THE VLA VIEW OF THE HL TAU DISK: DISK MASS, GRAIN EVOLUTION, AND EARLY PLANET FORMATION

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ABSTRACT

The first long-baseline ALMA campaign resolved the disk around the young star HL Tau into a number of axisymmetric bright and dark rings. Despite the very young age of HL Tau, these structures have been interpreted as signatures for the presence of (proto)planets. The ALMA images triggered numerous theoretical studies based on disk–planet interactions, magnetically driven disk structures, and grain evolution. Of special interest are the inner parts of disks, where terrestrial planets are expected to form. However, the emission from these regions in HL Tau turned out to be optically thick at all ALMA wavelengths, preventing the derivation of surface density profiles and grain-size distributions. Here, we present the most sensitive images of HL Tau obtained to date with the Karl G. Jansky Very Large Array at 7.0 mm wavelength with a spatial resolution comparable to the ALMA images. At this long wavelength, the dust emission from HL Tau is optically thin, allowing a comprehensive study of the inner disk. We obtain a total disk dust mass of $(1-3) \times 10^{-2} M_\odot$, depending on the assumed opacity and disk temperature. Our optically thin data also indicate fast grain growth, fragmentation, and formation of dense clumps in the inner densest parts of the disk. Our results suggest that the HL Tau disk may be actually in a very early stage of planetary formation, with planets not already formed in the gaps but in the process of future formation in the bright rings.

Key words: planets and satellites: formation – protoplanetary disks – stars: formation – stars: individual (HL Tau) – stars: protostars – techniques: interferometric

1. INTRODUCTION

HL Tau is a very young solar-type star surrounded by a dusty circumstellar disk and a remnant envelope. The object is located at a distance of $\sim$140 pc (Loinard et al. 2007), within the Taurus star-forming region. Showing all ingredients of a young system in the earliest stages of planet formation, HL Tau has attracted a lot of attention over the years. For a summary of the early observational data and the results of the first comprehensive radiative transfer modeling we refer to D’Alessio et al. (1997) and Men’shchikov et al. (1999).

HL Tau drives an ionized jet indicating ongoing accretion (e.g., Pyo et al. 2005; Anglada et al. 2007). Early interferometric observations revealed that emission at centimeter wavelengths traces the radio counterpart of this collimated jet, while the emission at wavelengths $\lesssim$1.3 cm predominantly traces dust emission from a disk (Rodríguez et al. 1994; Wilner et al. 1996). This source attracted renewed interest after high angular resolution interferometric observations indicated that the HL Tau disk, despite its youth, may already be forming planets. Observations performed with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at 1.3 and 2.7 mm ($\sim$20–120 au resolution) suggested a gravitationally unstable disk that might undergo fragmentation (Kwon et al. 2011). Very Large Array (VLA) observations at 1.3 cm ($\sim$12 au resolution) revealed a compact structure in the disk at 65 au radius, interpreted as a protoplanet candidate (Greaves et al. 2008). Subsequent high-sensitivity VLA observations at 7.0 mm ($\sim$7 au resolution) could not confirm this putative protoplanet, but found evidence for a depression at radius $\sim$10 au in the radial density profile of the disk, which was interpreted as being related to the presence of an orbiting protoplanet (Carrasco-González et al. 2009).

With the long baselines of the Atacama Large Millimeter/submillimeter Array (ALMA) becoming available (ALMA Partnership et al. 2015b), this facility produced iconic images of the dust emission at 2.9, 1.3, and 0.87 mm from the HL Tau disk ($\sim$3.5–10 au resolution), showing a number of axisymmetric bright and dark rings, most probably corresponding to
Images were made with the CASA task CLEAN using multi-scale, multi-frequency synthesis that fits the emission with a Taylor series with nterms = 2 during the deconvolution (Rau & Cornwell 2011). Since our multi-configuration observations are sensitive to emission at very different scales (from ~16” ≈ 2240 au to 0’’05 ≈ 7 au), we made images with different angular resolutions by adjusting the Briggs robust parameter (Briggs 1995) and the Gaussian uv-taper in CLEAN. We also made images by splitting the 8 GHz band in two sub-bands of 4 GHz each (central wavelengths of 6.7 and 7.3 mm). For comparison, images were aligned by assigning to the position of the central peak of the ALMA images the same absolute coordinates as in the VLA images, α (J2000) = 04h31m38s426, δ(J2000) = 18°13’57’’23. In Figures 1 and 2, we present the VLA images with different angular resolutions and comparisons to the ALMA images.

