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Enhanced dust emission in the HL Tau disc: a low-mass companion in formation?

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ABSTRACT
We have imaged the disc of the young star HL Tau using the Very Large Array (VLA) at 1.3 cm, with 0.08-arcsec resolution (as small as the orbit of Jupiter). The disc is around half the stellar mass, assuming a canonical gas mass conversion from the measured mass in large dust grains. A simulation shows that such discs are gravitationally unstable, and can fragment at radii of a few tens of au to form planets. The VLA image shows a compact feature in the disc at 65 au radius (confirming the 'nebulosity' of Welch et al.), which is interpreted as a localized surface density enhancement representing a candidate protoplanet in its earliest accretion phase. If correct, this is the first image of a low-mass companion object seen together with the parent disc material out of which it is forming. The object has an inferred gas plus dust mass of $\approx$14 $M_{\rm Jupiter}$, similar to the mass of a protoplanet formed in the simulation. The disc instability may have been enhanced by a stellar flyby: the proper motion of the nearby star XZ Tau shows it could have recently passed the HL Tau disc as close as ~600 au.

Key words: circumstellar matter – planetary systems: formation – planetary systems: protoplanetary discs – stars: pre-main-sequence – radio continuum: stars.

1 INTRODUCTION

The mechanisms by which giant planets form are uncertain. Core-accretion models (e.g. Pollack et al. 1996; Hubickyj, Bodenheimer & Lissauer 2005) have successfully linked high abundances of rocky elements in the star to higher planet probability (e.g. Santos, Israelian & Mayor 2004; Fischer & Valenti 2005), and may explain planets with substantial rocky cores (Sato et al. 2006) – but have theoretical difficulties with slow planetary cooling that limits mass-accretion rates and with rapid inwards migration leading to loss of cores into the star. Also, the time of around 6 Myr to complete Jupiter may conflict with the infrared-detection rate of discs that declines close to zero by 6 Myr (Haisch, Lada & Lada 2001), and with the latest ages of ~15 Myr when gas is detected (Dent, Greaves & Coulson 2005) since planet completion takes longer in low-mass discs. The alternative model of gravitational instability can create a protoplanet very rapidly, on dynamical (orbital) time-scales (Boss 1997; Rice, Lodato & Armitage 2005), provided that the disc-cooling time is similarly short (Gammie 2001; Rafikov 2005). Only relatively rare discs of $\gtrsim 0.1 M_{\rm star}$ will be unstable, but recent radio studies (e.g. Rodmann et al. 2006) that account for mass in large dust grains may boost more of the total disc masses into this category. Since metre-sized particles are gathered up into the gas fragments (Rice et al. 2006), this model may also account for solid cores to giant planets.

Imaging a planet within its birth disc would illuminate the processes involved. Companions of several Jupiter masses upwards have been imaged, but large separations from the primary and in some cases small mass ratios of the two components suggest that these objects may have formed like binary stars (Luhmann et al. 2006). No discs within these systems have been imaged, so the formation processes remain obscure – the most direct observational evidence for a forming object is a cleared cavity within the disc of AB Aur (Oppenheimer et al. 2008).

In this Letter, we present the first candidate for a low-mass companion imaged in the accretion stage and within the parent disc. Such an object would be expected to appear as a cool condensation of dust and gas, possibly without a distinct dense core as sedimentation time-scales for large dust grains can be a few 10^4 yr (Helled, Podolak & Kovetz 2008). Here, we use radio-wavelength data to trace the thermal emission from large dust particles in the disc around HL Tau. This pre-main-sequence Class I (remnant envelope) object has been modelled by Robitaille et al. (2007) at around 0.33 $M_\odot$ and 5 $L_\odot$, seen at $<10^5$-yr old. The HL Tau disc was selected as one of the brightest known at millimetre wavelengths, with estimates for gas plus dust mass of up to 0.1 $M_\odot$ (Beckwith et al. 1990), and thus within the disc-to-star mass regime where

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instability could occur. Millimetre interferometry (resolving out the envelope) has shown emission from the dust disc extending out to at least ∼100-au radius (Mundy et al. 1996; Wilner, Ho & Rodriguez 1996; Lay, Carlstrom & Hills 1997; Looney, Mundy & Welch 2000; Rodmann et al. 2006).

