

Modelling the Kinematics of HD 100546: ALMA Evidence for a Planetary Companion?

Cail Daley, Wesleyan University

Advisor: Catherine Walsh, Leiden University and University of Leeds

Abstract

HD 100546 is a nearby Herbig Be star surrounded by an early-stage transition disk. This disk is known to have a complex physical structure, and hosts a confirmed protoplanet at ~ 53 AU with a possible second companion at ~ 14 AU. We model the velocity structure of the CO ($J = 3 - 2$) line emission in the disk to compare with ALMA data and find the disk to be much flatter than previously expected. Modeling also reveals significant super-Keplerian velocities in the inner regions of the disk, possibly stemming from a dust-trap-induced vortex or a circumplanetary disk. Three components are needed to reproduce the observed velocity structure: a basic Keplerian velocity field with a position angle of 144° and inclination of 36° , a warped inner disk with position angle of 75° and inclination of 64° , and a non-axisymmetric “blob” of super-Keplerian gas.

Introduction

Young (< 10 Myr old) stars are often surrounded by circumstellar disks, huge rotating reservoirs of gas and dust left over from the process of star formation that are responsible for the genesis of nearly all of the known asteroids, comets, and planets in the universe. As dust grains in circumstellar disks collide and stick together, they can form larger bodies known as planetesimals, which can in turn grow large enough to exert significant gravitational attraction on the material surrounding them. Gas and dust fall towards such “protoplanets” in a process known as accretion, occasionally forming circumplanetary disks within the surrounding circumstellar environment. Planets can have significant effects on the structure of their parent circumstellar disks, for example clearing gaps or launching spiral density waves and vortices (Baruteau et al. 2014). Such planet-disk interactions provide scientists with a useful tool in planet detection, allowing them to infer the presence of unseen planets from the structure of the surrounding circumstellar disk.

HD 100546, a nearby Herbig B9V Be star surrounded by an early-stage transition disk, presents a promising opportunity to explore such relationships. The presence of a $5M_{Jup}$ protoplanet at 53 AU has been confirmed, and there is evidence for an older $10 - 20M_{Jup}$ protoplanetary companion at 14 AU (Quanz et al. 2015; Currie et al. 2015; Pinilla et al. 2015). This rich planetary environment is complemented by a complex disk structure complete with spiral arms and rings as well as several other unusual features (Grady et al. 2005; Boccaletti et al. 2013; Walsh et al. 2014). The abundance of protoplanets and structural features in HD 100546’s disk, as well as its proximity, distinguish the system as a particularly interesting location to study planet-disk interactions.

Methods & Analysis

The data used in this paper were taken on November 18, 2012 as part of ALMA Cycle 0 (program 2011.0.00863.S, P.I. C. Walsh). Observations made use of 24 antennas with baseline lengths ranging

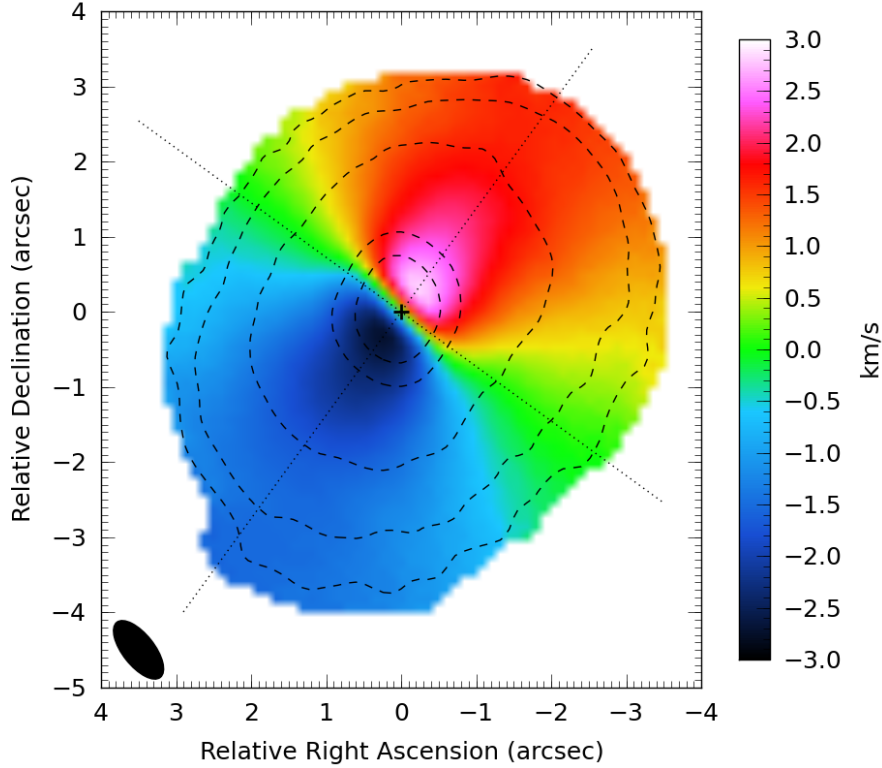


Fig. 1.— First moment map of HD 100546’s disk traced in line emission from CO ($J = 3 - 2$). The disk is rotating counterclockwise, with the lower left part of the disk blueshifted towards the observer and the upper right redshifted away. The gas with the same radial component as the star lies along the semi-minor axis of the disk, parallel to the observer’s line of sight. The image has a beam size (spatial resolution) of $0.94'' \times 0.42''$.

between 21 m and 375 m, and were taken at 300 and 345 GHz with velocity resolutions of 0.24 and 0.21 km/s respectively. For further details, see Walsh et al. (2014).

