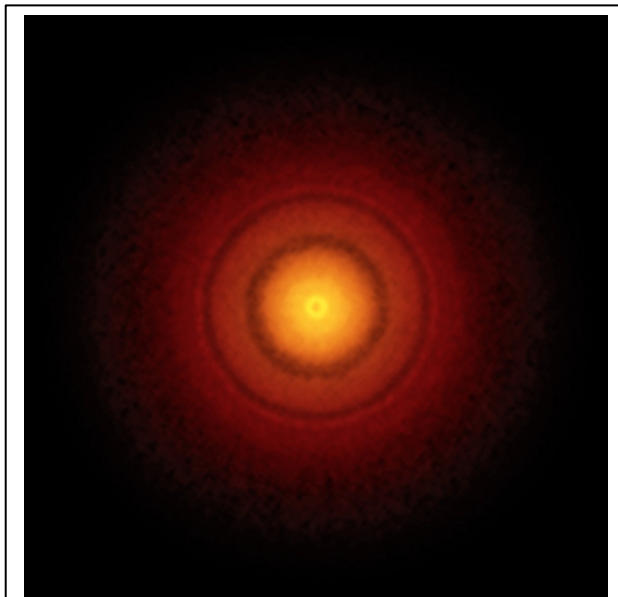


Figure 1: An ALMA image of the thermal emission from the dust in the gas disc surrounding TW Hydrae. (Different ALMA data with a coarser resolution are used in this experiment.) Image credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO).

## 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 around the central mass, which is a protostar. 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 hydrogen fusion. Instead, the primary source of energy for the protostar is the gravitational potential 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 and submillimetre telescope in the Atacama Desert in Chile. The telescope was designed specifically to image stars with gas and dust discs like TW Hydrae. The specific image used in this experiment covers spectral line emission from carbon monoxide (CO) in the protostellar disc. The CO traces the molecular gas in the disc, and the Doppler shifting of the spectral line from its central frequency (345.7960 GHz) is indicative of how the gas is moving in the disc. The image will be used to determine the rotational velocity of TW Hydrae. Using these results and Kepler's Third Law, it will be possible to estimate the mass of the central object.

### 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, 60 minutes in an hour, and 60 seconds in a minute. However, right ascension is sometimes 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).

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 nearest spiral galaxy, which is the Andromeda Galaxy, and the Pleiades cluster of stars are both 3 degrees across.

### 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

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

In the case of the ALMA data used for the analysis, the units are Jy/beam, which means that the flux density is spread over an area equivalent to the beam, which is the smallest object that can be seen by the telescope. Alternately, the beam is the area over which the emission from a point source will be spread out by the telescope. In the case of the ALMA image of the CO line emission from TW Hydrae, the beam is equivalent in size to a circle with a radius of 0.85 arcsec.

### Preparation Procedure

1. Download and install DS9 from the DS9 download page (<http://ds9.si.edu/site/Download.html>). This software is available for Windows, Mac, and Linux. Use version 7.2.1 for Windows.
2. 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. Follow these steps for Windows computers

- 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. 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. At the end of either of the above steps, you should have a folder named "TWHYA\_BAND7\_ReferenceImages". Copy the file named "TWHydra\_CO3\_2line.image.fits" to a folder where you can save your work.
- 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 you can save your work.

## 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", click on "log". This will change the way that the image values are displayed on the computer screen.
4. Click on a zoom factor under "Zoom" to increase the size of the image so that it fills the DS9 display window. Alternately, if you are using a mouse with a scroll wheel, you can use the scroll wheel to change the image magnification.
5. In the "Cube" window, move through frequencies (either by moving the slider or by using the "Previous", "Stop", "Play", and "Next" buttons) until the source is visible and appears

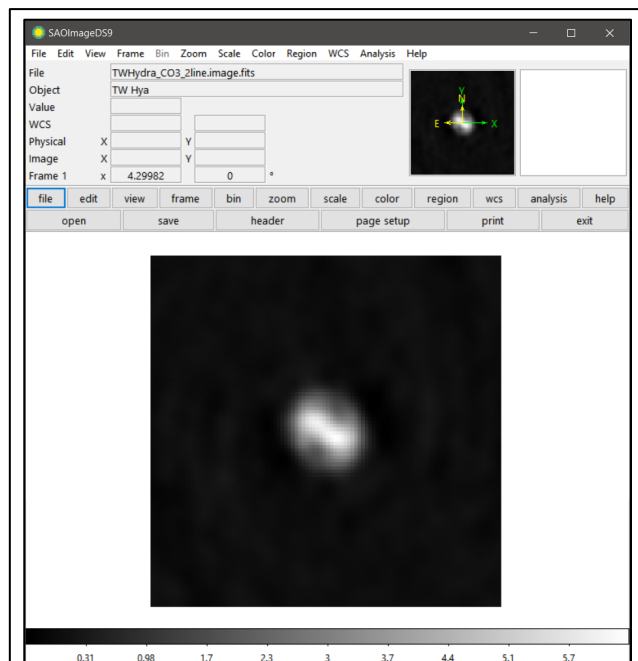


Figure 2: The CO spectral line image displayed in DS9 after setting the scale to log, adjusting the zoom, and changing the frequency so that the emission from the centre of the disc is visible.

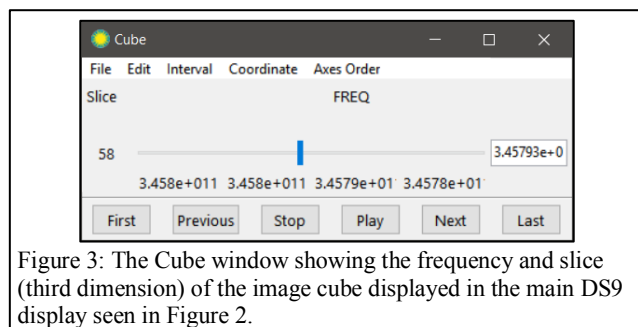


Figure 3: The Cube window showing the frequency and slice (third dimension) of the image cube displayed in the main DS9 display seen in Figure 2.

the most elongated. This should occur at slice 58 or a frequency of  $3.45793 \times 10^{11}$  Hz. See Figures 2 and 3 for examples.

6. Move the pointer to the image window. 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 move the cursor in the window to change the brightness and contrast of the image. Do this until the background is either dark grey or black and the disc is either light grey or white.
7. Optionally, change the colours by clicking on an alternate scheme under "Color". (It may be necessary to repeat step 6 after doing this.)
8. Under "Edit", click on "pointer" or, if that is not listed, "region".
9. In the image window, left click to draw a circle. When this circle is selected, it will have four small squares around it that can be used for resizing 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 4 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.)

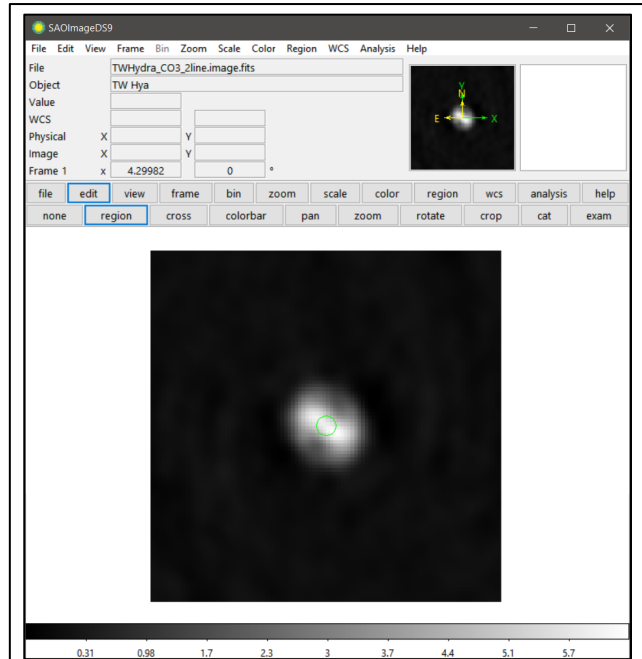


Figure 4: The same image as in Figure 2 but with a green circular region drawn in the centre.

10. Double click on the circle. This will open a new window. See Figure 5 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. Set the units of the circle radius to "arcsec". Make sure that "WCS" in the drop-down menu has a check mark next to it. After this, set the radius of the circle to 0.85 arcseconds.
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.