2 OBSERVATIONS

Observations of HL Tau in a 10-arcsec field centred at RA 04:31:38.4034, Dec. 18:13:57.748 (J2000) were made with the Very Large Array (VLA) at 1.3-cm wavelength. In the largest A-configuration plus the 50 km-distant Pie Town antenna, the VLA was sensitive to scales down to 0.08 arcsec, a factor of 3 higher than the best previous resolution of 0.25 arcsec (Welch et al. 2004). At the Taurus distance of ≈140 pc, this gives a resolution of just over 10 au, equivalent to the orbit of Jupiter. The 22.5-GHz data were obtained over two runs in 2006 March and April, with a total usable time of ≈12 h. We used the phase reference source 04311+20376, 2°.4 from HL Tau and the primary flux scale was provided by 3C 286. We also corrected the antenna pointing and refined the amplitude calibration with the aid of bright compact sources including 0552+398. We followed standard VLA observational and data reduction procedures as described at http://www.vla.nrao.edu/astro/ including procedures for high frequency data reduction. Natural weighting gave a beam size of 114 by 104 mas and 1σ sensitivity of 17 μJy beam^{-1}. The data were also reconstructed with uniform weighting, giving a smaller beam of 82 by 76 mas with 1σ sensitivity of 21 μJy beam^{-1}. Systematic positional uncertainties are ∼30 mas, less than the resolution.

We also observed HL Tau at 5-cm wavelength with the MERLIN array (using up to six antennas) in 2006 January and February for a usable total time of 20 h including calibration. We used the phase reference source B0425+174 at 1° separation and followed procedures described in Diamond et al. (2003). These were some of the first observations made with six 5-GHz receivers (not all cryogenic), reaching a 1σ sensitivity of 100 μJy beam^{-1} using a 100-mas restoring beam. The images were sensitive to scales of 0.04–0.8 arcsec depending on weighting. We re-observed in 2007 April at 6-cm wavelength; the combined data reached a sensitivity of 55 μJy beam^{-1}. This gives a formal 3σ upper limit for 5–6 cm emission on these scales of 165 μJy beam^{-1}. No emission brighter than 100 μJy beam^{-1} was detected within 0.2 arcsec of the compact object discussed in Section 3.

3 RESULTS

The image (Fig. 1) shows a bright inclined disc out to around 30 au, i.e. similar to Neptune's orbit. The elliptical morphology and similar orientation to lower resolution images confirm that this is emission from the dust disc, while the two orthogonal extensions

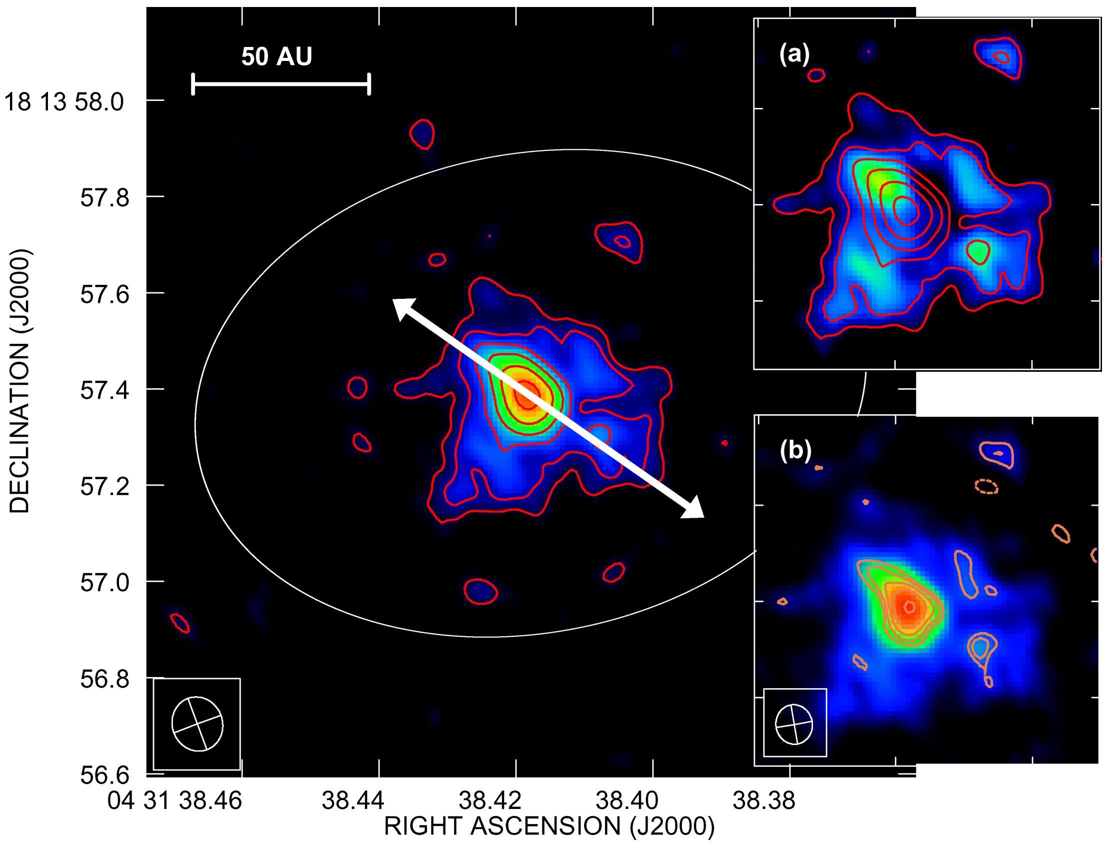

Figure 1. VLA 1.3 cm images towards HL Tau. Main image: natural weighting with a beam (small inset) of 0.11 arcsec for maximum sensitivity; contours increase by $\sqrt{2}$ and are at (4.0, 5.7, 8.0, 11.4, 16.0) ×17 μJy beam^{-1} (1σ). The arrow indicates the jet axes and the ellipse show the approximate extent of the inclined disc in a previous 0.6-arcsec resolution image at 2.7 mm (Looney et al. 2000). The compact object lies to the upper right-hand side. Upper inset: same but with central peak of 263 μJy subtracted, to highlight the jet bases and two features at ≈20 au at the ends of the disc major axis. Contours from the unsubtracted image are overlaid. Lower inset: uniform weighted image at higher resolution of 0.08 arcsec, with contours at (3.0, 4.2, 6.0, 8.5, 12.0) ×21 μJy beam^{-1} (1σ), highlighting the compact object.

(upper inset) are presumably the bases of the bipolar jet, previously seen at 1–2 arcsec from the star (Looney et al. 2000; Rodmann et al. 2006). Fainter dust emission is detected out to 100 au, declining with radius as $r^{-1.5\pm0.5}$ (from an error-weighted fit using elliptical annuli from 0.1 to 0.7 arcsec, with a correlation coefficient of 0.9). Assuming emission weighted by $r^{-1/2}$ for grains in thermal equilibrium with the star, the disc surface density declines at $r^{-1\pm0.5}$, roughly like the young outer Solar system (Davis 2005). Imaged features include the extended disc (∼1350 μJy); a central peak of ∼300 μJy located at (J2000) 04 31 38.4184, +18 13 57.387 (2-mas fit errors); the extensions to the NE and SW interpreted as jets, each of flux ≈100 ± 25 μJy and a clump of 78 ± 17 μJy offset from the central peak by 380 mas at position angle (PA) of 30° clockwise. The jet, disc and clump features are highlighted in a higher resolution image (lower inset).

This compact clump is at a projected stellar separation of 55 au, or orbiting at around 65 au if corrected for projection assuming a disc inclination of 60° (Wilner et al. 1996). The clump is here resolved for the first time. A 'nebulosity' was previously reported in a Berkeley–Illinois–Maryland Array (BIMA) 1.4-mm image of the disc (Welch et al. 2004), separated by 70 au from the star at PA −40°. Within the BIMA resolution of 0.25 arcsec (35 au), this is coincident with our VLA 1.3-cm peak at 55 au, −30°. The two independent detections give high confidence that this feature is real, while it is seen here, in detail, for the first time. The earlier image of an unresolved flux enhancement could have been attributed to an ordinary disc asymmetry such as a large-scale perturbation, but in our new data a clump is clearly seen. It is compact (full-width half-peak sizes of 20 ± 12 au by ≤12 au), three times brighter than the local flux level of the disc and clearly separated (by five resolution elements) from the stellar position. Given the similarity to protoplanets formed in simulations (Fig. 2), we propose this object as a candidate for the earliest stage of growth of a low-mass companion.

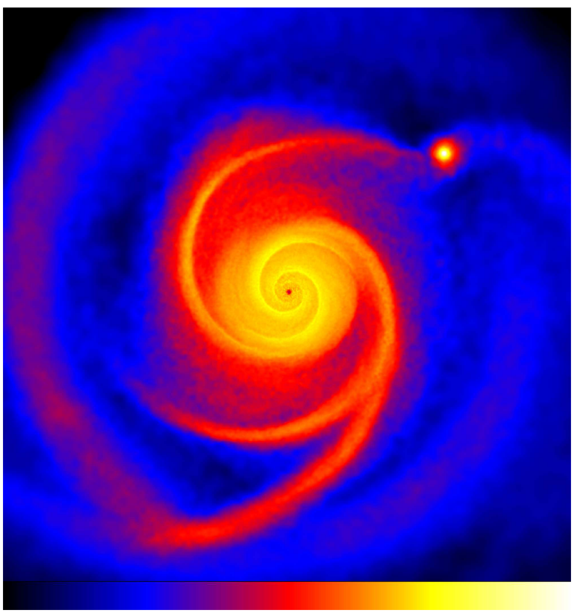

Figure 2. Example image from an SPH simulation (see the text) showing the surface density structure of a 0.3 $M_{\odot}$ disc around a 0.5 $M_{\odot}$ star. A single dense clump has formed in the disc (upper right-hand side), at a radius of 75 au and with a mass of ≈8 $M_{\rm Jupiter}$.

3.1 Robustness

We tested whether this +4.5σ feature could be an artefact. The noise/pixel has a very Gaussian distribution across the image, so the probability of a random fluctuation of ≥78 μJy beam^{-1} occurring within the projected disc area out to 100 au should be only ∼0.03 per cent. As a test, we added 33 fake 'planets' to the visibility data, with the flux density of the observed clump, scattered at 1–3 arcsec offsets, and followed the standard imaging process. The recovered objects follow a roughly Gaussian distribution, with mean and dispersion in flux density of 75 ± 25 μJy. This distribution was compared to the fluxes of 33 random positions, away from the disc, and no noise pixels at these positions exceed 3σ. The faintest fake 'planets', in the lower 1σ tail of their flux distribution, were close to the off-source 3σ noise level, showing that a true planet of such low intensity might be lost in the noise – but no false planet is seen emerging as a 3σ artefact, let alone at the 4.5σ level of the actual feature in the disc.

We then subtracted out the bright central emission (Fig. 1, upper inset) and found that the compact object is unaffected; conversely, we added a model of this emission at random positions across the field – no spurious features above 3σ were seen at the distance of our candidate. Hence, the clump is not an artefact arising from imperfect deconvolution of the interferometric image. Finally, we split the data into two separate frequency bands and alternatively into left and right circular polarizations. The clump was always recovered at a similar intensity, at between 2.5σ and 4.8σ significance depending on the quality in the partial data set, supporting a real detection.

We also investigated whether an unrelated source could be seen through the HL Tau disc – such background radio objects would typically be active galactic nuclei (AGN). This is improbable as even the most distant extragalactic faint radio sources are at least ∼0.4 arcsec in diameter (Muxlow et al. 2005), five times larger than our beam. Conversely, a source would need to be well over 1 mJy in lower resolution surveys to be detectable, and as AGN emission rises at long wavelengths (opposite to dust), this would be a rare bright object. Extrapolating a 1 mJy 1.3-cm source with a spectral index of $\alpha < -0.2$ [for 92 per cent of radio sources with multi-frequency data (Volmer et al. 2005) and flux $\propto \nu^{-\alpha}$] yields a signal >2 mJy at 20 cm. The VLA FIRST Survey (http://sundog.stsci.edu/first/) shows such an object would turn up in our 10 × 10 arcsec^2 field in about 1 in 3000 cases (actually much lower since in this flux range most sources are ≫0.4 arcsec in size). Moreover, such a source would have probably appeared at 5 cm: for $\alpha < -0.2$, the counterpart to the 1.3-cm feature would be of ≥100 μJy. The MERLIN image showed no features above 100 μJy in this region (3σ limit of 165 μJy), so a background synchrotron source is ruled out with high confidence. A *millimetre* counterpart (see below) indicates a dust-like spectrum for the clump – a distant starburst galaxy could potentially have such a spectral energy distribution, but these are rare. Extrapolating from the 1.3-cm flux would lead to a source of >20 mJy at 0.85-mm wavelength, with a corresponding probability of <10^{-6} (Coppin et al. 2006) within 100 au of HL Tau.

3.2 Measurements

The spectral energy distribution confirms that circumstellar dust is detected. The integrated centimetre flux was previously thought to be from the ionized stellar wind, but Fig. 3 shows dust emission to λ ≥ 3.6 cm. The dust spectrum of $F_\nu \propto \nu^{2.5-2.6}$ is characteristic of emission from a population of particles extending in size up to

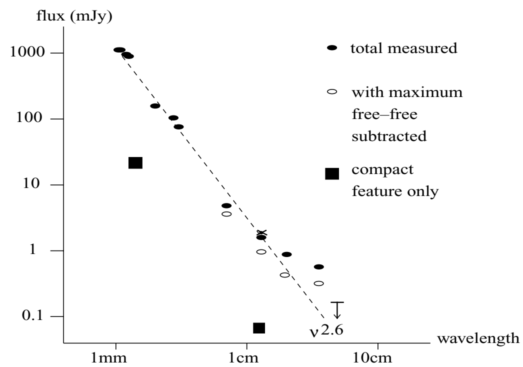

Figure 3. Spectral energy distribution of clump (squares) and integrated flux around HL Tau, including VLA (cross), MERLIN upper limit (arrow) and results from Rodmann et al. (2006) (filled ovals). Unfilled ovals show the *minimum* flux contribution from dust, after subtracting free–free flux extrapolated from the MERLIN upper limit assuming $F_\nu \propto \nu^1$, the steepest slope typically seen for ionized stellar winds (Anglada et al. 1998). A flatter ($\nu^{-0.1}$) subtraction gives an improved $\nu^{2.5}$ dust power-law fit.

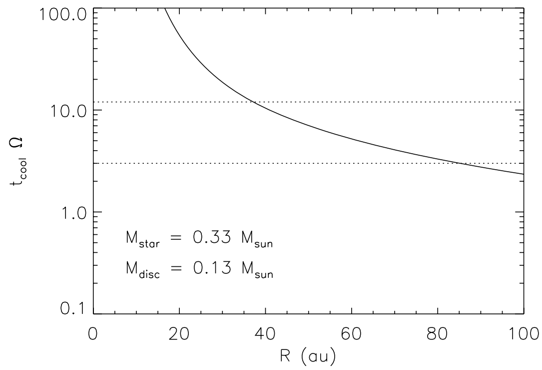

Figure 4. Plot of cooling time as a function of radius for a disc mass of $0.13\,M_\odot$ around a star of mass $0.33\,M_\odot$. The disc surface density declines as $r^{-1.5}$ to an outer radius of 100 au, and the instability parameter is $Q \sim 1$. The quantity $t_{\rm cool}\,\Omega$ is a dimensionless quantity relating the cooling time to the local orbital period; for $t_{\rm cool}\Omega = 2\pi$ the cooling time equals the orbital period. The dotted lines show critical values below which fragmentation occurs for different equations of state (Rice et al. 2005).

at least three times the observing wavelengths (Draine 2006), and hence here to bodies of >10 cm. The spectrum of the condensation is $\propto \nu^{2.5}$ from the fluxes of 23 ± 5 mJy at 1.4 mm and 78 ± 17 μJy at 1.3 cm (neglecting lower resolution data noted by Welch et al. 2004 as surrounding disc flux may be included), again implying that very large particles are present. This would agree with simulations (Rice et al. 2006) in which 'boulder'-like bodies of around metre size are most readily captured in unstable regions.

