Measuring Protoplanetary Disk Alignment in Young Binary Systems

Eric Jensen[1], Rachel Akeson[2], and Aaron Hersch[1],
[1]Swarthmore College, [2]Caltech/IPAC, NExSci

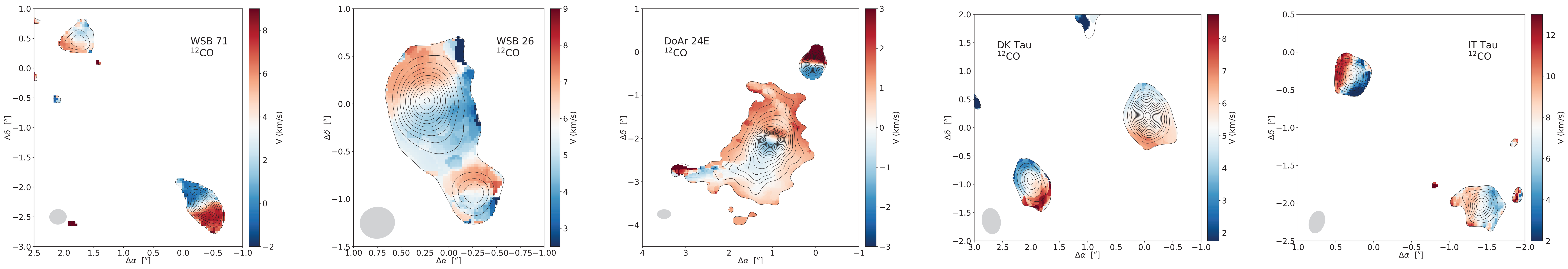

Figure 1: Velocity maps of CO 3–2 emission from circumstellar disks in five young binary systems (see a sixth system at lower right, Fig. 4). Note that the axis scales are different in each figure.

Results: Disks in a small sample of binary systems are neither perfectly aligned nor randomly oriented, showing more tendency toward alignment.

Context

Many of the known planetary systems are unlike our Solar System, containing hot Jupiters or planets orbiting their host stars on eccentric or inclined orbits. One possible explanation for producing such orbits is migration driven by Kozai-Lidov oscillations, which can be induced by a companion on a sufficiently inclined orbit. Observations of protoplanetary disks can help determine whether young binary companions are inclined relative to the individual stars' nascent planetary systems and thus could induce such migration.

Evidence of disk misalignment is provided by misaligned jets (Bohm & Solf 1994) and polarimetry (Monin et al. 1998; Jensen et al. 2004). Furthermore, images of several young binary systems show that the disk around one star is nearly edge-on (Stapelfeldt et al. 1998; Roccatagliata et al. 2011; Ratzka et al. 2009). While disk misalignment has previously been observed in binary systems such as Haro 6-10 (Roccatagliata et al. 2011), HK Tau (Jensen & Akeson 2014), and V2434 Ori (Williams et al. 2014) and triple systems such as T Tau (Skemer et al. 2008; Ratzka et al. 2009), AS 205 (Salyk et al. 2014, Kurtovic et al. 2019), and HT Lup (Kurtovic et al. 2019), there is no systematic study of disk orientation in a larger sample of sources. Our study here includes six binaries newly observed with ALMA (Figs. 1 and 4), as well as results for HK Tau and V2434 Ori from the literature. We exclude known triple systems from our sample.

Results

Are disk orientations in a given binary system randomly distributed?

To answer this, we used the Anderson-Darling and Kuiper statistics to compare measured position angle differences to a random distribution (Fig. 2), testing the hypothesis that the orientations of the two disks in each binary system are randomly distributed. We found probabilities of 0.0037 and 0.049, respectively, that the observed data are drawn from a random distribution of disk orientations.

While the sample is small, our data suggest that it is more likely for disks to be similarly aligned than to be randomly oriented (Figure 2). Theory predicts (Lubow & Ogilvie 2000, Foucart & Lai 2014) that disk misalignments should decrease on a timescale proportional to $a^{3.5}$, where a is the binary semimajor axis, so that closer binaries align more quickly. Excluding the widest system (GK/GI Tau) there is a hint that the closer systems are indeed more aligned, but the sample is too small to have confidence in this result (and there is no *a priori* reason to ignore one system).

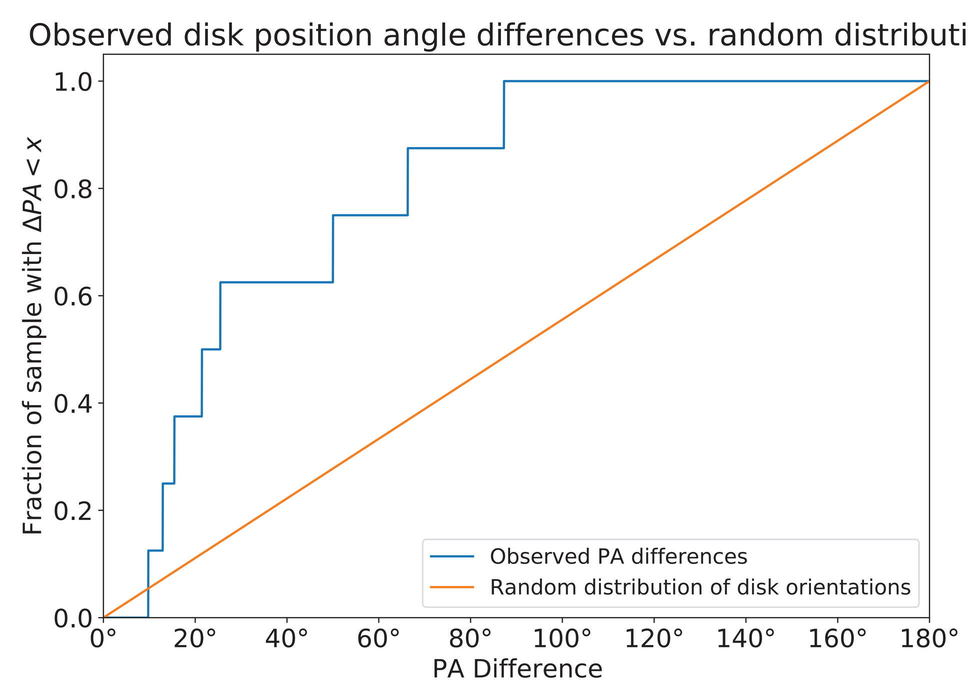

Figure 2: The empirical cumulative distribution function of the position angle differences of disks in eight binary systems is displayed in blue. Five out of the eight systems contain disks with PA differences less than 25°. A random distribution is displayed in orange. Since these two distributions are statistically different, we conclude that disks in binary systems are likely not randomly distributed.

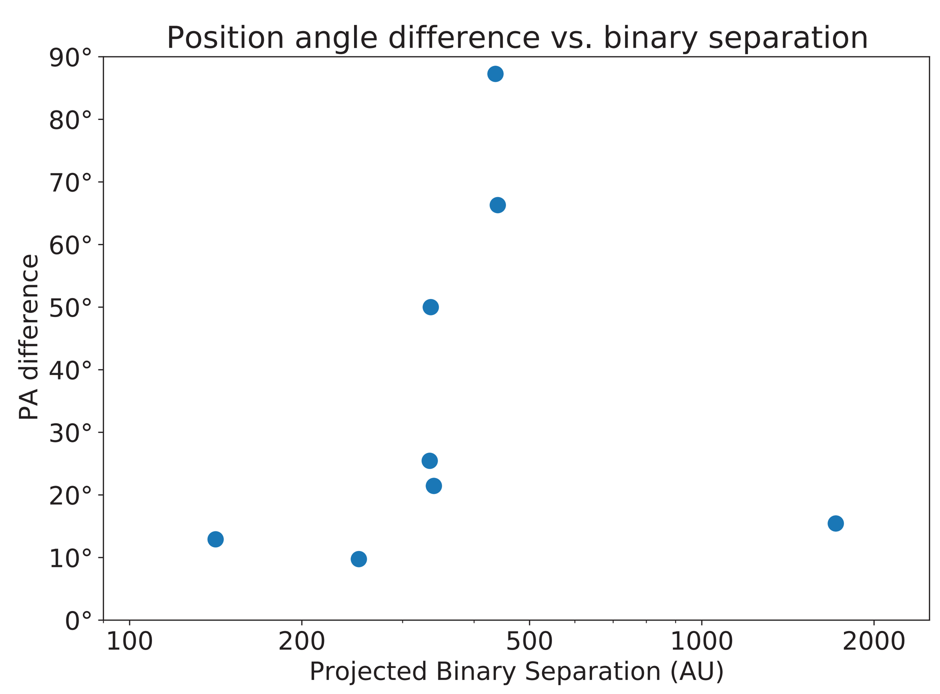

Figure 3: PA Difference vs. projected binary separation of all sources included in our study. Theory predicts that closer systems should align more quickly, and indeed the two systems with the smallest separations (WSB 26, DoAr 24E) have well-aligned disks. However, so does the widest system (GI/GK Tau).