We obtained radial profiles of the intensity of the ALMA images and our most sensitive VLA image at 7.0 mm (natural weighting; beam size ≈0’’067). For a proper comparison, we convolved all images to a common circular beam size of 0’’07 (the smallest beam size obtained from the public 2.9 mm ALMA uv-data with a uniform weighting). From these images, we obtained the average intensity within concentric elliptical rings of 0’’01 width at different radii, using the task IRING of the Astronomical Image Processing System (AIPS). The dimension and orientation of the elliptical rings match those of the HL Tau disk derived from the ALMA images (inclination angle, i ≈ 46°72, and position angle, P. A. ≈ 138°02; ALMA Partnership et al. 2015a).

Some contamination from free–free emission from the HL Tau jet is expected at 7.0 mm. From our 6.7 and 7.3 mm sub-band images we obtain a spectral index of ~1 at the center of the disk, consistent with comparable contributions from free–free and dust emission. To correct for the free–free contamination, we calibrated VLA A configuration archival data at 6 and 2 cm (project code: 12B-272), where emission is dominated by a partially optically thick radio jet in the NE–SW direction. From these images, the frequency dependence of the jet’s flux density and angular size (major axis) can be expressed as $S_r \approx 280 \times [\nu/10.5 \text{GHz}]^{0.4} \text{mJy}$ and $b_{maj} \approx 0'01 \times [\nu/10.5 \text{GHz}]^{-1}$, respectively, consistent with previous 7 mm observations (e.g., Wilner & Lay 2000). Thus, an upper limit to the free–free contribution at 7.0 mm is obtained by extrapolating the flux density from centimeter wavelengths with a spectral index of 0.4, while a lower limit can be obtained by assuming that the free–free emission becomes optically thin at 2 cm (i.e., spectral index of −0.1 from 2 cm to shorter wavelengths). Therefore, we expect unresolved (<0’’07) free–free emission with a flux density in the range ~200–400 µJy corresponding to ~35%–65% of the 7.0 mm emission at the disk center. This correction implies a larger uncertainty in the dust intensity at the center of the disk.

From the corrected intensity profiles, we derived brightness temperatures at each wavelength using the Planck equation for blackbody radiation, and we computed spectral indices between different wavelengths. We also derived profiles of optical depth and column density (assuming dust temperature power-laws and opacity; see Section 3.1). Radial profiles are shown in Figure 3.

2. OBSERVATIONS AND IMAGE ANALYSIS

We observed HL Tau with the VLA of the National Radio Astronomy Observatory (NRAO)\textsuperscript{14} using the Q-band receivers in the C, B, and A configurations (see Table 1 for details). We observed the frequency range 39–47 GHz (central wavelength ≈7.0 mm). Calibration of the data was performed with the data reduction package Common Astronomy Software Applications (CASA; version 4.4.0), using a modified version of the NRAO calibration pipeline.

\textsuperscript{14} The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

### Table 1

| Obs. Date       | Project Code | Conf. | Total Time |
|-----------------|--------------|-------|------------|
| 2014 Dec 07     | 14B-485      | C     | 1.7 hr     |
| 2015 Feb 15     | 14B-485      | B     | 1.6 hr     |
| 2015 Aug 13     | 14B-487      | A     | 1.1 hr     |
| 2015 Aug 25     | 14B-487      | A     | 1.1 hr     |
| 2015 Sep 19     | 14B-487      | A     | 1.7 hr     |
| 2015 Sep 20     | 14B-487      | A     | 3.8 hr     |
| 2015 Sep 21     | 14B-487      | A     | 3.4 hr     |

Note. The bandpass, flux density, and phase calibrators were 3C84, 3C147, and J0431+1731, respectively. The phase calibrator was observed every 3 minutes for the C configuration observations and every 2 minutes for the B and A configuration observations. We estimate a 10% uncertainty for the absolute flux calibration. Quoted flux errors in discussion are statistical uncertainties. Self-calibration was achieved. The phase center was α (J2000) = 04h31m38s429, δ(J2000) = 18°13’57’’29.

high- and low-density concentric dust structures in the disk (ALMA Partnership et al. 2015a). The images immediately triggered numerous theoretical works in order to explain these remarkable structures. Planet-related explanations range from the presence of embedded sub-Jupiter mass planets (Dipierro et al. 2015; Dong et al. 2015; Picogna & Kley 2015) to individual more massive planets (Gonzalez et al. 2015). Alternative explanations include magnetized disks without planets (Flock et al. 2015), fast pebble growth near condensation fronts (Zhang et al. 2015), and sintering-induced dust rings (Okuzumi et al. 2016).

The presence of massive planets (~10–15 $M_J$) in two prominent dips in the dust distribution at ~70 au was excluded utilizing deep direct L-band imaging with the Large Binocular Telescope (LBT; Testi et al. 2015), but the presence of lower-mass planets in the disk is not yet excluded and remains an interesting possibility.

Detailed radiative transfer analysis of the ALMA data shows that the emission from the various bright rings is probably optically thick, even at the longest ALMA wavelength of 2.9 mm (Jin et al. 2016; Pinte et al. 2016). The challenge of deriving density profiles and grain-size distributions can only be circumvented by observations at even longer wavelengths where the disk will be optically thinner. In this Letter, we present new high-sensitivity Karl G. Jansky VLA observations at 7.0 mm of the HL Tau disk. These data provide a deeper view of the HL Tau disk, with an angular resolution comparable to the ALMA images.
3. RESULTS AND DISCUSSION

The recent ALMA images of the HL Tau disk revealed several dark and bright rings (named D1–D7 and B1–B7, respectively; Figure 1). Our new 7.0 mm VLA observations are the most sensitive and highest angular resolution observations of the HL Tau disk performed to date at such a long wavelength. The low angular resolution 7.0 mm image shows an elliptical source with a similar size and orientation as the ALMA images (Figure 1). At higher angular resolution, the VLA is able to image with high signal-to-noise ratio (S/N) ratio (>4σ) the 7.0 mm emission from the inner half of the disk (≤50 au; see Figures 1 and 2). In our 7.0 mm images, we clearly identify several of the features seen in the ALMA images: the central disk and the first pair of dark (D1) and bright (B1) rings (Figures 1–3).

The importance of our sensitive 7.0 mm images is that, at such a long wavelength, the emission has a lower optical depth than in the ALMA data. This is especially critical for the study of the innermost part of the disk, where dust becomes opaque at all ALMA wavelengths and, as a consequence, physical properties are poorly constrained even with detailed modeling (e.g., Jin et al. 2016; Pinte et al. 2016). At the positions of the most opaque regions, the center of the disk and the first bright ring, the 7.0 mm brightness temperatures (∼45 and 15 K, respectively) are ∼4 times lower than those of the ALMA 0.87 mm image (∼130 and 60 K, respectively). Therefore, assuming that at 0.87 mm the emission from these two structures is optically thick, we obtain optical depths ≤0.4 at 7.0 mm. This implies that dust emission at 7.0 mm is optically thin at all radii, even in the densest parts of the disk.

Our new high-sensitivity 7.0 mm images of the HL Tau disk are an excellent basis for future comprehensive radiative transfer modeling to accurately obtain the physical properties of the disk. They are especially necessary in order to better constrain properties in the inner disk regions, where terrestrial planets are thought to form, in principle.

In the following, we analyze our VLA images of the HL Tau disk to obtain direct rough estimates of the different physical parameters (e.g., mass and grain-size distributions). We also analyze possible substructure in the disk and discuss our results in the context of planet formation.

