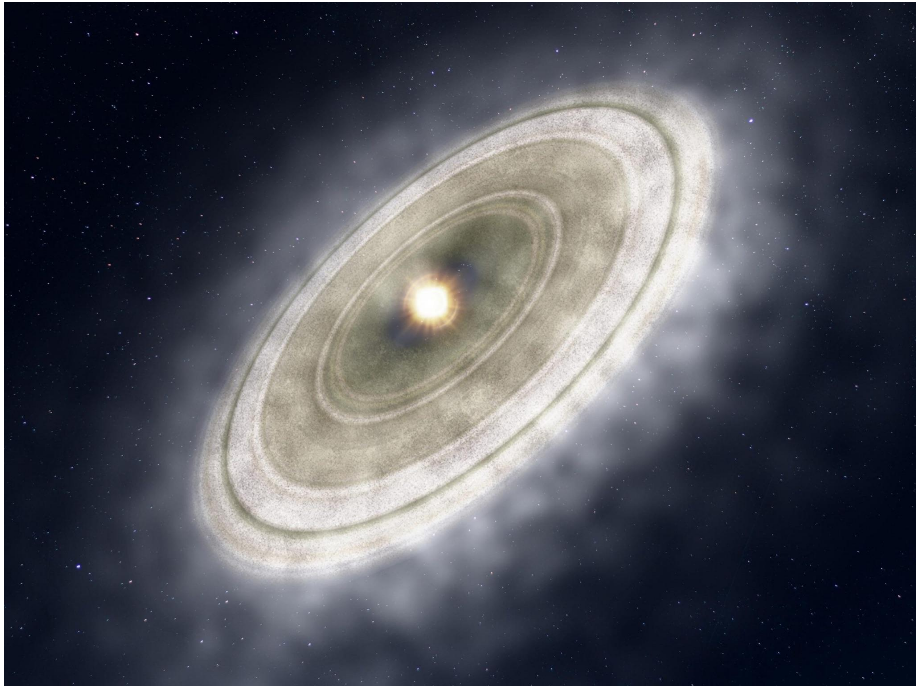
Dynamical Measurement of Host Star Mass in Debris Disks using ^{12}CO Line Emission

Owen Gonzales, Saad Waheed, Carlos Ordoñez

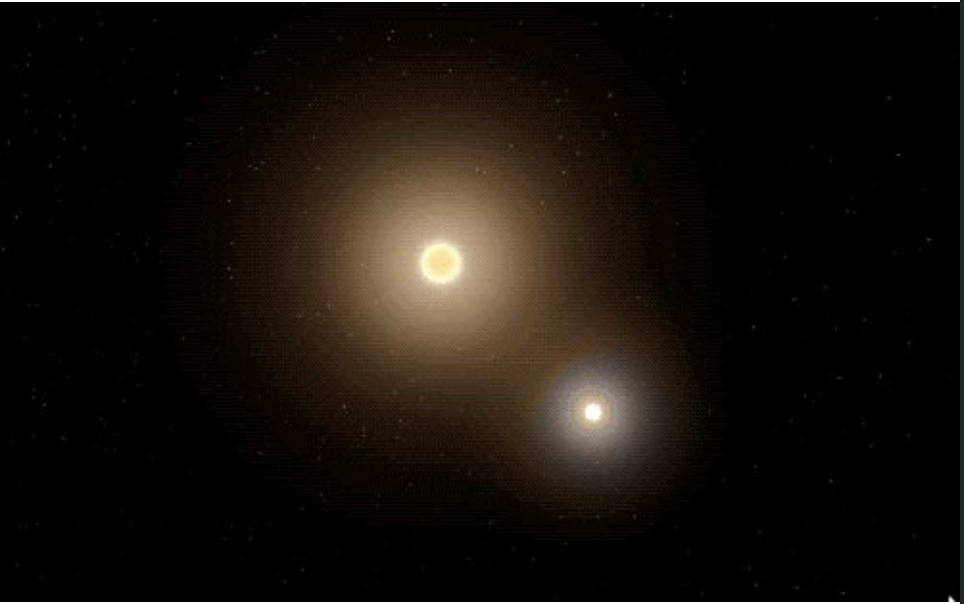
What is a Debris Disk?



Artist's conception of a debris disk. Credit: NAO

- Circumstellar disks of gas and dust
- Occur after planet formation
- Bright in the radio spectrum
- Smaller planetesimals grind themselves down in a process called the collisional cascade
- Larger and brighter extrasolar analogues to our own Kuiper Belt
- Some contain gas. This is a relatively recent discovery which allows us to observe spectral lines.

So, why look at debris disks?

