Magnetic fields in accretion disks play a dominant part during the star formation process but have hitherto been observationally poorly constrained. Field strengths have been inferred on T Tauri stars and possibly in the innermost part of their accretion disks, but the strength and morphology of the field in the bulk of a disk have not been observed. Spatially unresolved measurements of polarized emission (arising from elongated dust grains aligned perpendicularly to the field) imply average fields aligned with the disks. Theoretically, the fields are expected to be largely toroidal, poloidal or a mixture of the two, which imply different mechanisms for transporting angular momentum in the disks of actively accreting young stars such as HL Tau. Calculations of the solar magnetic field on a scale of 80 astronomical units are coincident with the major axis (about 210 astronomical units long) of the disk. From this we conclude that the magnetic field inside the disk at this scale cannot be dominated by a vertical component, though a purely toroidal field also does not fit the data well. The unexpected morphology suggests that the role of the magnetic field in the accretion of a T Tauri star is more complex than our current theoretical understanding.

HL Tau is located 140 pc away, in the Taurus molecular cloud. Although HL Tau is a T Tauri star, it is considered to be in an early stage of development owing to its bipolar outflow and possible residual envelope. Observations and modelling of this protostar assuming a thick, flared disk suggest a stellar mass of ~0.55 times the solar mass and a disk mass of 0.14 solar masses. A possible planet forming in the disk of HL Tau has been observed, though this detection was not confirmed. However, the disk of HL Tau is gravitationally unstable, which could favor fragmentation into Jupiter-mass planets. HL Tau has the brightest disk of any T Tauri star at millimetre wavelengths, allowing observations of the fractional polarization to have the best possible sensitivity. Previous observations of the polarization of the disk of HL Tau yielded marginally significant, spatially unresolved polarization detections with the James Clerk Maxwell Telescope and the Submillimetre Array. Polarization P has been measured at 0.6% at 2 AU resolution, archival observations released in this Letter. In addition, observations of HL Tau with the Combined Array for Millimeter-wave Astronomy (CARMA) have shown that the interferometric emission comes entirely from the disk with no contamination from large-scale envelope emission. HL Tau is therefore a very promising source to search for a spatially resolved polarization detection.

Only through observations of polarized dust emission can the morphology of the magnetic field be ascertained; however, higher-resolution dust polarimetric observations of T Tauri star disks do not detect polarization and place stringent upper limits (P < 1%) on the polarization fraction that disagree with theoretical models of high efficiency grain alignment with a purely toroidal field. There is a clear discrepancy between theoretical models of the magnetic fields in disks and the observations to date, requiring more sensitive observations of the dust polarization. The SMA recently detected the magnetic field morphology in the circumstellar disk of the Class 0 (that is, the earliest protostellar stage) protostar IRAS 16293–2422 B, but since this disk is nearly face-on, observations cannot detect the vertical component of the magnetic field. Moreover, this source is perhaps one of the youngest of the known Class 0 sources, increasing the chances that the polarized flux could be from the natal environment. Nevertheless, since the disk is the brightest component at the probed scale, magnetic field morphology most probably comes from the disk, and the magnetic field morphology hints at toroidal wrapping.

We obtained 1.25-mm CARMA polarimetric maps of HL Tau at 0.6" resolution and plot the magnetic field morphology in Fig. 1. This is a spatially resolved detection (with approximately three independent beams) of the magnetic field morphology in the circumstellar disk of a T Tauri star. The central magnetic field vector has a measured position angle (PA) of 0° = 143.6°.