In order to gain information about HD 100546’s disk, we modeled the velocity structure of the carbon monoxide (CO) $J = 3 - 2$ emission; Figure 1 displays the first moment map (intensity-weighted velocity distribution) of the CO in the disk. We extended the functionality of a code written by Catherine Walsh and Atilla Juhasz, which, when given a set of input parameters, analytically generates a Keplerian velocity field that can then be compared to the observed first moment map. Stellar mass was fixed at $2.4M_{\odot}$, and the distance was fixed at 96.9 parsecs (van den Ancker et al. 1998; Meeus et al. 2012); all other parameters were varied. For each combination of parameters, a sum-of-squares fit statistic was calculated. The best-fit model was then determined by finding the global minimum of a “grid” of these fits bounded by the parameter ranges found in Table 1.

The first iteration of our model was a simple Keplerian velocity field as described above. In this round of modeling, values for position angle (ϕ), inclination (i), cone aspect ratio, and cone face were allowed to range within the bounds described in Table 1. Aspect ratio is the ratio of disk scale height (z) to radius (r) for any given r . Cone face is only relevant for a non-flat disk, i.e. $\frac{z}{r} > 0$, and describes whether the “upper” or “lower” face of the disk’s double cone is closer to the observer.

A simple Keplerian velocity field fits the outer regions of the disk quite well; however, in the

inner regions of the disk the model under-predicts the data by over 1.5 km/s, as seen in Figure 2(a). In order to better reproduce the data, we added a second component to the model, an inner warp. In a warped disk, part of the disk has a different position angle and/or inclination; if the inner regions of HD 100546’s disk were warped to a higher inclination, the observed velocities would be higher than those predicted by a purely Keplerian model. The position angle and inclination of the outer disk were fixed to the best fits of the basic model, while the position angle, inclination, and transition radius of the inner disk were allowed to vary. The warp model was able to reproduce the redshifted portion of the disk, but significant residuals remained on the blueshifted side; this made it clear that the velocity structure could not be fit by an axisymmetric model.

In order to reproduce the non-axisymmetric, super-Keplerian “blob” visible in the residual map of Figure 2(b), we artificially increased the velocity within a wedge of the disk roughly corresponding to the size and orientation of the blob. Wedge start and end position angle, outer radius, and velocity were all allowed to vary. This “blob” model was able to account for the super-Keplerian velocities on the blueshifted side of the disk, but the residuals on the redshifted side of the disk that had been removed by the warp model reappeared. This led us to conclude that neither a blob nor warp model alone could reproduce HD 100546’s velocity structure, and that both the blob and warp models must be stacked with the basic Keplerian model. Due to the number of parameters and spatial resolution limits of the data, parameters were not allowed to vary; instead, a fit by eye technique was used to gain a qualitative understanding of the disk’s velocity structure. This three-component model fit the data well, with most of the first moment map residuals falling within one velocity resolution (0.22 km/s) of the source velocity.

