HD 100546 Modeling

2016

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Tasks

- Nada

Someday / Maybe

- Spectral profile of outer disk? Use polygon to make a ring, compare to Pineda
- PV/spectral profile where blob is?

For Catherine

- Please note, all tables and figures pertain to the original start velocity uniform CLEAN, NOT the more recent and better-fitting shifted start velocity robust=0.5 CLEAN.

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2 August 2016

Blob Modelling

To fit the residual blob, a velocity v_{blob} is set within a radial range $[r_{start}, r_{end}]$ and an azimuthal range $[\phi_{start}, \phi_{end}]$. As the residual blob is roughly the size of the beam, I will use the location of the residual blob to center the model blob, and the beam size to place upper limits on the radial and azimuthal width. The inner companion planet is thought to be ~10 AU from the star and one pixel is ~11 AU, so there is little motivation for setting the inner radius to anything greater than 0. The best fit position angle for the warp model was 64°, about 80°less than the outer disk position angle of 144°. The azimuthal angle is measured counterclockwise with respect to the semi-major axis of the disk, with 0 °in the upper right corner of the image; thus 80°less than the position angle of the outer disk corresponds to an azimuthal angle of 280°. The beam is .94 x .42; a rough calculation of the inverse tangent of the width-to-length at maximum width (.47 x .21) gives a total angle of $24 * 2 \approx 50°$.

As such, I will center the model blob at 280°, and let the azimuthal angle vary up to 30°on either side, while also varying the outer radius up to slightly more than the length of one beam, ~100 AU.

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26 July 2016

Added final results of warp model run; a summary of the model parameters can be found in Table 3, and a summary of the best-fitting models in Table 4. Figures 3 & 4 display fit and model plots.

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25 July 2016

Minimum disk radius– unimportant. Change of ~1.2 km/s in quadratic sum for a disk starting at 12 AU (1 pixel), and change of ~11.8 km/s for a disk starting at 24 AU (2 pixels). Seems like adding an inner radius won't have much effect if it is to be physically realistic.

Centered binned residual plot so that middle bin ranges from -0.5 km/s to 0.5 km/s.

Added isovelocity contours to channel maps and mirror channel plot; aspect ratio of 0.03 is not visibly different from flat disk.

A Circumplanetary Disk?

After meeting with Catherine and Paola, we agree that a warp seems unlikely. Not only do the positive residuals show up exclusively on the negative-velocity side of the disk, they are elongated along the semi-*minor* axis of the disk. A higher inclination is needed to fit the high-velocity blob, but this necessarily elongates the warp along its semi-*major* axis. Thus the warp can be rotated to eliminate different parts of the residual blob, but it is impossible to remove the entire blob.

A possible explanation for this asymmetrical blob is a circumplanetary disk, possibly rotating around the planet candidate at ~10 AU. [1] If part of the disk were hidden behind the planet or obscured by the circumstellar disk, it is conceivable that such a circumplanetary disk could contribute super-keplerian blueshifted emission while the corresponding redshifted emission is obscured. Moving forward, I will increase the velocity values of the unwarped model keplerian velocity field, simulating a half-visible circumplanetary disk, at the location of the blob in an attempt to reproduce the data.

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20 July 2016

Reorganized and updated the plots created by the model:

- Removed ratio plot; replaced with a version of the residual image binned to the velocity resolution (0.22 km/s)
- Added a histogram plotting the number of pixels in each velocity channel bin
- Added a quantification of the residual square sum for the outer disk (r>150)

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19 July 2016

Although a model with a sharp transition is unlikely to be physically realistic, this sharp transition is effectively smoothed during the convolution process and thus does not significantly differ from a more smooth inclination prescription. Additionally, the inclination power law of Equation 1 becomes significantly harder to implement when both position angle and inclination vary with radius. Models with a sharp transition will thus be used in this stage of the warp modeling as they are much simpler.

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6 July 2016

In amom.py, aspect ratio is defined as $\frac{4H_p}{r}$, where H_p is the pressure scale height.