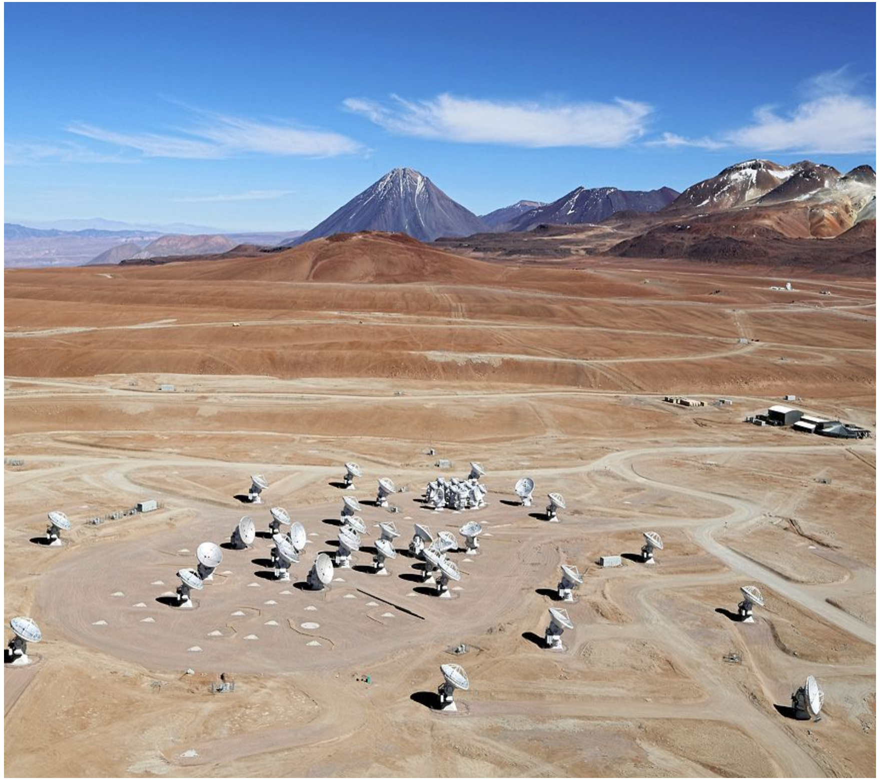


Simulation of a near edge on binary system. Credit: NASA

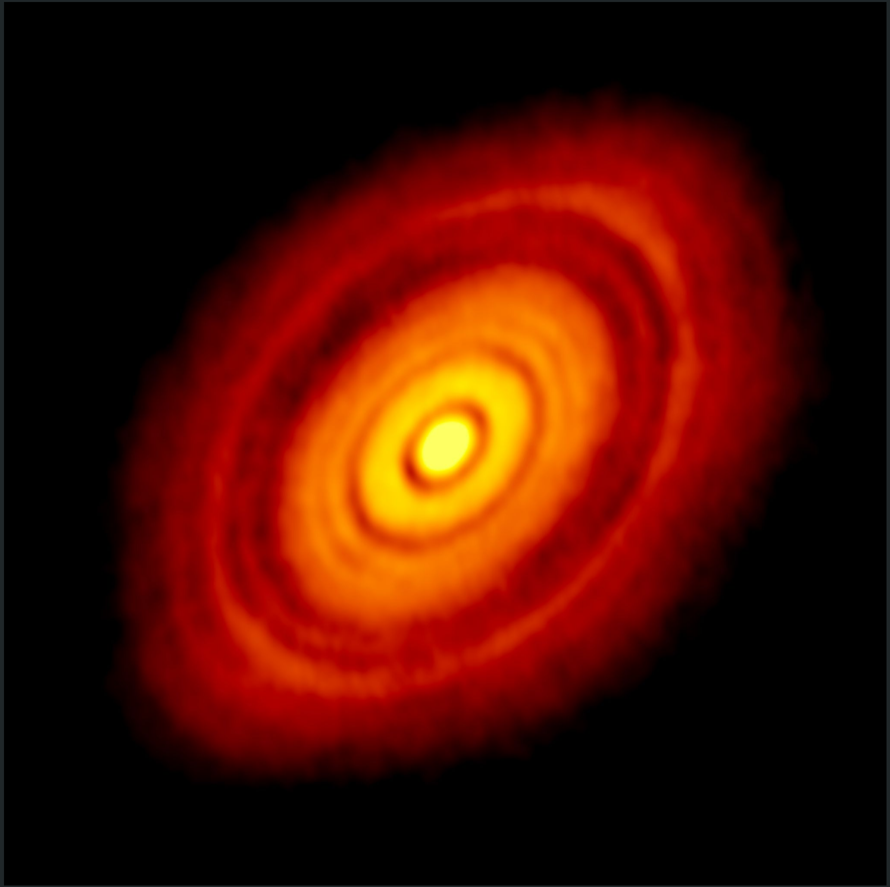
- Observations of debris disks are currently the only method of directly measuring a star’s gravitational effect on its system.
- As a result, most reported stellar masses are estimates based on stellar evolution models.
- Observations of spectral lines allow us to observe a Doppler shift created by the rotation of the disk - Kepler’s laws.
- We expand on previous research by applying this technique to a new class of stars.

ALMA

Atacama Large/Submillimeter Millimeter Array



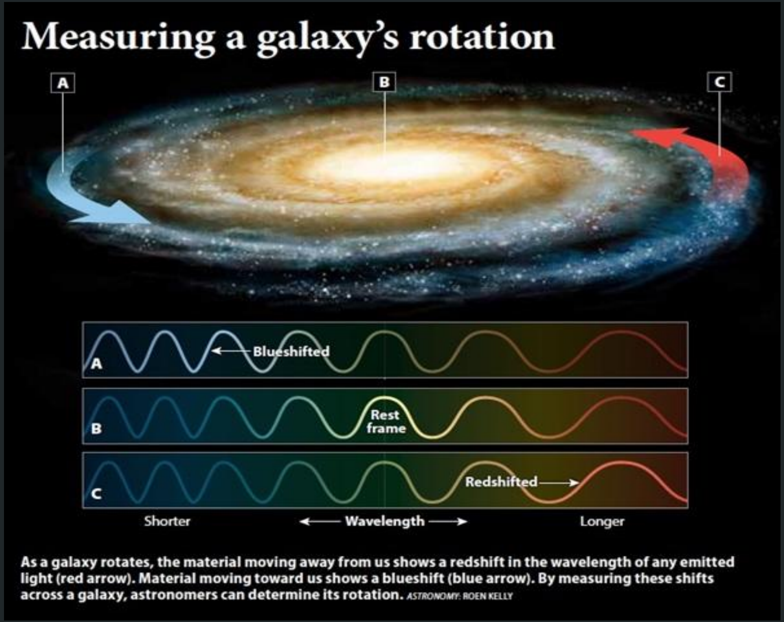
Alma array in the Atacama desert, Chile. Credit: Space.com



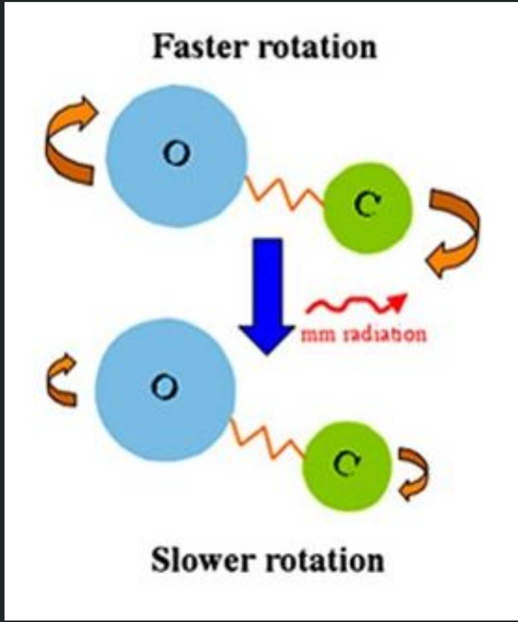
Continuum image of dust around HL Tau. Rings caused by active planet formation.
Credit: ALMA

Molecular Spectroscopy

- Electrons in atoms emit light at specific frequencies when they jump to a lower energy level.
- Molecules also have quantized rotational energies.
- Spectral lines act as a "fingerprint" for molecules present in an astronomical object.
- Motion of these molecules causes a Doppler shift in their spectral lines.



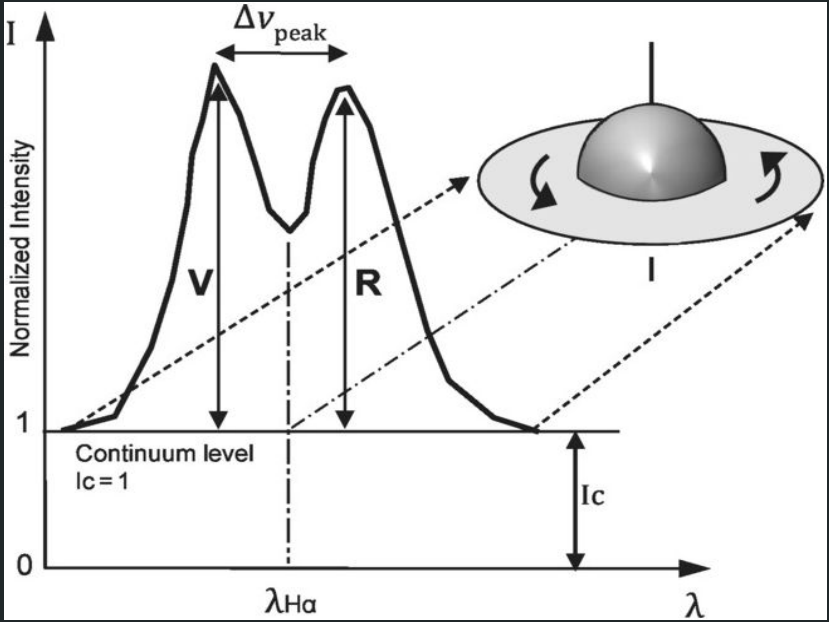
Doppler shift due to a rotating galaxy:
Credit: Astronomy Magazine



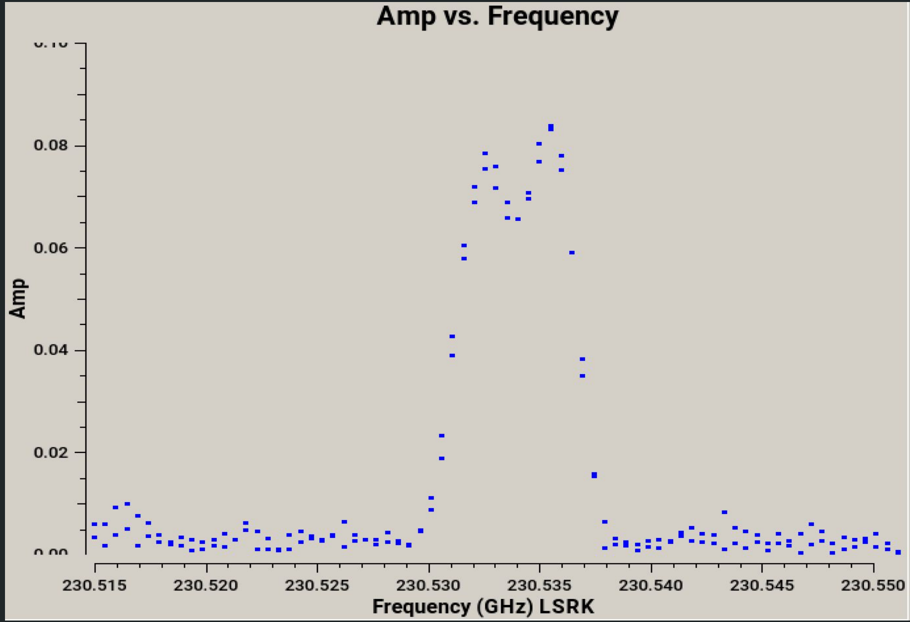
Rotation of CO molecule. Credit: NIST

How Do We Use Molecular Spectroscopy?

- We observed the CO (3-2) and CO (2-1) rotational transitions.
- Rotation of the debris disk causes a Doppler shift in the ^{12}CO spectral lines, leading to a double-peak' structure. This can be used to determine the velocity at different distances away from the star

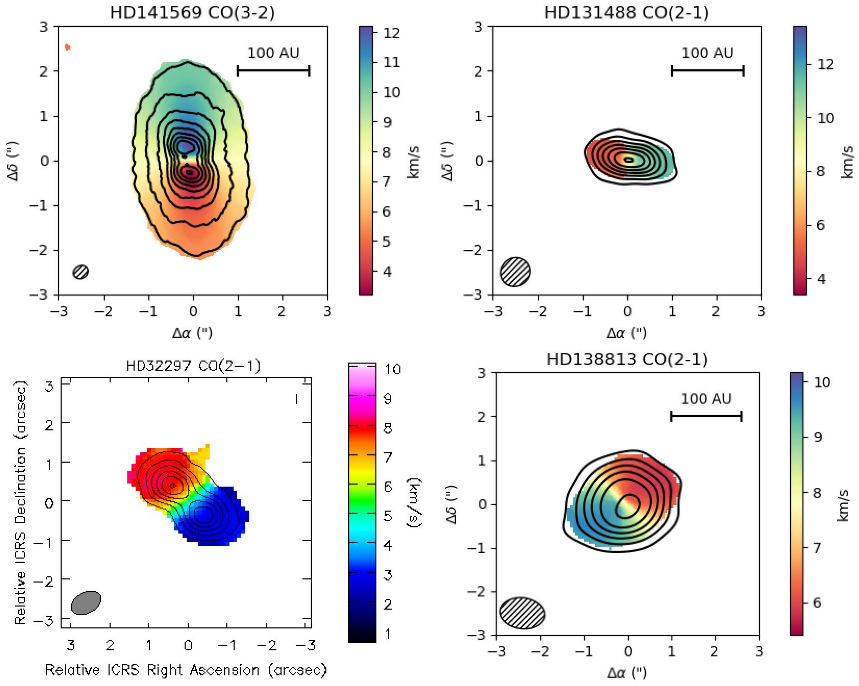


Double peaked structure due to rotation. Credit: Cambridge University Press



Frequency graph for HD32297 - clear double peaked structure.

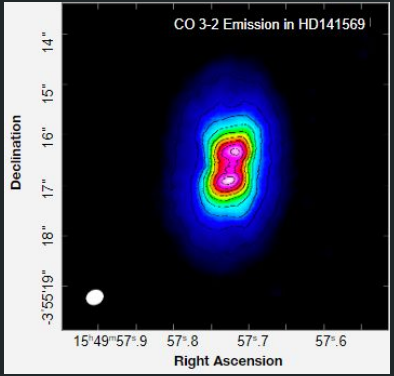
Picking our Targets

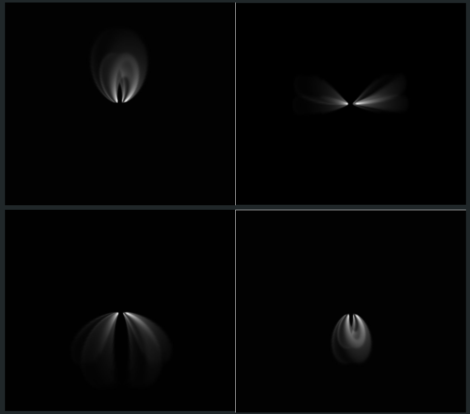


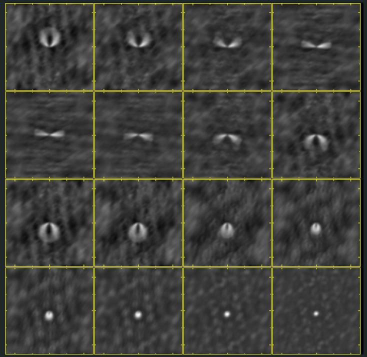
Moment 1 maps of our disks

- We searched recent literature to find debris disks with a conclusive ^{12}CO signature (~20 disks).
- Used the Common Astronomy Software Application (CASA) to generate line emission images, moment 0, and moment 1 maps with the CO(2-1) and CO(3-2) spectral lines.

Generating Models







Data processing

Split out frequencies with spectral line. Time averaged data to reduce its size.

Statistical weights

Gave each data point a weight, denoting confidence in its value.

Model Generation

Used a ray tracing code to generate models under the assumption of Local Thermal Equilibrium (LTE)