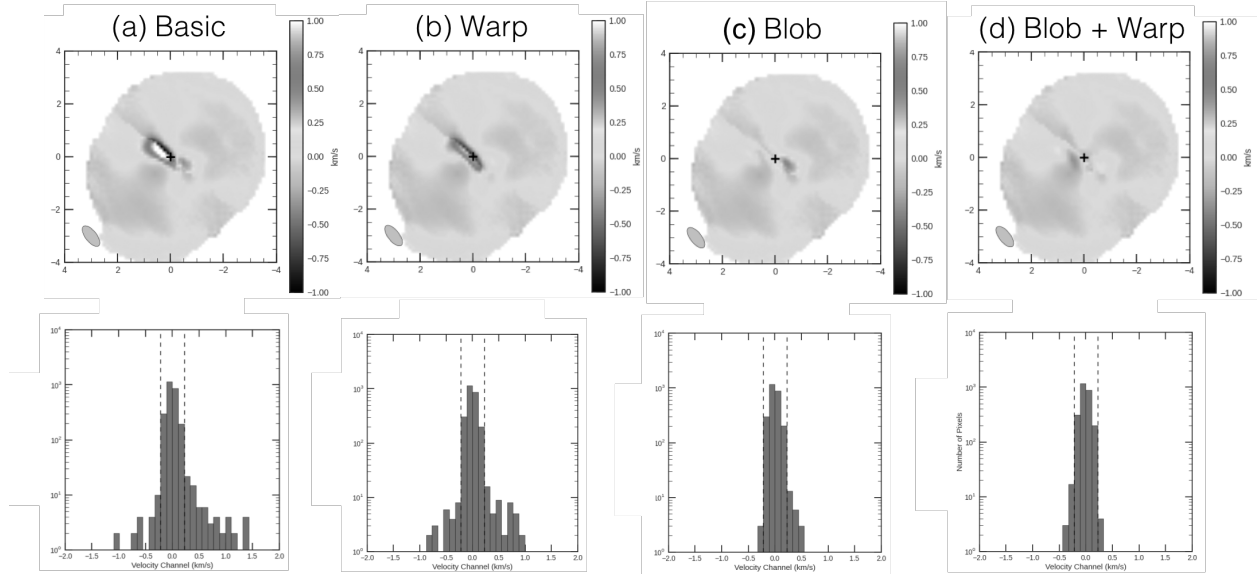


Fig. 2.— Evolution of the model over time. The top row contains model residuals, and the bottom row contains a histogram of the residual pixels. The residual “blob” can be seen above and left of the stellar location, which is marked with a ‘+,’ in the residual map of panel (a). The warp model of panel (b) eliminates the redshifted residuals to the right of the star, and the blob model (panel c) eliminates the blueshifted residuals to the right of the star only to reintroduce the redshifted residuals. Panel (d) shows the final best-fit model with no significant residuals.

Parameter	Range	Preferred Value
Flat Model		
Position Angle	[130,160] $^{\circ}$	144 $^{\circ}$
Inclination	[30,60] $^{\circ}$	36 $^{\circ}$
Aspect Ratio	[0,0.5]	0.02
Cone	[Lower, Upper]	Lower
Warp Model		
Transition Radius	[20,90] AU	40 AU
Inner Disk Position Angle	[130,160] $^{\circ}$	75 $^{\circ}$
Inner Disk Inclination	[30,60] $^{\circ}$	64 $^{\circ}$
Blob Model		
Velocity	[-5, -15]km/s	-5 km/s
Outer Radius	[30,100] AU	80 AU
Start PA	[9, 44] $^{\circ}$	39 $^{\circ}$
End PA	[44,84] $^{\circ}$	69 $^{\circ}$
Blob + Warp Model		
Warp Radius		40 AU
Warp PA		114 $^{\circ}$
Warp Inclination		56 $^{\circ}$
Blob Velocity		-8.2 km/s
Blob Outer Radius		65 AU
Blob Start PA		44 $^{\circ}$
Blob End PA		74 $^{\circ}$

Table 1: HD 100546 Parameters & Best Fits

Results & Discussion

Three different model components are needed to fit the velocity distribution of the CO in HD 100546’s disk: a basic Keplerian velocity field, a warped inner disk, and a non-axisymmetric “blob.” Parameter information, including best fits, can be found in Table 1. It is important to note that although the individual models are well constrained, degeneracies are likely in the combined blob and warp model due to the spatial resolution of the data.

The preferred aspect ratio, corresponding to a height angle of only 1 degree, indicates that the CO(3-2) emitting layer lies remarkably close to the midplane of the disk. This suggests that HD 100546 belongs to group II of Herbig Ae/Be stars, characterized by flat, unflared disks. This is in conflict with Meeus et al. (2001)’s classification of the disk as group I, associated with thick and highly flared disks, based on its spectral energy distribution.

There are several possible explanations for the super-Keplerian, non-axisymmetric “blob” in the inner regions of HD 100546’s disk. A dust trap could create a vortex on the blueshifted side of the disk, locally increasing velocities of the carbon monoxide; however, no evidence for a dust trap has been found (M. Kama, private communication). It also is possible that the observed super-Keplerian velocities are produced by a circumplanetary disk, possibly surrounding the protoplanet

candidate at 14 AU. If the candidate were accompanied by such a disk and were in the plane of the best-fit warp model ($i = 64^\circ$), the observed gas velocities would be roughly 18 km/s. As the spatial resolution of the data is 11 AU, and a $20 M_{Jup}$ protoplanet at 14 AU could harbor a circumplanetary disk with a radius of up to 2 AU, it is possible that the excess velocity stems from only one pixel and is “smeared” to a greater spatial extent by the restoring beam. The hypothesis of an unresolved source is further supported by the fact that the residual blob is roughly the same size and orientation as the beam itself. However, the spatial resolution of the data is not high enough to arrive at definite conclusions as to the nature of the blob, other than that three model components are needed to fit the data. Higher spatial resolution observations are needed to interpret the physical significance of HD 100546’s velocity structure, but findings such as these suggest that features on the scale of planets and their disks may soon lie at the frontier of sub-millimeter radio astronomy.

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