Adding Warp:

I wrote a script, analytical_warp.py, to create an analytical models of a warped disk using HD 100546's spatial grid. This script will plot offset as a function of radius in one-dimensional profile slices as well as two-dimensional heat maps. Models without a warp have failed to fit the data primarily within ~0.27", or 26 AU of the star, suggesting that the warp is most significant within this area. A model with a sharp transition between inclinations at the location of the warp (i.e. discontinuous) is unlikely to fit the disk well, and as the spatial resolution of the ALMA observations is ~12 AU, it is ungainly and nearly impossible to create a model with two separate inclinations and a smooth "transition band" in between. As such, I will be skipping straight to Katherine Rosenfeld's [2] 2012 prescription for a power-law inclination profile:

$$i(r) = i_0(\frac{r}{r_0})^{-y} \tag{1}$$

Inclination Power Law: Positive or Negative Second Derivative?

In this equation, inclination decreases with radius. The unwarped models with the smallest peak residuals seem to prefer lower inclinations and position angles, as these values better fit the positive residual blob close to the center of the disk that can be seen in the residual image of Figure 2). As this blob is close to the center of the disk, this suggests that the inner disk has a lower inclination than the outer.

However, I suspect that this is the wrong conclusion. As the resdual blob is positive, the model is *underpredicting* the data, i.e. the model velocities at the location of the blob are lower than those of the data. Given the available parameter space of an unwarped disk, the best fit solution seems to involve rotating the disk so that the high-velocity areas along the semi-major axis lie closer to the blob, and then decreasing the inclination of the disk so as to mitigate the effects of this rotation on other parts of the disk. This effect becomes evident when the peak best fits are compared to the sum best fits: the peak best fits, sensitive only to the largest residual, prefer lower position angles and inclinations (130, 30) than the sum best fits (144, 36) which are more sensitive to overall fit.

This is all to say that even though the best-fit models prefer a lower inclination, indicating a disk with an inclination power law profile that increases with radius, the positive residual blob in the inner parts of the disk may more strongly suggest a decreasing power law as described by Rosenfeld.

5 July 2016

Started taking notes on modeling work

Work Overview (so far)

This summer I have been using the script amom.py (jointly written by Catherine Walsh and Atilla Juhasz) to model the first moment map of HD 100546. This is done with the help of a front end, exectute_amom.py, that reads in the disk's first moment map, creates an ideal model given certain parameters, and then convolves the model with the ALMA image's beam. Unwarped model parameter information for can be found in Table 1.

Model Gridding

execute_amom.py creates a model for each possible permutation of a set of parameters. For each model, a plot is saved containing five images:

1. ALMA data first moment map
2. Convolved model first moment map
3. Residuals $(data - model)$
4. Residuals binned to the velocity resolution, 0.22 km/s.
5. Histogram of the number of pixels at each velocity, binned to the channel width, 0.11 km/s.

A Note on Residuals As the first moment map contains both positive and negative values, the residuals can be somewhat misleading. Positive resdiduals in parts of the disk corresponding to a positive velocity indicate that the model underestimates the data; however, in parts of the disk corresponding to a *negative* velocity, positive resdiduals indicate that the model *oversetimates* the data. To mitigate this potential source of confusion, the signs of residuals in parts of the disk corresponding to a negative veloctiy have been flipped so that positive residuals always suggest that the model is too weak, and negative residuals always suggest that the model is too strong.

For each combination of aspect ratio and cone, a plot (referred to from now on as a "fit plot") is saved containing the fit statistics of each model in a matrix of position values and inclinations. Position angle currently ranges between 130 and 160, and inclination ranges between 30 and 60. Two goodness of fit quantifications are used: a χ^2 with $\sigma = 1$ (i.e. $\sum(data - model)^2$), and the peak (absolute magnitude) residual. The sum of squares tends to be better for assessing overall goodness of fit, while the peak reveals where and how badly the model fails to fit the data. The models with the smallest sums of squares and smallest peaks are summarized in Tables 2 and 2, respectively. Fit plots and best fit models for aspect ratios 0 & 0.02 are included in Figures 1 and 2.