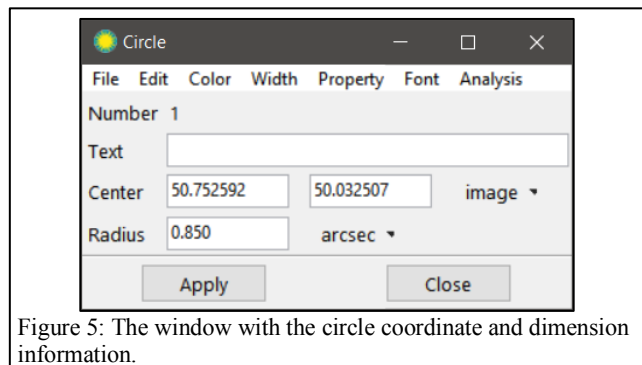


Figure 5: The window with the circle coordinate and dimension information.

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 6.
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. When the "Circle" window opens, 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 7. For this image, a typical plot should show a peak in line intensity 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

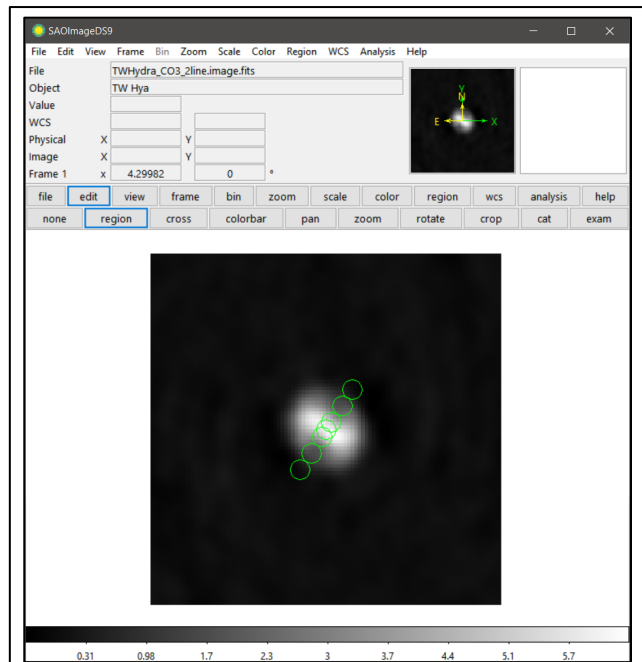


Figure 6: The same image as in Figure 2 but with multiple green circular regions drawn along the major axis of the disc.

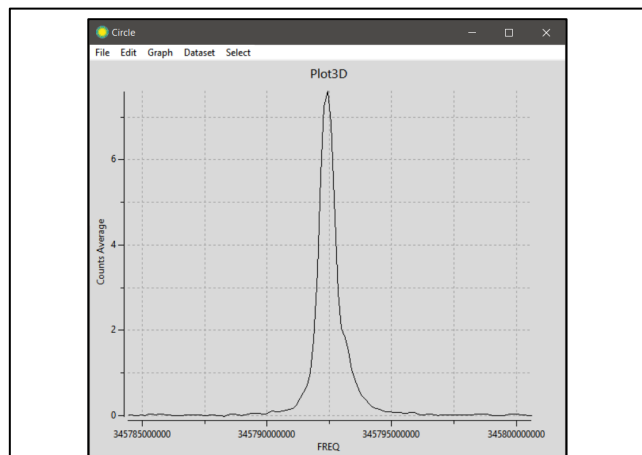


Figure 7: a plot showing the CO spectral line emission (labelled "Counts Average" but actually in units of Jy/beam) versus frequency in Hz for one of the regions in Figure 6.

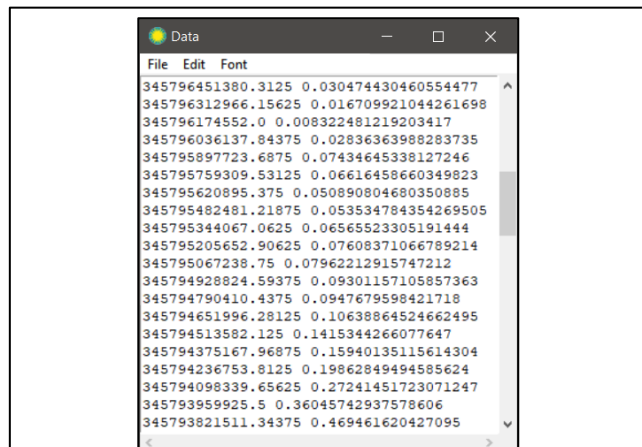


Figure 8: The window with numerical data used to create the plot of surface brightness versus frequency that is seen in Figure 7.

shifted by the rotation of the gas disc around TW Hya.

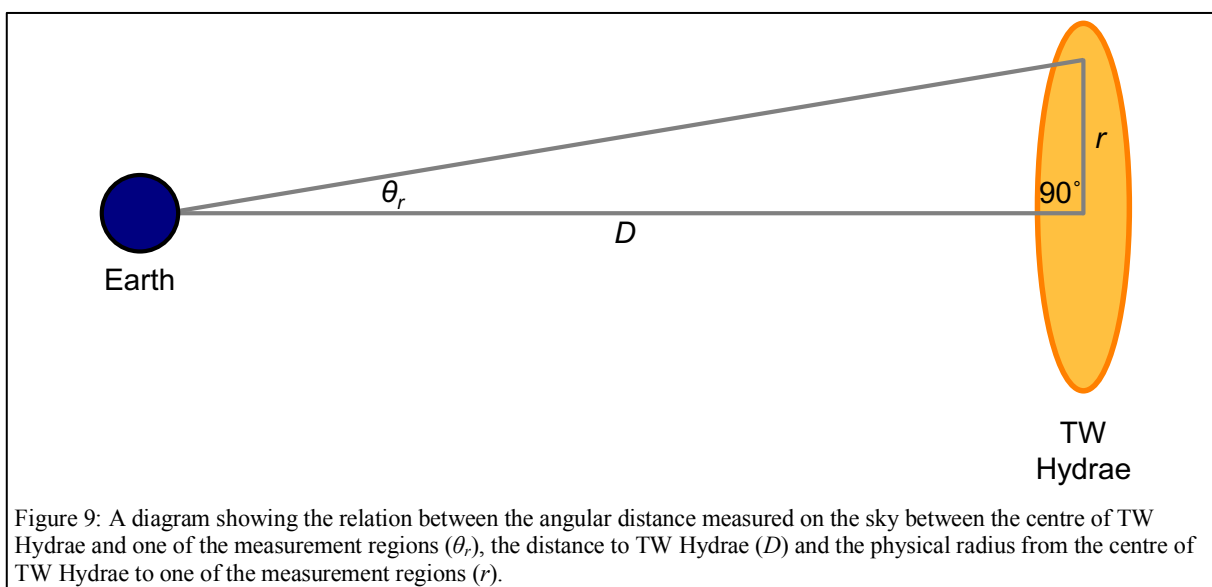
22. Under "File", click on "List Data". This will open a new window labelled "Data". See Figure 8.
23. The "Data" window contains two columns of data: the frequency in Hz on the left, and the surface brightness in Jy/beam on the right. Find the frequency that corresponds to the maximum surface brightness and record both values. (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 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, which will be labelled  $\theta_r$ .
2. The angular distances should be converted to physical distances using

$$r = D \sin \theta_r$$

where  $\theta$  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<sup>1</sup>. For reference, 1 pc is equal to  $3.086 \times 10^{16}$  m. See Figure 9 to see the geometry of the disc as seen from the Earth.



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 each circle.