At 1.3 cm, the measured disc flux excluding the jets and region inside 5 au is ∼1350 μJy. Assuming simplistically that the dust particles are in thermal equilibrium with the star, we adopt the best-fitting $5\,L_\odot$ from Robitaille et al. (2007), giving 90 K at a characteristic disc radius of ∼20 au (Fig. 1, upper inset) and 50 K at the clump orbit. For an opacity of 7×10^{-4} cm^2 g^{-1} at 1.3 cm [for populations extending up to 1–10 cm particles (Draine 2006), and assuming that all the original gas and dust are present so that a canonical gas-to-dust mass ratio of 100 applies], the disc contains around $0.13\,M_\odot$ in total. This exceeds previous estimates of up to $0.1\,M_\odot$ due to the additional large dust and consequent scaling up of the total mass. The clump comprises $\approx 14\,M_{\rm Jupiter}$, with the uncertainty dominated by the scaling with temperature; the errors in flux and distance contribute at up to ∼30 per cent levels while adopting a different opacity (e.g. $\nu^{0.5}$ extrapolation from a standard 0.01 cm^2 g^{-1} at 1 mm) reduces the mass by a factor of 2. The central peak may also contain a mass reservoir – the 1.3–6 cm spectrum is just consistent with a wind origin, but allows up to $\sim 13\,M_{\rm Jupiter}$ of gas and dust to be present if the 1.3-cm flux is dust dominated. This is similar to the primordial $12\,M_{\rm Jupiter}$ out to Jupiter's orbit (Davis 2005), and so planets might form here by core accretion; if large grains are present, this may also solve the planetary radiative cooling problem by reducing the dust opacity (Hubickyj et al. 2005).

3.3 Simulations

We ran an example 250 000-particle smoothed particle hydrodynamics (SPH) simulation to investigate if the HL Tau disc could be gravitationally unstable (Fig. 2). The disc is assumed to have an initial surface density profile of $\Sigma \propto r^{-1.5}$ and initial outer radius of 100 au. The simulation evolves under a radiative transfer formalism (Stamatellos et al. 2007) in which each particle is allowed to cool towards its equilibrium temperature, determined using the local optical depth (dependent on material opacity, here taken to be half solar). The disc is allowed to heat up through $p\,{\rm d}V$ work and viscous dissipation. Relative to the local dynamical time-scales, the cooling times are slow in the inner disc where the optical depth is high and faster in the outer disc. Fragmentation is expected if the cooling time is less than a few orbital periods, and depends on the equation of state (Rice et al. 2005). For the estimated star and disc masses of HL Tau, Fig. 4 shows that the cooling time should be fast enough for fragmentation beyond ≈40 au. In the simulation, we adopted somewhat higher star and disc masses (but within the uncertainties) and allowed the disc to cool as low as 10 K, which favours fragmentation (Fig. 2). A single dense clump has formed in the disc, and is located at a radius of 75 au and has a mass of $\sim 8\,M_{\rm Jupiter}$, although it may continue to accrete from the disc. These properties are similar to those of the actual observed object around HL Tau. The simulation results will vary with the chosen opacity – a smaller value produces additional clumps, while a larger one could inhibit fragmentation altogether – and with the surface density profile – a flatter profile yields more outer disc mass and higher tendency to fragment.

4 DISCUSSION

Including the large grains now detected, the HL Tau disc mass is $\approx 0.13\,M_\odot$. Robitaille et al. (2007) find good fits to the stellar mass for 0.2–1 $M_\odot$; for their best-fitting value of $0.33\,M_\odot$, the disc is around $0.4\,M_{\rm star}$. This proportionally massive disc should be gravitationally unstable, and a simulation at the higher end of the $M_{\rm disc,\,star}$ ranges confirms that planetary objects could form at a few tens of au. The VLA data show such a flux peak in the parent disc material, interpreted here as a surface density enhancement. (The clump is three times brighter than the local disc flux, while warming of the gas by gravitational collapse should only contribute marginally to higher emission; simulation results suggest the beam-averaged dust temperature is raised by ≈50 per cent.) This clump at 65 au from HL Tau lies in the appropriate unstable region, and is compact as expected for a low-mass object accreting from the disc.

The simulated disc is unstable for the adopted parameters, but external forces could have increased the real disc's tendency to fragment. Notably, another cluster member, XZ Tau, appears close by, which is unusual within the diffuse Taurus association, and the relative motions suggest a possible recent encounter of the two stars. Their line-of-sight distances are unknown, but the similar radial velocities (Folha & Emerson 2000) suggest they are not located in very different parts of the association, and in 2D the stars are presently diverging. XZ Tau lies 23 arcsec east of HL Tau and the proper motions (Ducourant et al. 2005) are (+11, −19) and (−3, −21) mas yr^{-1}, respectively (errors of 2–5 mas yr^{-1}). Around 1600 yr earlier, the stars could thus have passed within ∼600 au (in 2D projection). Such an event would have been dynamically recent, given that the compact object has an orbital period of 900 yr for M_{star} of 0.33 $M_{\odot}$.

The final mass of this still forming companion may increase, by absorbing more of the disc, but our estimate of 14 $M_{Jupiter}$ for the condensation is well down into the substellar regime. If all this material is accreted, the final object would be around the brown dwarf/planet boundary by the definition of short-lived deuterium-burning capability, which occurs at $\gtrsim$12–13 $M_{Jupiter}$. A more recently developed definition of a planet is a low-mass object that formed in the disc of a star. This 'origins' definition sidesteps the deuterium-burning issue, which as Chabrier et al. (2007) point out is irrelevant for the evolution of brown dwarfs. In the case of HL Tau 'b', imaging the object within the parent disc marks it as a candidate protoplanet by this origins definition.

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REFERENCES

Anglada G., Villuendas E., Estalella R., Beltrán M., Rodrígues L., Torrelles J., Curiel S., 1998, AJ, 116, 2953
Beckwith S. V. W., Sargeant A. I., Chini R. S., Güsten R., 1990, AJ, 99, 924
Boss A. P., 1997, Sci, 276, 1836
Chabrier G., Baraffe I., Selsis F., Barman T. S., Hennebelle P., Alibert Y., 2007, in Reipurth B. et al., eds, Protostars & Planets V. Univ. Arizona Press, Tucson, p. 623
Coppin K. et al., 2006, MNRAS, 372, 1621
Davis S. S., 2005, ApJ, 627, L153
Dent W., Greaves J., Coulson I., 2005, MNRAS, 359, 663
Diamond P. J. et al., 2003, MERLIN User Guide, http://www.merlin.ac.uk/user_guide/
Draine B. T., 2006, ApJ, 636, 1114
Ducourant C., Teixeira R., Périé J. P., Lecampion J. F., Guibert J., Sartori M. J., 2005, A&A, 438, 769
Fischer D. A., Valenti J., 2005, ApJ, 622, 1102
Folha D. F. M., Emerson J. P., 2000, VizieR Catalog, 336, 50090
Gammie C. F., 2001, MNRAS, 553, 174
Haisch K. E., Lada E. A., Lada C. J., 2001, ApJ, 553, L153
Helled R., Podolak M., Kovetz A., 2008, Icarus, 195, 863
Hubickyj O., Bodenheimer P., Lissauer J. J., 2005, Icarus, 179, 415
Lay O. P., Carlstrom J. E., Hills R. E., 1997, ApJ, 489, 917
Looney L., Mundy L., Welch W., 2000, ApJ, 529, 477
Luhmann K. L. et al., 2006, ApJ, 649, 894
Mundy L. G. et al., 1996, ApJ, 464, L169
Muxlow T. W. B. et al., 2005, MNRAS, 358, 1159
Oppenheimer B. R. et al., 2008, ApJ, 679, 1574
Pollack J. B., Hubickyj O., Bodenheimer P., Lissauer J. J., Podolak M., Greenzweig Y., 1996, Icarus, 124, 62
Rafikov R. R., 2005, ApJ, 621, L69
Rice W., Lodato G., Armitage P., 2005, MNRAS, 364, L56
Rice W. K. M., Lodato G., Pringle J. E., Armitage P. J., Bonnell I. A., 2006, MNRAS, 371, L80
Robitaille T. P., Whitney B. A., Indebetouw R., Wood K., 2007, ApJS, 169, 328
Rodmann J., Henning Th., Chandler C. J., Mundy L. G., Wilner D. J., 2006, A&A, 446, 211
Santos N. C., Israelian G., Mayor M., 2004, A&A, 415, 1153
Sato B. et al., 2006, ApJ, 633, 465
Stamatellos D., Whitworth A. P., Bisbas T., Goodwin S., 2007, A&A, 475, 37
Vollmer B., Davoust E., Dubois P., Genova F., Ochsenbein F., van Driel W., 2005, VizieR Catalog, VIII/74A, 8074
Welch W. J., Webster Z., Mundy L., Volgenau N., Looney L., 2004, in Norris R., Stootman F., eds, ASP Conf. Ser. Vol. 213, Bioastronomy 2002. Astron. Soc. Pac., San Francisco, p. 59
Wilner D., Ho P., Rodriguez L., 1996, ApJ, 470, L117

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