3.1. Mass Distribution

An accurate determination of the mass distribution in the HL Tau disk requires detailed radiative transfer modeling. For this Letter, we obtain first estimates by assuming a simple power law for the dust temperature in the form

\[ T_{\text{dust}} = T_0 \left( \frac{R}{R_0} \right)^{-q}. \]

While the exponent seems to be well constrained in the range \( q = 0.5 \sim 0.6 \) by previous studies, there is large uncertainty in the reference temperature, with different proposed values in the range \( T_0 \sim 70 \sim 140 \text{ K at } R_0 = 10 \text{ au} \) (e.g., Men'shchikov et al. 1999; Kwon et al. 2011; Pinte et al. 2016). For the dust opacity at 7.0 mm, we use a range of typical values for the dust-averaged opacity, \( K_{\nu, \text{mm}} = 0.13 \sim 0.2 \text{ cm}^2 \text{ g}^{-1} \) (e.g., Men'shchikov et al. 1999; Pérez et al. 2012). Thus, at each radius, we calculate ranges for the optical depth and the dust column density taking into account these uncertainties (see Figure 3). Our calculations are consistent with the inner features of the disk being optically thick at all ALMA wavelengths, while at 7.0 mm the emission is optically thin at all radii (see Figure 3(b)). We estimated values of the dust column density around ∼1 g cm\(^{-2}\) at the center of the disk (see Figure 3(c)). This suggests a denser disk at inner radii (<50 au) than previously obtained by detailed modeling (e.g., Pinte et al. 2016 predict ≤0.2 g cm\(^{-2}\) at the center of the disk).

We also estimated dust masses for the inner disk (ID) and the bright rings (B1 to B6; see Table 2). For those features that are optically thin in the ALMA images, i.e., B2–B6, we obtain dust masses consistent with previous estimations (Pinte et al. 2016). However, our optically thin 7.0 mm data suggest large dust masses for the inner disk and the first bright ring (B1) for which only lower limits were obtained previously (see Table 2). Finally, we estimate that the total dust mass of the disk is within the range \((1 \sim 3) \times 10^{-3} M_\odot\), which is also somewhat larger than previous estimates, \((0.3 \sim 1) \times 10^{-3} M_\odot\) (e.g., D'Alessio et al. 1997; Men'shchikov et al. 1999; Kwon et al. 2011; Pinte et al. 2016).
3.2. Dust Particle-size Distribution

Grain growth and mixing lead to changes in particle-size distribution and dust composition throughout the disk (Henning & Meeus 2011). This has been recently studied in several objects for which segregation by particle-size (e.g., Menu et al. 2014) and radial changes in dust optical properties (e.g., Guilloteau et al. 2011; Pérez et al. 2012, 2015) are observed.

The fully resolved ALMA and VLA images of the HL Tau disk now offer an excellent opportunity for a detailed study of the properties of the particle-size distribution in a very young disk. In particular, changes in the dust properties can be inferred from changes in the spectral index of the emission, $\alpha$, but only for optically thin emission in the Rayleigh–Jeans regime (e.g., Beckwith et al. 2000). When derived from the short ALMA wavelengths, the observed radial variations of $\alpha$, from $\sim$2 to 2.5 (Figure 3(d)), reflect high optical depths inward of $\sim$50 au. Thus, these ALMA observations cannot be used to infer grain growth in the densest, inner disk regions. In contrast, the observed radial variations of $\alpha$ derived from the two most optically thin wavelengths, 7.0 and 2.9 mm, show a different behavior: (1) at all radii, except at the location of the dark gap D5, we obtain $\alpha_{7.0-2.9\,\text{mm}} > \alpha_{1.3-0.87\,\text{mm}}$, consistent with the emission at shorter wavelengths being more optically thick and not in the R-J regime, and (2) a clear gradient in $\alpha_{7.0-2.9\,\text{mm}}$ is observed between $\sim$10 and 50 au, consistent with a change in the dust optical properties and a differential grain-
The width of the lines represents the 1σ uncertainty of each quantity. (a) Brightness temperature at different wavelengths (2.9, 1.3, and 0.87 mm from ALMA; 7.0 mm from VLA). Obtained by averaging the density in concentric ellipses over the ALMA and VLA images convolved to a common circular beam size of 0′′07. A dust temperature law, also convolved to a beam size of 0′′07, is also shown (see Section 3.1). (b) Optical depth obtained by assuming the dust temperature profile in panel (a). The thick dashed horizontal line marks the threshold between optically thin (<1) and optically thick (>1) emission. (c) Column density profile obtained from the 7.0 mm data and the dust temperature profile. (d) Spectral index profiles between several wavelengths. Error bars in the bottom right corner indicate uncertainties due to absolute flux calibration (not affecting spectral index gradient).

Figure 3. Radial profiles of several quantities in the HL Tau disk. In all panels, the width of the lines represents the 1σ uncertainty of each quantity. (a) Brightness temperature at different wavelengths (2.9, 1.3, and 0.87 mm from ALMA; 7.0 mm from VLA). Obtained by averaging the density in concentric ellipses over the ALMA and VLA images convolved to a common circular beam size of 0′′07. A dust temperature law, also convolved to a beam size of 0′′07, is also shown (see Section 3.1). (b) Optical depth obtained by assuming the dust temperature profile in panel (a). The thick dashed horizontal line marks the threshold between optically thin (<1) and optically thick (>1) emission. (c) Column density profile obtained from the 7.0 mm data and the dust temperature profile. (d) Spectral index profiles between several wavelengths. Error bars in the bottom right corner indicate uncertainties due to absolute flux calibration (not affecting spectral index gradient).

Table 2

| Covered Disk Feature | Radius (au) | Flux Density at 7.0 mm (mJy) | Dust Mass ($M_{\oplus}$) |
|----------------------|------------|------------------------------|--------------------------|
| ID                   | <13        | 0.61 ± 0.04                 | 10–50                    | >2.3                     |
| B1                   | 13–32      | 1.45 ± 0.02                 | 70–210                   | >47                      |
| B2                   | 32–42      | 0.48 ± 0.01                 | 30–90                    | 30–69                    |
| B3                   | 42–50      | 0.35 ± 0.01                 | 20–80                    | 14–37                    |
| B4                   | 50–64      | 0.36 ± 0.01                 | 30–90                    | 40–82                    |
| B5                   | 64–74      | 0.18 ± 0.01                 | 10–50                    | 5.5–8.7                  |
| B6                   | 74–90      | 0.45 ± 0.01                 | 40–140                   | 84–129                   |

Notes.

a Calculated by integration of the column density profile obtained from the 7.0 mm data between adjacent dark rings.
b Calculated by radiative transfer modeling of the ALMA images by Pinte et al. (2016).

The presence of dark and bright concentric rings has been commonly interpreted as the result of planet formation already ongoing in the HL Tau disk. However, since HL Tau is a very young T Tauri star, the presence of several (proto)planets sufficiently massive to carve holes in the disk at this early stage is somewhat surprising. On the other hand, alternative formation mechanisms, not requiring the presence of protoplanets, seem also possible. Moreover, sensitive searches for massive (proto)planets in the outer dark rings have yielded negative results (see Section 1 and references therein).

We propose a scenario in which the HL Tau disk may have not formed planets yet, but rather is in an initial stage of planet formation. Instead of being caused by (proto)planets, the dense rings could have been formed by an alternative mechanism. Our 7.0 mm data suggest that the inner rings are very dense and massive, and then they can be gravitationally unstable and fragment. It is then possible that the formation of these rings result in the formation of dense clumps within them like the one possibly detected in our 7.0 mm image. These clumps are very likely to grow in mass by accreting from their surroundings, and then they possibly represent the earliest stages of protoplanets. In this scenario, the concentric holes observed by ALMA and VLA would not be interpreted as a consequence of the presence of massive (proto)planets. Instead, planets may be just starting to form in the bright dense rings of the HL Tau disk.

3.4. Planet Formation in the HL Tau Disk

We propose a scenario in which the HL Tau disk may have not formed planets yet, but rather is in an initial stage of planet formation. Instead of being caused by (proto)planets, the dense rings could have been formed by an alternative mechanism. Our 7.0 mm data suggest that the inner rings are very dense and massive, and then they can be gravitationally unstable and fragment. It is then possible that the formation of these rings result in the formation of dense clumps within them like the one possibly detected in our 7.0 mm image. These clumps are very likely to grow in mass by accreting from their surroundings, and then they possibly represent the earliest stages of protoplanets. In this scenario, the concentric holes observed by ALMA and VLA would not be interpreted as a consequence of the presence of massive (proto)planets. Instead, planets may be just starting to form in the bright dense rings of the HL Tau disk.

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