Table 1: Model parameters (without warp).

	Range (°)	Best Fit(°)
Height Angle	0, 27	2
Position Angle	130, 160	144
Inclination	30, 60	36

Table 2: Best-fitting models without a warp, quantified using sum of squares and peak residual.

Aspect Ratio	Cone	Position Angle	Inclination	Sum of Squares
0	N/A	144	36	76.59
0.01	Lower	144	36	76.22
0.01	Upper	144	36	77.17
0.02	Lower	144	36	**76.05**
0.02	Upper	144	36	77.95
0.03	Lower	144	36	76.08
0.03	Upper	144	36	78.93
0.04	Lower	144	36	76.31
0.04	Upper	144	36	80.13
0.1	Lower	144	34	81.00
0.1	Upper	144	34	91.64
0.2	Lower	144	34	102.79
0.2	Upper	142	34	124.51

Aspect Ratio	Cone	Position Angle	Inclination	Peak Offset	Peak Residual
0	N/A	130	30	$(0.24, 0.12)$	1.31
0.01	Lower	130	30	$(0.24, 0.12)$	1.32
0.01	Upper	130	30	$(0.24, 0.12)$	1.31
0.02	Lower	130	30	$(0.24, 0.12)$	1.32
0.02	Upper	130	30	$(0.24, 0.12)$	1.31
0.03	Lower	130	30	$(0.24, 0.12)$	1.32
0.03	Upper	130	30	$(0.24, 0.12)$	1.31
0.04	Lower	130	30	$(0.24, 0.12)$	1.32
0.04	Upper	130	30	$(0.24, 0.12)$	1.31
0.1	Lower	130	30	$(0.24, 0.12)$	1.34
0.1	Upper	130	30	$(0.24, 0.12)$	**1.29**
0.2	Lower	130	30	$(0.24, 0.12)$	1.36
0.2	Upper	158	30	$(0.96, -0.36)$	-1.30
0.3	Lower	158	30	$(-1.32, 0.24)$	-1.57
0.3	Upper	158	30	$(1.08, -0.24)$	-1.45

Table 3: Model parameters (with warp).

Parameter	Start Value	Preferred Value
Stellar Mass	2.5 [3]	N/A
Distance (parsecs)	96.9 [4]	N/A
Aspect Ratio	0.0	N/A
Outer Position Angle	144	N/A
Outer Inclination	36	N/A
Inner Position Angle	55	64
Inner Inclination	55	76
Transition Radius (AU)	25	60

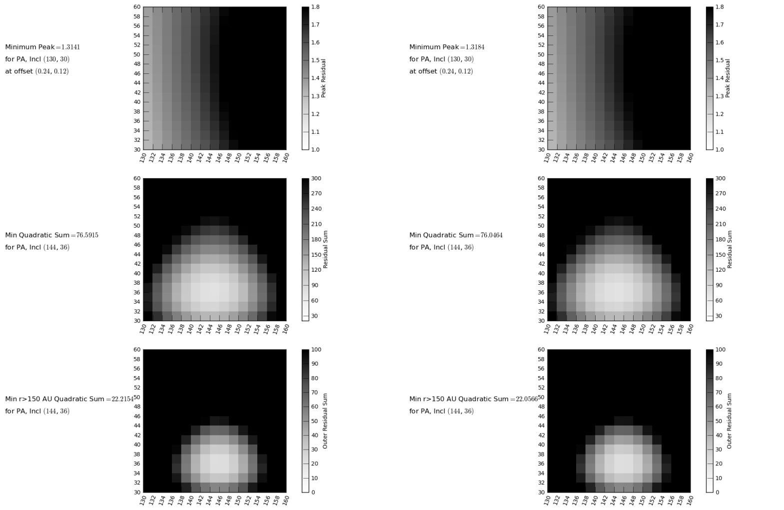

Figure 1: Fit plots for models without a warp.
Left: Flat disk.
Right: Best fit aspect ratio $\frac{4H_p}{r} = 0.02$. The difference between a flat disk and the best fit aspect ratio is negligible.

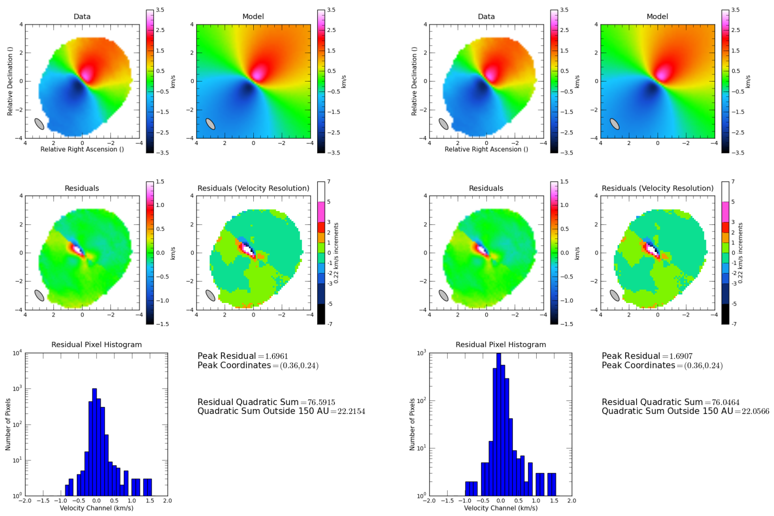

Figure 2: Models without a warp.
Left: Best fit model for a flat disk.
Aspect=0
Cone=N/A
Position Angle=144
Inclination=36
Right: Best fit model overall.
Aspect=0.02
Cone=Lower
Position Angle=144
Inclination=36

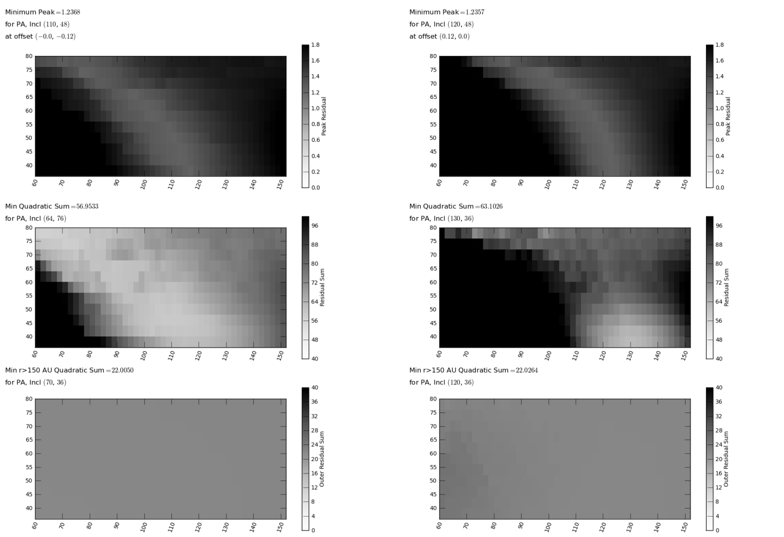

Figure 3: Fit plots for warp models.
Left: Best fit transition radius $r_0 = 60$ AU.
Right: Transition radius $r_0 = 90$ AU.

Transition Radius	Inner Position Angle	Inner Inclination	Sum of Squares
10 AU	60	36	76.59
20 AU	76	52	69.78
30 AU	72	60	62.71
40 AU	72	56	58.32
50 AU	76	64	57.23
60 AU	64	76	**56.95**
70 AU	68	76	58.77
80 AU	126	36	62.19
90 AU	130	36	63.10

Table 4: The best-fitting warp models for each transition radius, quantified using sum of squares and peak positive residual. The positive peak reveals the extent to which the model is capable of eliminating the residual blob. Outer position angle and inclination are fixed at 144 and 36 degrees respectively.

