Gas temperature structure across transition disk cavities

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ABSTRACT

Context. Most disks observed at high angular resolution show signs of substructures, such as rings, gaps, arcs, and cavities, in both the gas and the dust. To understand the physical mechanisms responsible for these structures, knowledge about the gas surface density is essential. This, in turn, requires information on the gas temperature.

Aims. The aim of this work is to constrain the gas temperature as well as the gas surface densities inside and outside the millimeter-dust cavities of two transition disks: LkCa15 and HD 169142, which have dust cavities of 68 AU and 25 AU, respectively.

Methods. We use some of the few existing ALMA observations of the $J = 6\rightarrow5$ transition of $^{13}$CO together with archival $J = 2\rightarrow1$ data of $^{12}$CO, $^{13}$CO, and C$^{18}$O. The ratio of the $^{13}$CO $J = 6\rightarrow5$ to the $J = 2\rightarrow1$ transition is used to constrain the temperature and is compared with that found from peak brightness temperatures of optically thick lines. The spectra are used to resolve the innermost disk regions to a spatial resolution better than that of the beam of the observations. Furthermore, we use the thermochemical code DALI to model the temperature and density structure of a typical transition disk as well as the emitting regions of the CO isotopologs.

Results. The $^{13}$CO $J = 6\rightarrow5$ transition of LkCa15 and HD 169142 disks, respectively. For LkCa15, the steep increase toward the star in the $^{13}$CO $J = 6\rightarrow5$ transition, in contrast to the $J = 2\rightarrow1$ line, shows that the gas is too warm to be traced by the $J = 2\rightarrow1$ line and that molecular excitation is important for analyzing the line emission. Quantitatively, the $6\rightarrow5$/$2\rightarrow1$ line ratio constrains the gas temperature in the emitting layers inside the dust cavity to be up to 65 K, warmer than in the outer disk, which is at 20–30 K. For HD 169142, the lines are optically thick, complicating a line ratio analysis. In this case, the peak brightness temperature constrains the gas in the dust cavity of HD 169142 to be 170 K, whereas that in the outer disk is only 100 K. The data indicate a vertical structure in which the $^{13}$CO $6\rightarrow5$ line emits from a higher layer than the $2\rightarrow1$ line in both disks, consistent with exploratory thermochemical DALI models. Such models also show that a more luminous central star, a lower abundance of polycyclic aromatic hydrocarbons, and the absence of a dusty inner disk increase the temperature of the emitting layers and hence the line ratio in the gas cavity. The gas column density in the LkCa15 dust cavity drops by a factor of $>2$ compared to the outer disk, with an additional drop of an order of magnitude inside the gas cavity at 10 AU. In the case of HD 169142, the gas column density drops by a factor of 200–500 inside the gas cavity.

Conclusions. The gas temperatures inside the dust cavities steeply increase toward the star and reach temperatures of up to 65 K (LkCa15) and 170 K (HD 169142) on scales of $\sim 15$–30 AU, whereas the temperature gradients of the emitting layers in the outer disks are shallow, with typical temperatures of 20–30 and 100 K, respectively. The deep drop in gas column density inside the HD 169142 gas cavity at $<10$ AU could be due to a massive companion of several $M_\odot$, whereas the broad dust-depleted gas region from 10 to 68 AU for LkCa15 may imply several lower mass planets. This work demonstrates that knowledge of the gas temperature is important for determining the gas surface density and thus whether planets, and if so what kinds of planets, are most likely to be carving the dust cavities.

Key words. protoplanetary disks – methods: observational – submillimeter: planetary systems – stars: individual: LkCa15 – stars: individual: HD 169142