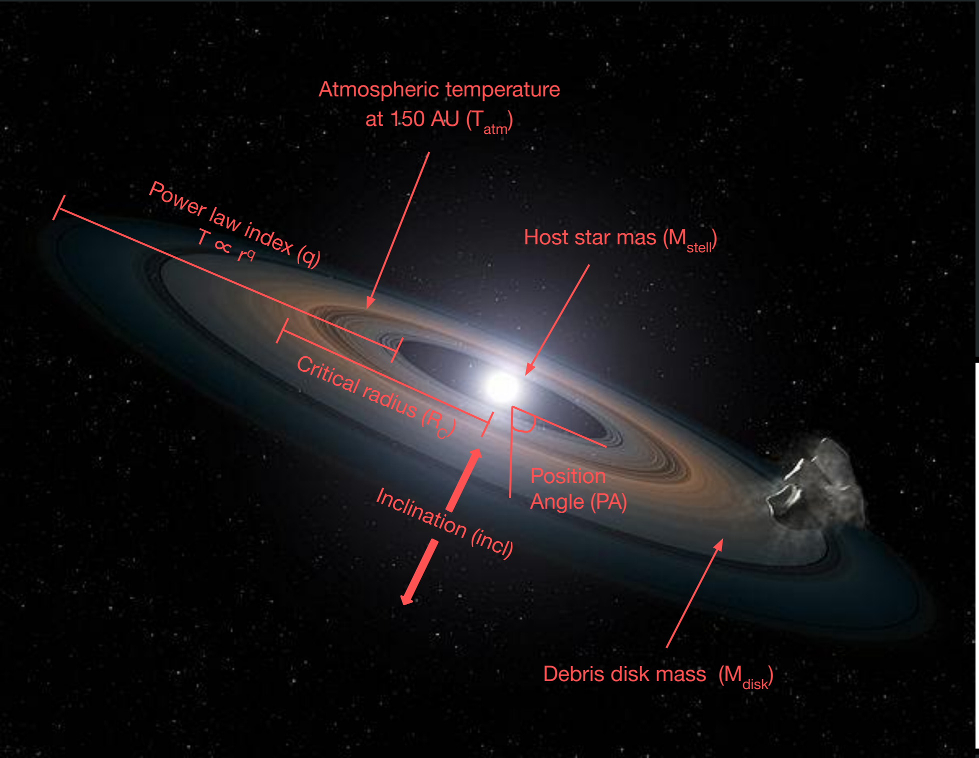
Fourier Transform

Used Galario software to Fourier transform model images to frequency domain for comparison with ALMA data.

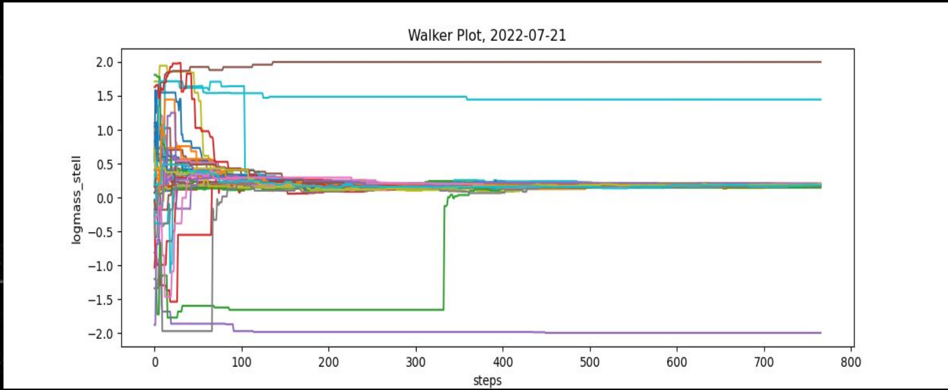
Markov Chain Monte Carlo (MCMC)

- Used affine invariant MCMC to probe the parameter space of our models.

- Seven parameters varied, shown to the left.
- Ran for a minimum of 2000 steps, each step containing 40 walkers.
- Compared models to data using chi-squared metric. Gradual conversion around best fit value for each parameter via acceptance of models whose parameters result in a lower chi-squared value.



Graphic showing parameters varied during the generation of our models. Original image credit: Astrobites



Walker plot of stellar mass for HD131488. Shows gradual convergence of walkers around best fit value

Channel Maps and DMR

- DMR: Data - model = residual
- Model with lowest χ^2 was subtracted from our ALMA data. Residuals that look like noise are an indication that the model is a good fit to the data.

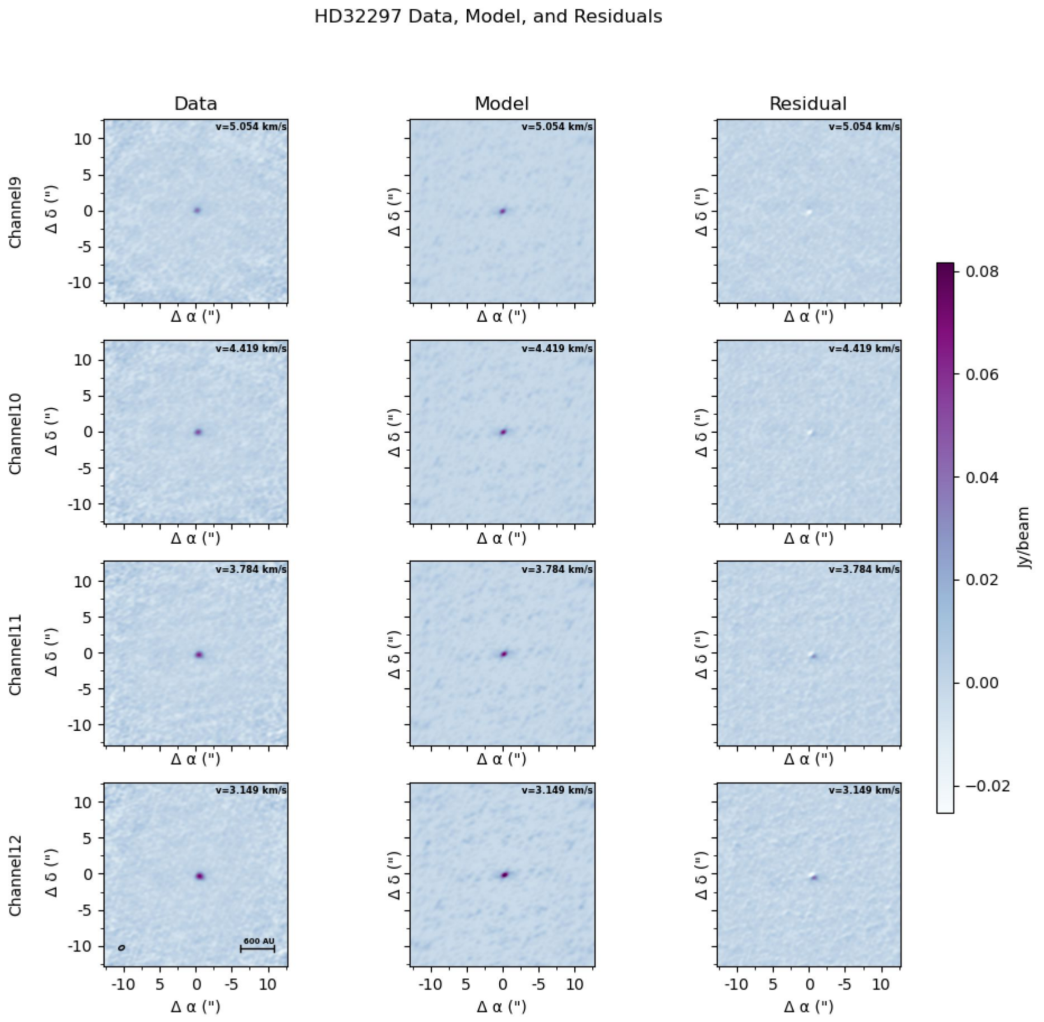
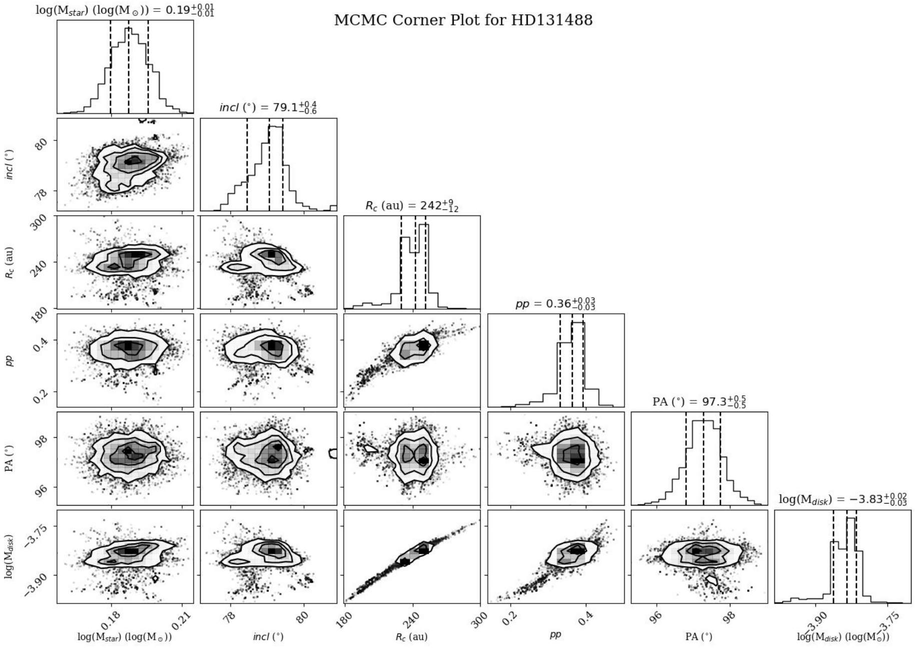


Figure displays DMR for four channels of HD32297

Results from MCMC

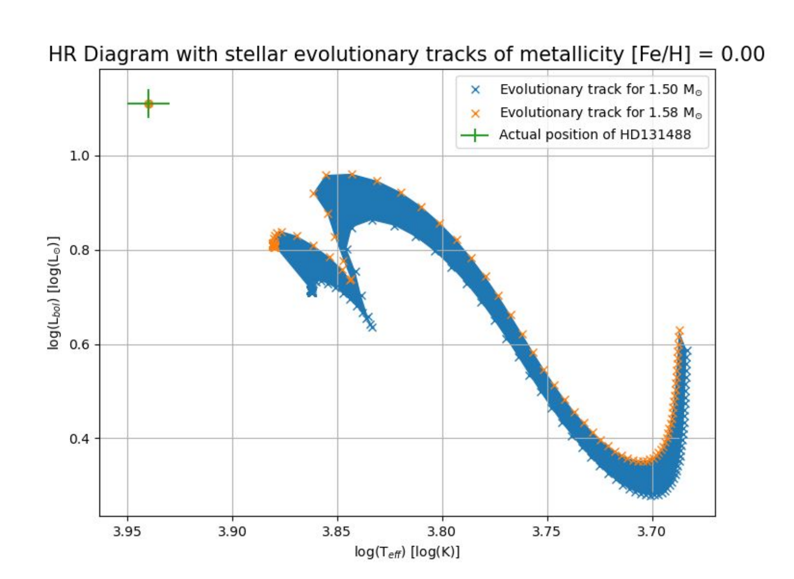


Corner plot for HD131488. Shows distribution of best fit values and degeneracies between parameters.