Figure 1 | Detected magnetic field morphology of HL Tau at 0.6° resolution. The polarization vectors (short coloured lines) have been rotated by 90° to show the inferred magnetic field orientation. Red vectors are detections >3σ, while blue vectors are detections between 2σ and 3σ, where σ is the r.m.s. noise of P. We do not show vectors when the signal-to-noise ratio for Stokes I is below 2. The sizes of the vector are proportional to the fractional polarization, P, with the red scale bar corresponding to P = 1%. Stokes I contours are shown for [−3, 3, 4, 6, 10, 20, 40, 60, 80, 100] × σ, where σ is 2.1 milliarcseconds per beam and is the r.m.s. noise of I. The dashed line shows the major axis of PA = 136° (ref. 12). The synthesized beam is shown at bottom right and has a size of 0.65° × 0.56° and PA = 79.5°. Dec., declination; RA, right ascension.
± 4.4°, which is within 9° of the previously measured PA of the major axis of the HL Tau disk12. This angle is in agreement with that measured by the JCMT (Θ₀ ≈ 140 ± 20°) and archival observations from the SMA analysed here (Θ₀ ≈ 137 ± 13°). The central vector has a fractional polarization of P = 0.59 ± 0.09%, and P varies over the disk between 0.54 ± 0.13% and 2.4 ± 0.7% with an average and median of 0.90% and 0.72% respectively, in agreement with the upper limits (P < 1%) of other T Tauri star polarimetric observations17-19. This median value is significantly less than in IRAS 16293–2422 B (1.4%), which could indicate disk evolution; the dust grains could be growing larger and becoming more spherical with time, and/or the magnetic field is becoming more turbulent.

To constrain the intrinsic magnetic field configuration inside the disk of HL Tau, we made a simple model which incorporates a combination of a toroidal and a vertical component; any radial field component inside the bulk of the disk (most probably probed by our polarization observation) is expected to be sheared quickly into a toroidal configuration by differential rotation on the short timescale of the disk rotation. We use the best estimates of disk parameters12 (PA = 136° and inclination i = 40°, both accurate to within a few degrees) and vary the relative strength of the two field components from 100% toroidal and 0% vertical to 0% toroidal and 100% vertical in 1% increments (see Methods for modelling details). Using the ≥3σ detections in Fig. 1, we find that a completely toroidal field is the best-fit model. However, the reduced χ² value is high (69, where a value of 1 indicates an optimal fit). If we do not constrain the magnetic field to be aligned with the best-fit disk12 we can achieve a better fit. For a disk with a PA of 151°, the best-fit model to the observations is almost completely edge on, with an inclination of i = 89° (reduced χ² value of 1). Figure 2 shows the observed and modelled parameters for a PA of 136° and i = 40° as well as a PA of 151° and i = 89°. Although a PA of 151° is not very different from the major axis of the disk (15° difference), i = 89° is inconsistent with our disk dimensions and the well-constrained continuum observations of other studies12-21. There is also no detected polarized flux in the northeast (upper-left) and southwest (bottom-right) of the disk where P for a toroidal field should be highest due to less beam smearing. This fact, along with the poor fit with the constrained disk parameters, indicates that although there is probably a toroidal component, the field apparently has substantial contributions from other components.

We note that adding a vertical component to all our models makes the fit worse. This lack of any vertical component in our model suggests that dominant poloidal fields are probably absent inside the disk because, as we argued earlier on dynamical grounds, a predominately radial field is unlikely inside the disk because of rapid differential rotation. Moreover, although points with ≥5σ polarization detections fit a toroidal morphology even for the i = 40° model, we cannot be sure that the disk field is only toroidal; this is because a straight, uniform field in the plane of the disk, although physically unlikely for a disk system, also fits the data well.

If the disk of HL Tau has a dominant toroidal component, then it is uncertain what causes the outer vectors to not fit the toroidal morphology based on the best-fit disk dust model12 (Fig. 2a). Perhaps the grains in some parts of the disk do not efficiently align with the disk field. Another possibility is that the magnetic field towards the inner disk is toroidal and beam-averaged to be aligned with the major axis of the disk. However, towards the edge of the disk, where the disk field may be less tightly wound and weaker, the magnetic field may be dominated by external field lines that are already toroidal (for example, due to a rotating envelope). The incoming fields may strongly influence or even dominate the magnetic field in the outer disk. In any case, the discrepancy indicates that, at least for this particular source, one needs to go beyond the simplest magnetorotational instability2 magnetic field models that do not include any external influence or distortion. Both theoretical studies tailored to HL Tau and higher-resolution polarization observations are needed to resolve this puzzle.

At the 1,000 AU scale, structured magnetic fields are observed around young, low-mass protostars22,23, but the fields appear to be randomly aligned with respect to the inferred disk24,25. Misalignment of the field lines with the rotation axis can help overcome magnetic braking to create a centrifugally supported disk at the 100 AU scale26. Further disk evolution can be driven by magnetorotational instability2 or a magnetocentrifugal wind27; a toroidally dominant disk field is expected in the former scenario, and a significant poloidal field is required for the latter (at least near the wind launching surface). Both processes can possibly contribute to the disk accretion at the same time.

Until now, we have been unable to observationally constrain the magnetic field morphology in disks. Along with the Class 0 source IRAS 16293–2422 B, our observations of HL Tau show that a toroidal field component may last from the low-mass protostar’s initial formation to the T Tauri star stage—approximately the first 10⁶ years of a proto-star’s life28. The apparent absence of vertical fields in these observations implies that magnetocentrifugal winds driven along large-scale poloidal magnetic fields27 are probably not the dominant mechanism for redistributing the disk’s angular momentum during the accretion process of a star at the 80 AU size-scale of our observations. However, the morphology detected in HL Tau also cannot be fully explained by a simple mix of toroidal and vertical components, requiring future observations at both large scale and small scale to truly understand the role of magnetic fields in the formation of solar systems like our own.

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.

Received 11 April; accepted 9 September 2014. Published online 22 October 2014.

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Acknowledgements We thank R. L. Plambeck and C. L. H. Hull for consultation during the data reduction process and C. F. Gammie for discussions. This research made use of APLpy, an open-source plotting package for Python hosted at http://aplpy.github.com. Work at the Universities of Illinois and Maryland was supported by NSF AST-1139998 and AST-1139998, respectively. Support for CARMA construction was derived from the states of California, Illinois and Maryland, the James S. McDonnell Foundation, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported under a cooperative agreement (NSF AST 08-38226) and by the CARMA partner universities.

Author Contributions Data acquisition and reduction were performed by I.W.S., L.W.L. and M.F.-L. Polarization modelling was performed by W.K. and fitted by I.W.S. All authors analysed and discussed the observations and manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to I.W.S. (ianws@bu.edu).
METHODS

Data reduction. The CARMA dual polarization receivers allow for the measurement of polarized dust emission. Polarimetric maps can thus be created, which provide the flux density (Stokes I), the PA of the dust polarization, and P at every point within the map. CARMA continuum observations in Full Stokes mode were taken at 237 GHz in two different resolutions with each resolution having multiple tracks. The C-array observations (~0.79” resolution) consisted of four tracks in October and November 2013 while the B-array observations (~0.37” resolution) consisted of three more tracks in November and December 2013.

We have reduced the CARMA observations using the MIRIAD package. The dual-polarization receivers of CARMA measure right- (R) and left- (L) circular polarization and the four cross-polarization (RR, LL, LR, RL) terms. In order to calibrate CARMA Full Stokes observations, apart from the usual interferometric calibrations (bandpass, phase and flux corrections), two additional calibrations are required: XYPhase (due to L and R channel phase differences) and leakage (due to L and R channels cross-coupling). These calibrations were done in the typical manner for CARMA. The leakage terms for each antenna were consistent from track to track, with a steady increase of a few degrees with each newer track. Intraday variability is a well-known phenomenon which affects the total flux density, the linearity of polarized flux density, and the polarization angle and probably explains the variations of a few degrees seen in 0510 + 180 from track to track. Since the variation of the polarization in 0510 + 180 was not very large, the consistency of polarization measurements of 0510 + 180 between tracks made us confident that our calibration is accurate. For B-array tracks, we also saw that the bandpass calibrator, 3C454.3, showed consistency for polarization measurements for all the tracks. Other calibrators observed did not have polarization detected, signifying that our polarization detection of HL Tau is not a spurious detection. We also note that there was a slight difference in the polarization angle between the lower and upper sideband; this difference may be due to Faraday rotation and was almost constant for all tracks.

For bandpass calibration, C-array observations used 3C84 and B-array observations used 3C454.3. The phase calibrator used for both arrays was 0510 + 180. Observations of MWC349, with an adopted flux of 2.1 Jy (ref. 30), provided the absolute scale for the flux calibration at 237 GHz in most of the tracks. The bootstrapped flux of 0510 + 180 using MWC349 was consistent within 10% and 15% with bootstrapped fluxes using Mars and Uranus, respectively, in other tracks. Since planets are resolved at these resolutions, MWC349 is likely to have a more accurate flux calibration and was bootstrapped for all tracks. The absolute flux uncertainty is estimated to be 15%, but only statistical uncertainties are discussed in this work. When imaging, natural weighting was used to maximize the sensitivity.

Detects of polarization were found in every HL Tau track with consistent polarization angles and measurements. Since polarization is calculated from Stokes Q and U and can only have positive values, there exists a bias in the polarized intensity; hence, all our polarization measurements have been de-biased. The sensitivity in Stokes I is limited by dynamic range rather than the flux sensitivity of the observations. The uncertainty in the absolute position angle of CARMA is approximately 3° (ref. 25).

These high resolution interferometric observations are insensitive to large scale structure. Single dish and interferometric HL Tau observations find very similar compact fluxes, suggesting that the envelope dust continuum is negligible, and the flux appears to come entirely from the disk.

Also reported in this study are unpublished polarization observations (PA and P) of HL Tau from the SMA. These observations were taken in the compact configuration in October 2005 in the 345 GHz atmospheric window with the Local Oscillator tuned to 341.5 GHz. The polarization data reduction process was done in the typical manner employed by the SMA.

Linear polarization modelling. We employed a flared viscous accretion disk model that was constrained by high angular resolution data and a broad spectral energy distribution, detailed in another paper. The accretion disk model has a power-law density distribution with an exponential tapering, and the vertical density distribution is assumed to be 1.5 times thicker than the hydrostatic equilibrium case. The temperature distributions are calculated by interpolation of two power-law distributions at the cold mid-plane, comparable to the results of the Monte-Carlo radiative code RADMC-3D and at the surface based on radiation equilibriums: $T_{\text{in}}[K] = 190/(r/[\text{AU}])^{-0.43}$ and $T_{\text{out}}[K] = 600/(r/[\text{AU}])^{-0.43}$, where $T_{\text{in}}$ and $T_{\text{out}}$ are the temperatures of the disk at the mid-plane and surface, respectively. The disk parameters employed were the volume density power-law index, taken as 1.6/15, the dust opacity spectral index $\beta$ = 0.729, the disk mass $M_d = 0.134 M_{\odot}$, the inner radius $R_{\text{in}} = 2.4$ AU, and the characteristic radius $R_{\text{ch}} = 78.9$ AU. As described in the main text, we investigated various cases of different inclination and position angles.

Our polarization modelling consists of toordial and vertical magnetic fields. Instead of constraining the detailed morphology of magnetic fields, we intended to constrain which morphology is preferred. In order to achieve this goal, we examined 101 cases spanning relative polarization fractions of the two orthogonal fields in steps of 1% (that is, 100% toroidal, 99% toroidal and 1% vertical, 98% toroidal and 2% vertical, . . .). For constructing linear polarization information, we built Stokes I, Q and U maps by numerically solving radiative transfer (necessary for a thick disk). In individual integral elements of radiative transfer along the line of sight, we compute the intensity for Q and U. The fractional intensities added up to the Q and U maps by an integral element are:

$$\Delta Q = I \Delta f_p (f_{\text{rot}} + f_{\text{vert}})$$

$$\Delta U = I \Delta f_p (f_{\text{rot}} + f_{\text{vert}})$$

where $f_p$ is a total polarization fraction ($\sqrt{Q^2 + U^2}/I$), $f_{\text{rot}}$ and $f_{\text{vert}}$ are relative fractions of the toroidal and vertical fields (for example, $f_{\text{rot}} = 0.7$ and $f_{\text{vert}} = 0.3$ for 70% toroidal and 30% vertical fields), and q_{rot} and u_{rot} are $\cos(2\alpha_{rot})$ and $\sin(2\alpha_{rot})$ respectively. $\alpha_{rot}$ is the angle, $\chi$, of the toroidal magnetic field measured anticlockwise from the north. Similarly, $q_{\text{vert}}$ and $u_{\text{vert}}$ for vertical fields are $\cos(2\alpha_{\text{vert}})$ and $\sin(2\alpha_{\text{vert}})$, where $\alpha_{\text{vert}}$ is the angle of the vertical magnetic field. Since the disk is optically thin and we are only concerned with the morphology, $f_p$ can be given an arbitrary value (for example, 0.01 or 0.1). Note that the toroidal and vertical magnetic field vectors at each integral element have been tilted and rotated based on the inclination and the position angle of the angle of the model disk, before the calculation of the fractions. Q and U maps are convolved with the synthesized beam from the polarisation observations, and the modelled position angles of the magnetic field morphologies are created using $\chi = 0.5 \tan^{-1} (U/Q)$.

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