- Calculate the velocity  $v_{los}$  along the line of sight of the gas in each circle using

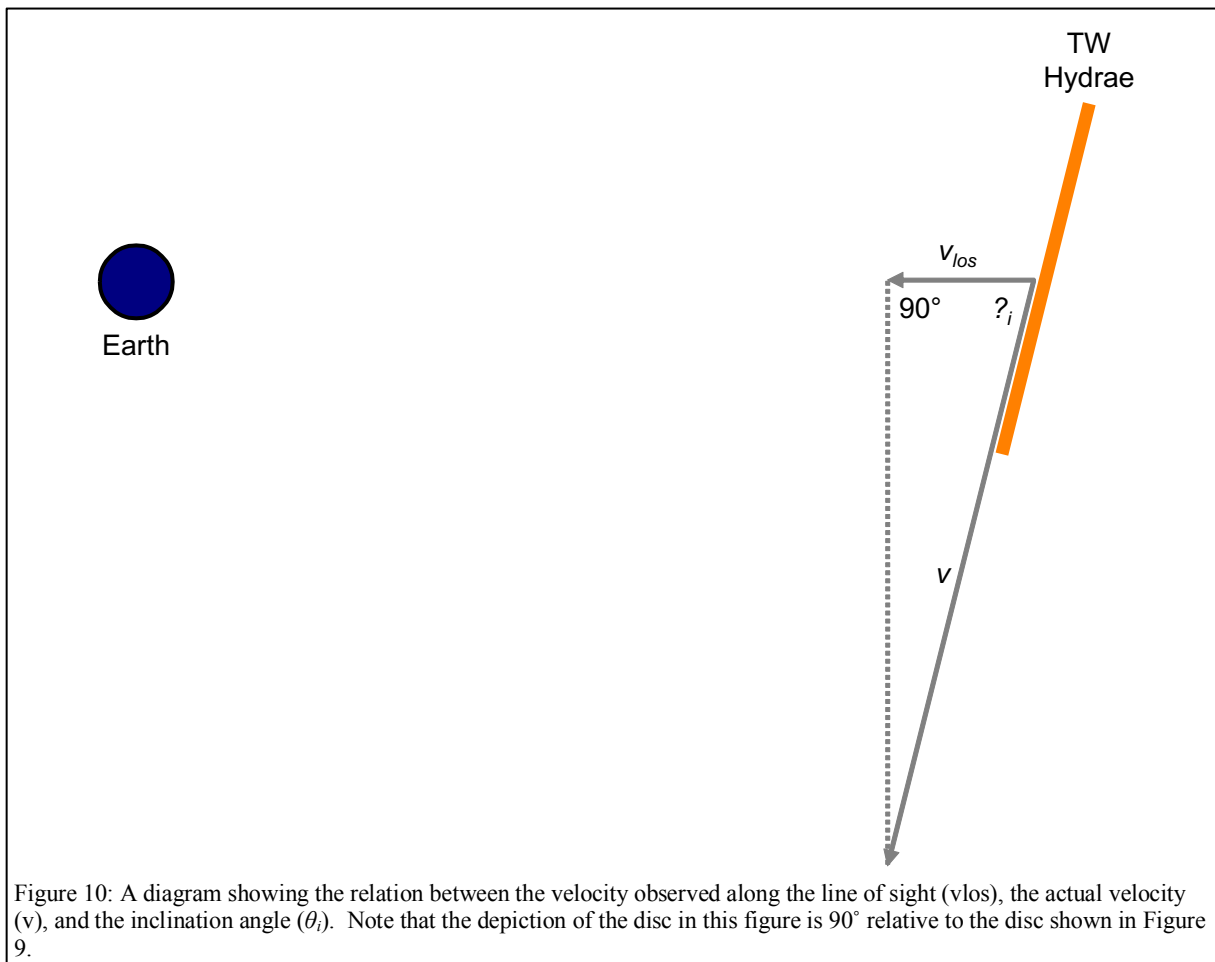
$$v_{los} = (3.00 \times 10^8 \text{ m/s}) \left( 1 - \frac{\bar{f}}{345.7960 \text{ GHz}} \right)$$

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

- 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  $\theta_i$  of  $7^\circ$ <sup>23</sup>. 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 10 to see a diagram depicting this projection effect.



- 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  $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ . After doing this, average all of the mass measurements and then convert the mass to units of solar masses  $M_{\odot}$  by dividing by  $1.99 \times 10^{30} \text{ kg}/M_{\odot}$ . 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  $1^{\circ}$ , how would the estimated mass change?

### References

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

<sup>2</sup> Qi C. et al., *Imaging the Disk Around TW Hydrae with the Submillimeter Array*, 2004, *Astrophysical Journal*, 616, L11

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