1. Introduction

High angular resolution observations of protoplanetary disks show structures in both gas and dust (e.g., Andrews et al. 2010, 2018; van der Marel et al. 2015; Fedele et al. 2017; Huang et al. 2018; Long et al. 2018; Öberg et al. 2021; see Andrews 2020 for review). One favored mechanism that can explain most of these substructures is planet-disk interactions ($>20 M_\text{Earth}$) (e.g., Bryden et al. 1999; Zhu et al. 2014; DiPierro et al. 2015; Rosotti et al. 2016; Dong et al. 2018; Zhang et al. 2018; Szulágyi et al. 2018; Binkert et al. 2021). If these structures are caused by embedded planets, these gaps should be deep in both gas and dust (at least a factor of 10 depletion in the gas). However, the structures could also be caused by a change in the temperature that is unrelated to a potential embedded planet. Therefore, knowledge of the temperature profile across these structures is needed to distinguish truly empty gaps from emission drops related to temperature decreases.
There are only a few cases where young exoplanets have been caught in the act of formation. Two young planets and their disks have recently been directly imaged in the central dust cavity of the PDS 70 disk (Kepler et al. 2018; Haffert et al. 2019; Isella et al. 2019; Benisty et al. 2021), and three more have been located in gaps in the HD 163296 and HD 97048 disks based on localized azimuthal perturbations in the disk velocity structure traced by CO kinematics (Teague et al. 2018, 2019; Pinte et al. 2019; Izquierdo et al. 2022). Two of these disks are typical transition disks with large millimeter-dust cavities, supporting the expectation that planets are present in most (transition) disks. The presence of massive planets (> several $M_{\text{jup}}$) in a number of other disks, including those around HD 100546 and HD 169142, has been suggested, but confirmation by direct imaging is still lacking (e.g., Quanz et al. 2013a,b; Osorio et al. 2014; Reggiani et al. 2014; Walsh et al. 2014; Currie et al. 2017; Follette et al. 2017; Rameau et al. 2017; Casassus & Pérez 2019; Toci et al. 2020). Similarly, planets have been proposed and refuted in the LkCa15 disk (Kraus & Ireland 2012; Sallum et al. 2015; Currie et al. 2019). Other explanations for the structures seen in disks include disk winds, internal photoevaporation, opacity variations, chemical effects, and magnetohydrodynamics (e.g., Clarke et al. 2001; Birnstiel et al. 2015; Zhang et al. 2015; Flock et al. 2015; Simon et al. 2016). Spatially resolved observations of gas in and near a gap or cavity can help us distinguish between these scenarios. In particular, the presence of massive planets should result in deep gas cavities (gas depleted by at least a factor of 10) that are somewhat smaller than the deep dust cavities.

In this work we focus on transition disks with large cavities as they are more easily resolved by current Atacama Large Millimeter/submillimeter Array (ALMA) observations. Fully resolving the cavity with multiple beams is crucial for deriving the properties of the gas and dust in the cavities (Bruderer 2013; Szulágyi et al. 2018). The gas shows a different morphology than the dust, with the gas cavity indeed typically smaller than that in the dust (e.g., Bruderer et al. 2014; Perez et al. 2015; van der Marel et al. 2015, 2016; Wöllfer et al. 2021). However, observations do not trace the column density of the gas and dust directly. A gas cavity seen in molecular line emission can be due to an actual decrease in the surface density, but it can also be caused by a drop in the gas temperature in that region of the disk or a combination of both (Facchini et al. 2017, 2018). Therefore, the temperature needs to be known to accurately derive the surface density in the gas cavity.

The gas temperature inside and outside the cavity is controlled by a number of heating and cooling processes, including the photoelectric effect on polycyclic aromatic hydrocarbons (PAHs) and small grains exposed to UV radiation, gas–grain coupling, and atomic and molecular line emission (e.g., Bakes & Tielens 1994; Kamp & van Zadelhoff 2001; Weingartner & Draine 2001; Gorti & Hollenbach 2004; Woiteke et al. 2009; Bruderer et al. 2012; Bruderer 2013). A crucial ingredient is the local UV field. The radiation field at each point in the disk depends on a number of parameters: the stellar type of the host star, the UV luminosity from accretion of material onto the star, the abundance of dust and PAHs and their properties, and the presence of an inner disk that shields radiation from the host star. Polycyclic aromatic hydrocarbons that heat the gas through the photoelectric effect and dusty inner disks are commonly observed in transition disks (Habart et al. 2006; Brown et al. 2007; Geers et al. 2007a,b; Merin et al. 2010; Isella et al. 2019; Pérez et al. 2019; Facchini et al. 2020; Francis & van der Marel 2020). Detailed modeling by Jonkheid et al. (2006), Woiteke et al. (2009), Bruderer et al. (2012), Bruderer (2013), Facchini et al. (2017, 2018), Alarcón et al. (2020), and Rab et al. (2020) shows that the temperature of the gas changes when a gap or cavity is introduced in the model. Whether the gas becomes warmer or colder than the gas in the full disk model depends on parameters such as the grain sizes and on the gas-to-dust ratio. A planet in the gap can locally increase the temperature by several tens of kelvins (Cleeves et al. 2015; Szulágyi et al. 2018).

Pre-ALMA, the gas temperature in the emitting layers was derived by comparing observations of various CO lines, up to $J_u \geq 14$ lines observed with ground-based telescopes and Herschel (e.g., van Zadelhoff et al. 2001; Sturm et al. 2010; Bruderer et al. 2012; Dent et al. 2013; Fedele et al. 2013; Meeus et al. 2012, 2013; Green et al. 2013). These observations mainly probe the temperature in intermediate disk layers $(z/r \sim 0.5)$ at 10–200 AU from the central star (Fedele et al. 2016).

With the advent of ALMA, spatially resolved observations have been used together with detailed modeling of individual disks with large dust cavities (e.g., