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Is HL Tau expecting a planet? Where was XZ Tau?

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HL Tau is an $M_{\star} \approx$0.3 $M_{\odot}$ young star $<$ 0.1 Myr old, in the L1551 star-forming complex at a distance of $\sim$140 pc. It has one of the brightest-known discs at mm wavelengths; the dust opacity suggests that at least millimetre-sized dust aggregates are present [2]. HL Tau also produces a jet in the NE-SW direction. The problem is to disentangle emission from ionised gas in the jet (and possibly a disc wind) and from dust. We set out to look for the first stages of planet formation using the early enhancements of the VLA and MERLIN en route to the EVLA and *e*-MERLIN, which provide a resolution comparable to the orbit of Jupiter at the distance of HL Tau. Regions dominated by plasma or dust emission are distinguished by their radio spectral indices which also constrain the dust grain size. There are signs of coagulation into pebbles and inhomogeneities in the disc, probably due to the accretion of planetismals. We identify an intriguing potential, protoplanetary condensation. Finally, we look forward to future observations with *e*-MERLIN, the EVLA and eVLBI. We invite anyone interested in a related *e*-MERLIN legacy project to contact the authors.

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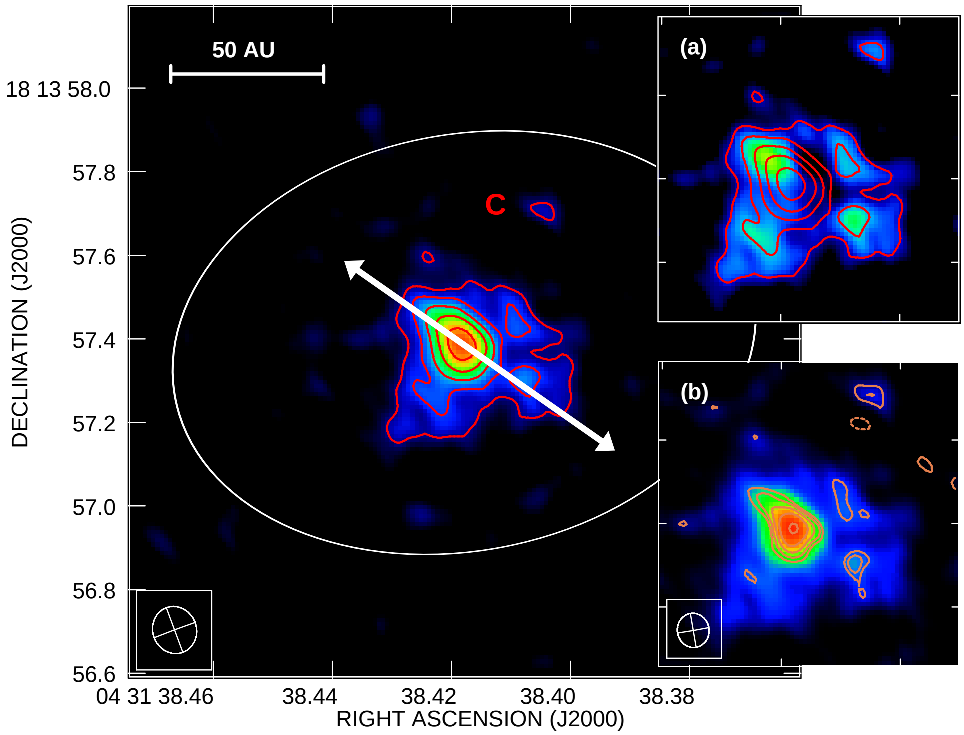

Figure 1: The main image shows HL Tau at λ=1.3 cm, 0.11-arcsec resolution. The contours are at (4.0, 5.7, 8.0, 11.4, 16.0)$\times$ 17 μJy beam^{-1} (1σ). The arrow indicates the jet axis and the ellipse shows the approximate extent of the inclined disc imaged by [1] at λ=2.7 mm. The clump is labelled with a red **C**. This clump is also seen in inset (a), which shows the full contours overlaid on an image made after subtracting the central 263-μJy peak, and in inset (b) which shows contours at (3.0, 4.2, 6.0, 8., 12.0)$\times$ 21 μJy beam^{-1} (1σ) from an image made at 0.08-arcsec resolution, overlaid on the original colour scale.

