Misaligned protoplanetary disks in a young binary star system

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Many extrasolar planets follow orbits that differ from the nearly coplanar and circular orbits found in our Solar System; their orbits may be eccentric, or inclined with respect to the host star's equator, and the population of giant planets orbiting close to their host stars suggests appreciable orbital migration. There is at present no consensus on what produces such orbits. Theoretical explanations often invoke interactions with a binary companion star in an orbit that is inclined relative to the planet's orbital plane. Such mechanisms require significant mutual inclinations between the planetary and binary star orbital planes. The protoplanetary disks in a few young binaries are misaligned, but often the measurements of these misalignments are sensitive only to a small portion of the inner disk, and the three-dimensional misalignment of the bulk of the planet-forming disk mass has hitherto not been determined. Here we report that the protoplanetary disks in the young binary system HK Tauri are misaligned by 60 to 68 degrees, such that one or both of the disks are significantly inclined to the binary orbital plane. Our results demonstrate that the necessary conditions exist for misalignment-driven mechanisms to modify planetary orbits, and that these conditions are present at the time of planet formation, apparently because of the binary formation process.

Although the three-dimensional orbital orientation is not yet measurable for any of the known extrasolar planets, measuring the orientation of protoplanetary disks has the potential to provide information about planetary orbits during the planet formation process. Because these disks are hundreds of astronomical units (1 AU is the average Sun–Earth distance) in diameter, they can be spatially resolved at the 120–160 pc distances of the nearest star-forming regions. If the disks around both stars in a binary system can be shown to be misaligned, then it is clear that both cannot be aligned with the (usually undetermined) binary orbital plane. Indirect evidence of disk misalignment is provided by misaligned jets and by polarimetry. More directly, images of several young binary systems show that the disk around one star is nearly edge-on to Earth. In some of these systems, infrared interferometry or imaging constrains the inclination of the disk around the other star, giving a lower limit on the degree of misalignment of the disks, although the position angle of the disk is uncertain and the direction of rotation is unknown. For systems with detectable millimetre-wavelength emission, measurement of Keplerian rotation in both disks in a binary system provides the opportunity to measure the full three-dimensional orientation of the disks' angular momenta.

One such system is HK Tauri, a young binary system with a projected separation of 2.4 arcsec (ref. 15), which is 386 AU at the distance (161 pc) of this part of the Taurus clouds. Age estimates for this system range from 1 to 4 Myr (ref. 17), placing it in the age range at which planet formation is thought to occur. The southern, fainter star, HK Tau B, is surrounded by a disk that blocks the starlight; the disk can thus be clearly seen in scattered-light images at near-infrared and visible wavelengths to be nearly edge-on. Statistical arguments suggest that the disk is unlikely to be completely aligned with the binary orbit. The northern star, HK Tau A, has strong millimetre-wavelength continuum emission, showing that it too is surrounded by disk material; however, because the disk does not block the starlight, the disk cannot be seen in scattered light owing to the brightness of the star. The striking difference in their visible-light appearance shows that these two disks are not perfectly aligned, but the degree of misalignment has not previously been known because the molecular gas in the northern disk has not been resolved, and a modest inclination difference would be sufficient to explain the different scattered-light morphologies.

We observed HK Tau with the Atacama Large Millimeter Array (ALMA) at frequencies of 230.5 and 345.8 GHz, covering continuum emission from dust and line emission from the carbon monoxide (CO) 2–1 and 3–2 rotational transitions, respectively. The northern and the southern components of the binary are clearly detected in the continuum and the CO line emission. The CO maps (Fig. 1) show the clear signature of rotating disks around each star, with one side of the disk redshifted and the other side blueshifted. The orientations of the two disks are significantly different, with the northern disk axis elongated nearly north–south, roughly 45° from the elongation axis of the southern disk.

We used a Markov chain Monte Carlo analysis to fit disk models to our data to determine the three-dimensional spatial orientations of the disks (Methods). For HK Tau B, the disk orientation is well known from previous scattered-light imaging, and so we adopt from that work an inclination $i = 85° \pm 1°$ and position angle $PA = 42°$. Although the disk inclination and position angle were previously known, our imaging of HK Tau B provides new spatial information because the direction of disk rotation, apparent in Fig. 1b, removes a 180° ambiguity in the disk's orientation. In what follows, we adopt the convention that the position angle is measured east of north and that the quoted position angle is that of the redshifted edge of the disk. Our model fitting reproduces the individual velocity channel images well for both sources (Fig. 2), allowing us to determine the position angle, inclination and direction of rotation of the molecular gas disk in the northern source, HK Tau A. The Markov chain Monte Carlo analysis gives $PA = 352° \pm 3°$ and $i = 43° \pm 5°$ (Extended Data Fig. 1); all uncertainties are given as 68.3% credible intervals.

Measurement of the PA and the inclination of both disks lets us determine the angle between the two disks' angular momentum vectors, with one ambiguity. Equal inclinations on either side of edge-on ($i = 90°$) will appear identical unless it can be determined which edge of the disk is nearer to the observer, for example if high-resolution imaging can determine that one edge of the disk is shadowed by a flared disk edge and the other is not. In the case of HK Tau B, this orientation is known from scattered-light imaging, but it is still unknown for HK Tau A. Combining the observational constraints, we find that the angle between the two disks' angular momentum vectors is $60° \pm 3°$ if both vectors point to the same side of the sky plane, or $68° \pm 3°$ if they do not (Fig. 3).

The clear misalignment between the two disks has important implications for planet migration and orbital evolution, as well as for theories of binary formation. Although nothing in our observations constrains the orientation of the binary orbital plane, the fact that the two disks are misaligned with each other means that they cannot both be aligned.

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with the binary orbital plane. At least one of the disks must be misaligned with the binary orbit by 30° (half the total misalignment) or more. The misalignment for one or both disks is probably greater than this, because this minimum misalignment occurs only for one specific orientation of the binary orbit. This misalignment means that planets formed from these disks will be subject to Kozai–Lidov oscillations\textsuperscript{21–23} that may drive changes in their eccentricities and orbital inclinations, or that the disks themselves may be driven into misalignment with the stars’ rotation axes\textsuperscript{5}. It is sometimes stated that only misalignments greater than the critical angle of 39.2° can cause Kozai–Lidov oscillations\textsuperscript{21,23}, but it has recently been shown that this is not strictly true if the body in the inner orbit is relatively massive or has an eccentric orbit, or both\textsuperscript{24}. In any case, it is quite likely that the inclination relative to the binary orbit exceeds this critical angle for one or both of the disks; only 1.6% of all possible binary orbits are inclined to both disks by less than 39.2° if the disks are misaligned by 60°.

This result is consistent with recent simulations of binary formation\textsuperscript{25–27}, which predict that disks will be misaligned with the binary orbit, especially in systems with orbital semimajor axis lengths greater than 100 AU, where dissipation mechanisms do not act quickly to align the disks with the orbit\textsuperscript{25,28}. In earlier simulations of the formation of individual binary systems from isolated cloud cores, the level of misalignment depended on the choice of initial conditions\textsuperscript{25}. However, more recent simulations\textsuperscript{26,27} focus on the formation of entire clusters and thus do not presuppose specific initial conditions (or even a particular formation mechanism) for an individual binary\textsuperscript{29}. In the cluster simulations of ref. 26, all binary systems with orbital semimajor axes greater than 30 AU have disks that are misaligned with each other, with a mean angle of 70° ± 8°. The misalignment we observe here is thus consistent with formation by means of turbulent fragmentation rather than disk instability\textsuperscript{30}.

Although it remains to be seen how the protoplanetary disks in a statistical sample of young binary systems are oriented, it is suggestive...
that in the handful of systems where this measurement has been made, the misalignments are large. If this is a common outcome of the binary formation process, and especially if it extends to lower-mass binary companions (which may easily go undetected), then perturbations by distant companions may account for many of the orbital properties that make the present sample of extrasolar planets so unlike the planets of our own Solar System.

**METHODS SUMMARY**

The CO(2–1) and CO(3–2) ALMA observations of HK Tau were calibrated using standard techniques. The antenna configuration yielded respective spatial resolutions (here defined by beam sizes from the CLEAN algorithm for image reconstruction) of 1.06 arcsec × 0.73 arcsec and 0.69 arcsec × 0.51 arcsec and spectral resolutions of 1.3 km s⁻¹ and 0.85 km s⁻¹ in the two bands. To determine the disk orientations, we calculated azimuthally symmetric, vertically isothermal parameters distributions for the disk parameters.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

We observed HK Tau with the Atacama Large Millimeter Array (ALMA) as part of a survey of pre-main-sequence binaries in the Taurus–Auriga star-forming region. Band-6 observations were taken on 17 November 2012 with 27 antennas and band-7 observations on 16 November 2012 with 28 antennas. The correlator was configured with each of the four basebands covering a total bandwidth of 1.875 GHz with a channel spacing of 488 kHz. In band 6, one of the correlator basebands was set to cover the CO(2–1) transition at 230.5 GHz, whereas in band 7, one baseband covered CO(3–2) at 345.8 GHz. We took one observation of HK Tau in each band, bracketed by observations of the gain calibrator J0510+02 180041, which measures the phase and amplitude response as a function of time. We calibrated the data for each band separately using the CASA software and scripts provided by the NRAO ALMA centre. The system temperature, water vapour phase corrections and flagging were applied using the standard scripts. The amplitude and phase as functions of frequency were calibrated against J0423+013. The absolute flux calibration used Callisto and the 2012 flux models, which resulted in a zero-spacing flux of 8.5 ± 0.2 Jy at 230 GHz and 19.45 ± 0.05 Jy at 345 GHz.

We generated continuum and CO images using the CLEAN task within CASA, with a robust beam weighting of –1.0. These settings resulted in a clean beam size of 1.06 arcsec × 0.73 arcsec in band 6 and 0.69 arcsec × 0.51 arcsec in band 7. The continuum flux of HK Tau is sufficient to provide a self-calibration reference, and we applied a phase-only self-calibration using HK Tau as the reference. Given the short time on source, we averaged the continuum data to a single point in calculating the self-calibration corrections. The channel spacing, combined with Hanning smoothing in the correlator, provides a spectral resolution of 0.85 km s⁻¹ for the CO(3–2) line and 1.3 km s⁻¹ for the CO(2–1) line. The continuum emission is not strong enough to substantially affect the individual channels in the CO data and, thus, we did not subtract it.

The maps show clearly detected CO emission centred at an LSR velocity of roughly 6.1 km s⁻¹. Examination of the individual channels of the CO data shows the presence of foreground absorption in the LSR velocity range of roughly 5.8–8.8 km s⁻¹, consistent with the absorption seen in the single-dish 12CO spectrum.

To quantify the disk properties, in particular the spatial orientation of each disk, we fitted a survey of models to the 345 GHz CO(3–2) data. Following many recent authors, we adopt a form for our disk model that is given by a self-similarity solution to the hydrostatic stability equation. We assume that the dust and gas have the same temperature at a given radius, that the gas is in local thermodynamic equilibrium, that the gas-to-dust ratio by number fraction of CO in the gas is 10⁻⁴. With these assumptions, there are six free parameters that characterize the disk emission and kinematics in the model: $\bar{M}_{\text{disk}}$, $r_c$, $T_{\text{circ}}$, $M_*$, $\gamma$, and $q$. In addition, there are the two orientation parameters for the disk: its position angle PA and its inclination i to the line of sight. It is these latter two properties that are of primary interest to us in determining the disks’ misalignments, as the other six are varied to reproduce the observed emission adequately, but we make no claim that they represent the true disk properties in detail, given the simplicity of the model and degeneracies between the parameters. We fix the position of each component at the coordinates determined from fits to the velocity-integrated (first-moment) maps of the CO emission, and we fix the line centres for both components at 6.1 km s⁻¹.

To find the distributions of parameter values that fit the data, we calculate a set of model disks using the Monte Carlo radiation transfer code RADMC-3D version 0.35 (ref. 38). The standard approach to comparing models to interferometric data is to transform the model images into complex visibilities in the $u$–$v$ plane (where the visibility is the Fourier transform of the sky brightness distribution and $u$ and $v$ are the coordinates in that plane) so that they can be compared directly with the calibrated data recorded by the interferometer, without the intervening, nonlinear step of creating an image from the interferometric data. In the case of a binary system where both disks have strong emission, this presents an additional complication; although the two disks are cleanly separated in the image plane, their emission overlaps in the $u$–$v$ plane. Thus, it is necessary to compute models for both disks to compare models to data in the $u$–$v$ plane. This increases the number of free parameters for each step in the model–data comparison from 8 to 16, complicating the exploration of the parameter space.

To make this problem more tractable, we pursued a modelling strategy that rests on the assumption that the best-fit disk parameters for one star are uncorrelated with those of the other star, allowing us to fit for only 8 parameters at a time. As a preliminary step, we model the two disks in the HK Tau system individually. For each component of the binary, we use RADMC-3D with the model described above to create a single model disk, with images at different velocities across the CO(3–2) line that are separated by the velocity resolution of our observations. We then use the NRAO software CASA to sample the model image with the same $u$–$v$ coverage as our ALMA observations, and we create a CLEAN image in exactly the same way as we imaged our observations of HK Tau. The resultant model image is compared with a sub-image of our data with the same field of view, velocity channel spacing and pixel scale, and we calculate $\chi^2$ between model and data. Using this image-plane modelling and the MCMC analysis described in more detail below, we find the model parameters that provide the best fits for the A and B disks in the image plane.

With these disk parameter estimates, we then proceed with the more robust $u$–$v$ plane modelling. To make the exploration of parameter space tractable, we vary parameters for only one disk at a time. In each model run, we hold constant the 8 parameters for one disk at values previously found to give a good fit, and vary only the 8 parameters for the other disk. We combine the two disk model images (one of which is always the same for a given run) into a single image with the images centred at the known positions of HK Tau A and B. We then sample this model image with the same projected baselines used in the ALMA observations to generate model visibilities that can be compared with the data. We use two sets of models for each component, one set with the CO(3–2) line images with a velocity resolution of 0.85 km s⁻¹ channels, the spectral resolution of the observations, and the other with the 345 GHz CO(2–1) line images.

Because multiple combinations of the model parameters can provide almost equally good fits to the data, and because the parameter space is large, we use MCMC to determine the posterior probability distribution of each parameter. As noted above, in each chain we vary only the 8 parameters for one of the disks. We use the Python code emcee, which implements an affine-invariant ensemble sampler. For most parameters we use a flat prior probability, with the exception of the inclination, where we use a sin(i)/i prior probability to account for the fact that randomly distributed inclinations do not have equal probabilities of a given i. We evaluate the posterior probability of each model as $\exp(-\chi^2/2)$ times the prior probability. We ran several separate chains to explore a variety of starting positions for the disk’s free parameters, and different fixed parameters for the other disk. In each chain, the ensemble had 30 walkers’ and ran for at least 500 steps. For each chain, we discarded the first 150 steps (4,500 model evaluations) as ‘burn-in’ so that the results would be independent of the starting parameter values. The results from different chains were consistent with each other, we combined them to produce our final parameter estimates. Not including the burn-in steps, our final results for HK Tau A and HK Tau B are based on 66,000 and 30,000 model evaluations, respectively. As noted above, in the case of HK Tau B, the position...
angle and inclination are well known from scattered-light imaging, and so for HK Tau B we adopt the PA and $i$ values found from previous work in the analysis that follows, combined with our new measurements for HK Tau A.

The key quantity we are interested in determining is the angle $\Delta$ between the two disks' angular momentum vectors. It is related to the measured position angles and inclinations through spherical trigonometry by

$$\cos(\Delta) = \cos(\ell_1) \cos(\ell_2) + \sin(\ell_1) \sin(\ell_2) \cos(PA_1 - PA_2)$$

With both inclinations specified in the usual range of $0^\circ$ to $90^\circ$, the above equation effectively assumes that both disks have their angular momentum vectors oriented on the same side of the plane of the sky. For the case where the two vectors are on opposite sides of the sky plane, one $i$ above should be replaced with $180^\circ - i$ if $i$ is defined always to be less than $90^\circ$. Here we adopt the convention used in specifying the inclination of visual binary orbits\textsuperscript{44},\textsuperscript{45}, where $i$ ranges from $0^\circ$ to $180^\circ$. In this convention, $i < 90^\circ$ corresponds to the case where the disk's orbital motion is in the direction of increasing position angle, or, equivalently, where the disk's angular momentum vector is inclined by an angle $90^\circ - i$ towards the observer relative to the sky plane. Thus, although our adopted convention for position angle (that of the redshifted edge of the disk) is the same as that typically adopted in previous work\textsuperscript{42}, our inclination convention differs.

By this convention, the inclination of the HK Tau B disk is $95^\circ$ (because it is known from scattered-light images that the northern face of the disk is tilted towards Earth), and the best-fit inclination of the HK Tau A disk could be either $43^\circ \pm 5^\circ$ or $137^\circ \pm 5^\circ$. In practice, the two cases do not yield greatly differing values of $\Delta$ because HK Tau B is so close to edge-on.

In the near future, it may be possible to distinguish between these two inclinations for HK Tau A. A recently discovered Herbig-Haro object, HH 678, lies 10 arcmin west of HK Tau\textsuperscript{46,47}. Its position angle of $267^\circ$ with respect to HK Tau places it on a line that is nearly perpendicular to the HK Tau A disk, suggesting that it may be associated. If so, the sign of the radial velocity of the Herbig-Haro object would break the inclination degeneracy of the HK Tau A disk.

We used fixed values of the orientation of the HK Tau B disk, and the values of PA and $i$ for HK Tau A from our MCMC chains, to find the posterior distribution of $\Delta$ for the two disks (Fig. 3). We take the median of the posterior distribution as the most probable value, and we find the values above and below the median that encompass 34.15% of the total probability in each direction to define the 68.3% credible interval (dashed lines); we similarly calculate the 95.4% credible interval (dotted lines). A plot of the posterior distributions of PA and $i$ for HK Tau A (Extended Data Fig. 1) shows that they are uncorrelated, as expected.

Although our primary focus is the relative orientations of the disks, the modelling used here has the potential to determine other parameters of interest, in particular the stellar mass. Pre-main-sequence stellar mass measurements are particularly of interest because they place valuable constraints on pre-main-sequence evolutionary models\textsuperscript{44,45}. Unfortunately, owing to our modest spatial resolution, the physical parameters used here has the potential to determine other parameters of interest, in particular the stellar mass. Pre-main-sequence stellar mass measurements are particularly of interest because they place valuable constraints on pre-main-sequence evolutionary models\textsuperscript{44,45}. Unfortunately, owing to our modest spatial resolution, the physical parameters

$$\Delta \approx \arccos \left( \frac{\cos(\ell_1) \cos(\ell_2) + \sin(\ell_1) \sin(\ell_2) \cos(PA_1 - PA_2)}{\sqrt{\cos^2(\ell_1) + \cos^2(\ell_2) - 2 \cos(\ell_1) \cos(\ell_2) \cos(PA_1 - PA_2)}} \right)$$

where $\Delta$ is the angle between the two disks' angular momentum vectors. It is related to the measured position angles and inclinations through spherical trigonometry by

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Thus, we suspect that our stellar mass estimate for HK Tau B may be inaccurate. It may be that our simple models do not adequately reproduce the vertical structure of the disk, which is likely to be much more important in modelling a nearly edge-on disk, like HK Tau B, than in modelling one that is more face-on, like HK Tau A. For example, ALMA science verification data of the disk around HD 163296 show that a vertical temperature gradient is necessary to reproduce the CO emission\textsuperscript{46,47}. It is also possible that the uncertainty in the exact systemic velocity of the system (due to contamination from the molecular cloud) is a factor. Using a fixed systemic velocity parameter may introduce a small bias in the fit parameters, particularly the stellar mass. However, we see no structure in the residuals that would arise from using a systemic velocity far from the correct value.

We emphasize that the position angle and inclination for HK Tau B used in the analysis of disk misalignment were taken from previous scattered-light imaging, and that modelling uncertainties for HK Tau B thus do not affect our main result here. Future ALMA data with better spatial resolution and using an isotopomer that is less sensitive to cloud absorption may help resolve the puzzle of HK Tau B’s stellar mass.
Extended Data Figure 1 Posterior probability distributions for the position angle and inclination of the disk around HK Tau A.