Transition Radius	Inner Position Angle	Inner Inclination	Peak Offset	Peak Positive Residual
10 AU	60	36	$(0.36, 0.24)$	1.70
20 AU	60	56	$(0.24, 0.12)$	1.43
30 AU	60	56	$(0.24, 0.12)$	1.28
40 AU	100	40	$(0.24, 0.12)$	1.24
50 AU	72	72	$(0.24, 0.12)$	1.24
60 AU	110	48	$(0, -0.12)$	1.24
70 AU	118	40	$(0.12, 0)$	1.24
80 AU	116	52	$(0, -0.12)$	1.24
90 AU	120	48	$(0.12, 0)$	1.24

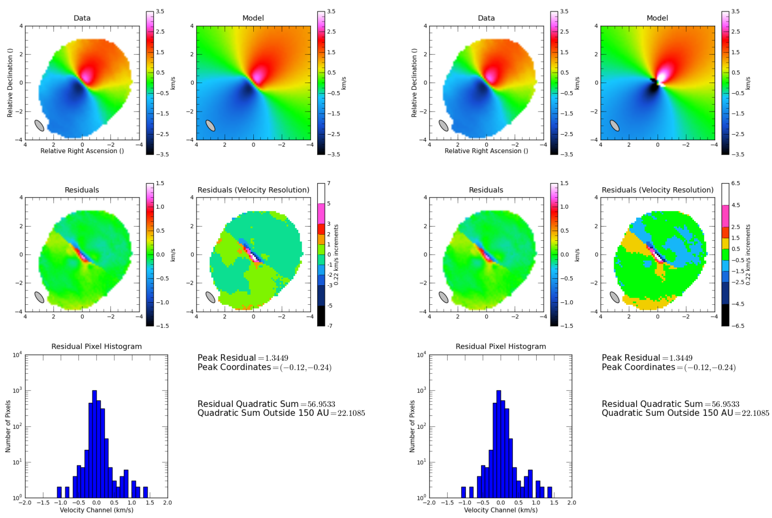

Figure 4: Best fit warp model.
Aspect=0
Cone=N/A
Transition Radius=60 AU
Inner Position Angle=64
Inner Inclination=76
Outer Position Angle=144
Outer Inclination=36
Left: Best fit warp model with the model image convolved.
Right: Best fit warp model with the model image left unconvolved, revealing the shape of the warp. The binned residual plot has also been redone so that the middle bin is centered around zero, making it easier to assess where the model actually deviates from the data.

References

[1] C. Walsh, A. Juhász, P. Pinilla, D. Harsono, G. S. Mathews, W. R. F. Dent, M. R. Hogerheijde, T. Birnstiel, G. Meeus, H. Nomura, Y. Aikawa, T. J. Millar, and G. Sandell. ALMA Hints at the Presence of two Companions in the Disk around HD 100546. ApJ, 791:L6, August 2014.

[2] K. A. Rosenfeld, C. Qi, S. M. Andrews, D. J. Wilner, S. A. Corder, C. P. Dullemond, S.-Y. Lin, A. M. Hughes, P. D'Alessio, and P. T. P. Ho. Kinematics of the CO Gas in the Inner Regions of the TW Hya Disk. ApJ, 757:129, October 2012.

[3] P. Manoj, H. C. Bhatt, G. Maheswar, and S. Muneer. Evolution of Emission-Line Activity in Intermediate-Mass Young Stars. ApJ, 653:657–674, December 2006.

[4] G. Meeus, B. Montesinos, I. Mendigutía, I. Kamp, W. F. Thi, C. Eiroa, C. A. Grady, G. Mathews, G. Sandell, C. Martin-Zaïdi, S. Brittain, W. R. F. Dent, C. Howard, F. Ménard, C. Pinte, A. Roberge, B. Vandenbussche, and J. P. Williams. Observations of Herbig Ae/Be stars with Herschel/PACS. The atomic and molecular contents of their protoplanetary discs. A&A, 544:A78, August 2012.