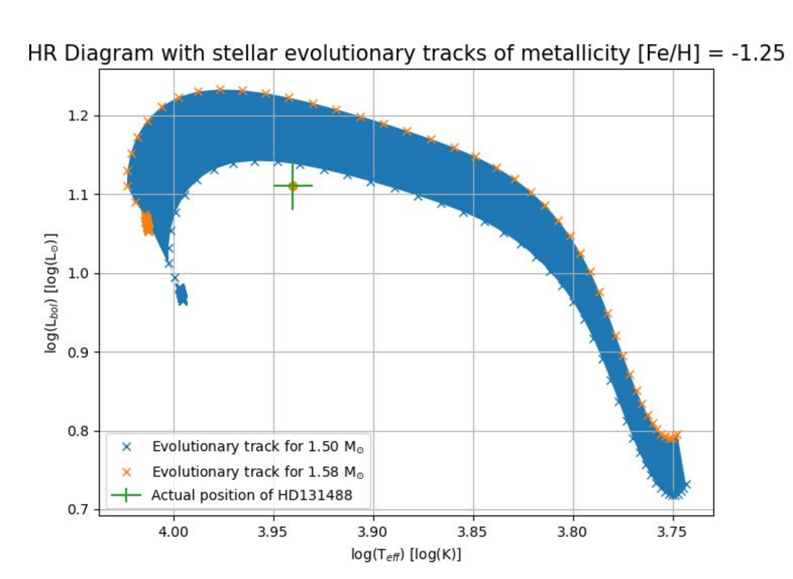
- Visual comparison of model-residual plots led us to believe that the MCMC chain runs were successful for HD131488 and HD138813.
- Resulting posterior distributions plotted for each model parameter, and median and best fit values recorded.
-

Disk		$M_{\rm stell}$ ($M_\odot$)	Inclination (°)	Critical Radius R_c (au)	pp	Position Angle (°)	$M_{\rm disk}$ ($10^{-4} \times M_\odot$)
HD131488	Median	$1.55^{+0.04}_{-0.04}$	$79.1^{+0.4}_{-0.6}$	242^{+9}_{-12}	$0.36^{+0.03}_{-0.03}$	$97.3^{+0.5}_{-0.5}$	$1.48^{+0.07}_{-0.10}$
	Best-fit	1.55	79.1	249	0.39	97.4	1.52
HD138813	Median	$1.48^{+0.11}_{-0.07}$	$33.7^{+1.1}_{-1.5}$	216^{+11}_{-10}	$-0.09^{+0.03}_{-0.03}$	$226.7^{+1.0}_{-1.1}$	$1.23^{+0.09}_{-0.08}$
	Best-fit	1.56	32.6	206	−0.12	228.0	1.17

Comparison of Dynamical Mass Measurements with Photometric Model Estimates



Generic metallicity value of [Fe/H] = 0.0



Metallicity value of [Fe/H] =-1.25 (closest in MESA database to estimate of -1.3)

- M_{star} measurement from the MCMC chain used to generate photometric evolutionary tracks for HD131488 in the period of 1 Myr - 100 Myr (age range of stars in the Sco-Cen OB constellation)
- Compared with HD131488’s actual temperature-luminosity data on an HR diagram

Key Takeaways and Future Direction

- Our approach works! The MCMC results for HD131488 and HD138813's stellar masses lie within the general ranges quoted for their spectral types.
- Initial results hint towards agreement between our photometric models and dynamical measurements.
- Going forward, better constraints on stellar metallicity would be necessary for improved comparisons.
- We plan to extract dynamical mass measurements for our entire sample of gas bearing disks in the future, and use that to populate a database comparing dynamical mass measurements with photometric model estimates.

THANK YOU!

We would like to thank our advisor, Meredith Hughes, the program head, Seth Redfield, and Wesleyan University for the opportunity to do research. Thank you to everyone in the Wesleyan Astronomy Department this summer for their support and guidance, and to Wellesley University for giving us an opportunity to present our research.