Observations and Methods

We used ALMA to observe continuum and CO(3-2) emission from 14 young binary systems in Taurus-Auriga, Ophiuchus, and Lupus. The kinematics of the CO emission allows us to deduce the spatial orientation of the disks, even for disks that are near our resolution limit. Six systems had strong enough emission for both components to be detected in CO. We used CASA to image the sources and create velocity maps. We also included in our analysis the previously measured position angles of the disks in V2434 Ori (Williams et al. 2014) and HK Tau (Jensen & Akeson 2014) .

Most of the disks are unresolved in the continuum, but the channel-to-channel movement of the CO emission allows us to determine the disk position angle. We measured the CO emission centroid in each channel and fit a straight line to the points to find the disk PA.

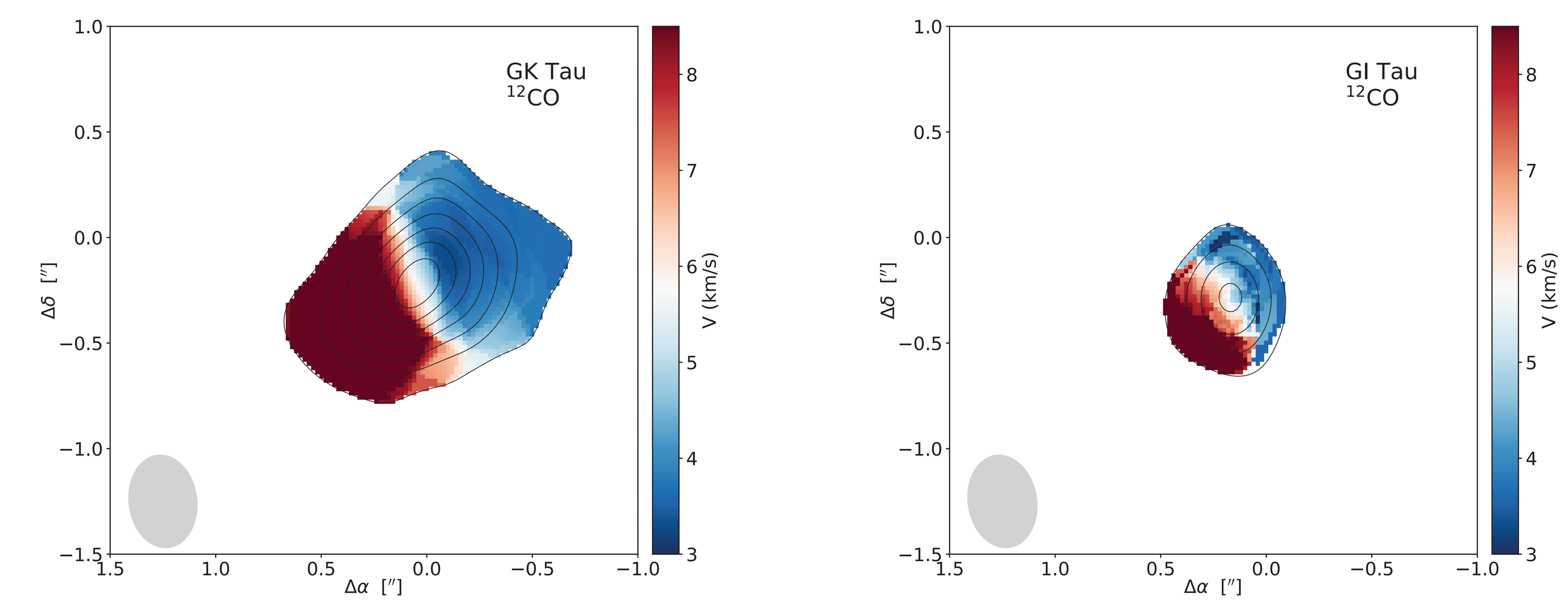

Figure 4: First-moment maps of the primary (GK) and secondary (GI) disks in the binary system GK/GI Tau. Although this system has the largest projected binary separation in our sample at 13.2" (1700 AU), its disks show similar position angles.