1. HL Tau at 0.1 arcsec resolution

We made lengthy observations of HL Tau at 22 GHz (λ = 1.3 cm) with the VLA + Pie Town and at 5–6 GHz using new receiver systems allowing all the antennas of MERLIN to operate in the λ = 5 cm band. This provided a matching resolution of 0.05 –0.1 arcsec and sensitivities (3$\sigma_{\rm rms}$ noise) of 50 μJy beam^{-1} and 165 μJy beam^{-1} at 22 and 6 GHz, respectively. All observations were phase-referenced, giving an absolute astrometric accuracy of $\approx$30 mas.

The VLA + Pie Town image is shown in Fig. 1. Bright emission is detected from an inclined disc $\sim$ 30 AU in radius. Radial averaging reveals the presence of fainter emission out to 100 AU, with a flux profile decreasing with radius $\propto r^{-1.5\pm0.5}$, as in the young Solar system. The clump **C** is detected at 4.5σ significance and simulations show that it is very unlikely to be an artefact, especially as it is also present in a λ=1.4 mm image taken by Welch[3]. HL Tau was not detected by MERLIN using a total of $\sim$2 days data at 5 and 6 GHz. This gives an upper limit of 165 μJy (3$\sigma_{\rm rms}$). HL Tau has previously been detected by the VLA at 1.3–3.6 cm wavelenths with a flux density of a few hundred μJy at 1$''$.5–3$''$.0 resolution [2] and the high noise level in the MERLIN images suggests that some large-scale flux is present but resolved-out by the present instrument.

2. Disentangling dust, pebbles, plasma and protoplanets

Free-free emission from plasma has a spectral index $\alpha \leq 0.6$ (using the convention $S \propto \nu^{\alpha}$) depending on its optical depth. Thermal emission from dust can have $\alpha > 2$ in the mm regime depending on the nature of the grains. We combined our measurements and upper limits with values from the literature After subtracting the maximum likely contribution from plasma, the dust emission behaves as $S \propto \nu^{2.5}$, suggesting that the distribution of particle sizes extends to at least 3 times the longest wavelength measured, i.e. 10-cm pebbles or larger. We deduce that the disc contains ~ 0.13 $M_{\odot}$ of gas and dust. The flux densities of clump **C** alone at 1.4 mm and 1.3 cm are also consistent with emission from dust grains and pebbles. The clump is marginally resolved (Fig. 1, inset b) with full-width half-peak sizes of $20\times \leq 12$ AU and an estimated mass of ~ 14 $M_{\rm jupiter}$.

Clump **C** is 65 AU from the central star if the disc is at an inclination of 60° [4]. The cooling timescale is less than a few orbital periods at ~35–55 AU from HL Tau, allowing disc fragmentation in the region of clump **C**. We performed a hydrodynamical simulation of a 0.13 $M_{\odot}$ disc around a 0.3 $M_{\odot}$ star with a surface density profile $\propto r^{-1.5}$ and an initial radius of 100 AU. This produced a single dense clump in a 75-AU radius orbit, mass ~8 $M_{\rm jupiter}$ but likely to continue accreting (whilst not exceeding the planetary limit) and an approximate expected diameter of ~17 AU during the condensation phase. This is in excellent agreement with our observations.

XZ Tau, another member of L1551, is 23″ from HL Tau and their proper motions suggest divergence. If they are at a similar distance from Earth, they would have had an encounter at only 600 AU about 1600 years ago, which could have triggered an instability in the HL Tau disc.

3. Conclusions and future plans

Our high-resolution 22-GHz images of the disc around the 0.3 $M_{\odot}$ HL Tau show that it contains up to 0.13 $M_{\odot}$ of gas and dust, with a grain size distribution extending at least to 10 cm. Such a proportionately massive disc is gravitationally unstable and we indeed detect an inhomogeneity in the unstable region. This is likely to be a protoplanetary condensation (also detected at λ=1.4 mm, [3]). Within the next few years, the sensitivity of *e*-MERLIN and the EVLA will increase by an order of magnitude, and ALMA will come into operation at (sub-)mm wavelengths. This will enable multi-frequency spectral index maps with the same resolution as Fig. 1, showing the detailed distribution of gas and differences in the dust particle size, such as accretion around clump **C**. We will even be able to measure its proper motion by combining *e*-MERLIN, EVLA and VLBI data, since at the orbital distance of **C**, a planetismal should have a proper motion of a few mas year^{-1}.

References

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