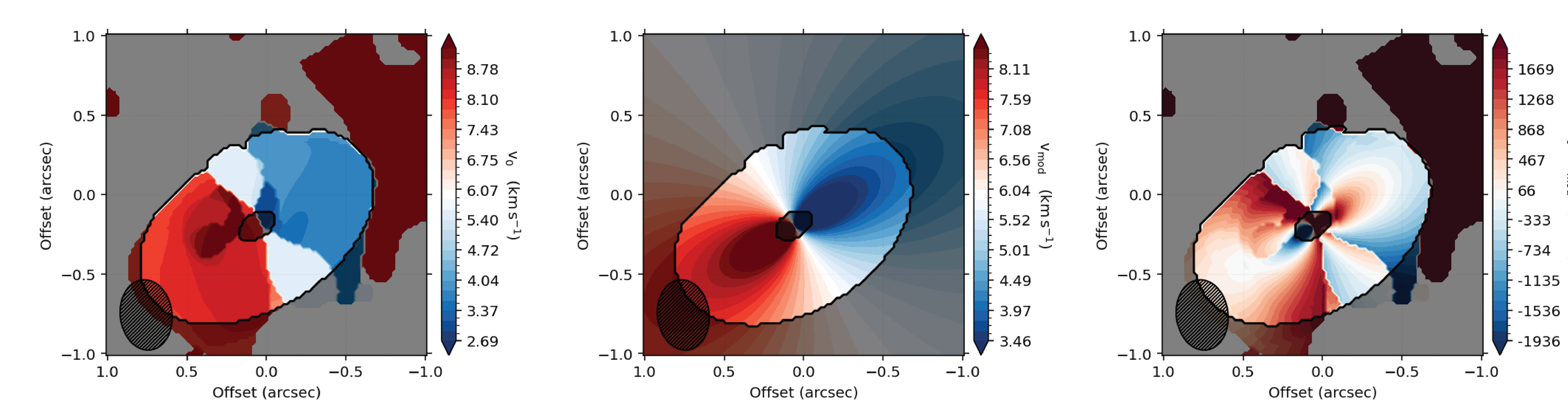

Figure 5: Work in progress: we are exploring the fitting of the first-moment maps, along with constraints on the stellar mass, to determine disk inclinations in order to find the full three-dimensional orientation difference in these systems. Above, left to right: data, model, and residuals for a fit to GK Tau using eddy (Teague 2019).

References

Bohm, K. H. & Solf, J. A sub-arcsecond-scale spectroscopic study of the complex mass outflows in the vicinity of T Tauri. Astrophys. J. 430, 277-290 (1994).
Foucart, F., & Lai, D., Evolution of linear warps in accretion discs and applications to protoplanetary discs in binaries. MNRAS 445, 1731-1744 (2014).
Jensen, E. L. N. & Akeson, R. Misaligned Protoplanetary Disks in a Young Binary System. Nature, 511, 576 (2014).
Jensen, E. L. N., Mathieu, R. D., Donar, A. X. & Dullighan, A. Testing Protoplanetary Disk Alignment in Young Binaries. Astrophys. J. 600, 789-803 (2004).
Kurtovic, N. T. et al. DSHARP IV. Characterizing Substructures and Interactions in Disks around Multiple Star Systems Astrophys. J. Lett. 869, L44 (2018).
Lubow, S. & Ogilvie, G. On the Tilting of Protostellar Disks by Resonant Tidal Effects, Astrophys. J 538, 326-340 (2000).
Monin, J. L., Menard, F. & Duchêne, G. Using polarimetry to check rotation alignment in PMS binary stars. Principles of the method and first results. Astron. Astrophys. 339, 113-122 (1998).
Ratzka, T. et al. Spatially resolved mid-infrared observations of the triple system T Tauri. Astron. Astrophys. 502, 623-646 (2009).
Roccatagliata, V. et al. Multi-wavelength observations of the young binary system Haro 6-10: The case of misaligned discs. Astron. Astrophys. 534, A33 (2011).
Salyk, C. et al. ALMA Observations of the T Tauri Binary AS 205: Evidence for Molecular Winds and/or Binary Interactions. Astrophys. J. 792:68 (2014).
Skemer, A. J. et al. Evidence for Misaligned Disks in the T Tauri Triple System: 10 μm Superresolution with MMTAO and Markov Chains. Astrophys. J. 676, 1082-1087 (2008).
Stapelfeldt, K. R. et al. An Edge-on Circumstellar Disk in the Young Binary System HK Tauri. Astrophys. J. 502, L65-L69 (1998).
Teague, R. eddy: Extracting Protoplanetary Disk Dynamics with Python. JOSS 4, 1220 (2019).
Williams, J. P. et al. ALMA Observations of a Misaligned Binary Protoplanetary Disk System in Orion. Astrophys. J. 796, 120 (2014).

Acknowledgments

We thank Geoff Blake for permission to use the DoAr 24E data in advance of publication. This work makes use of the following ALMA data: ADS/JAO.ALMA#2015.1.00637.S and ADS/JAO.ALMA#2015.1.00168.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.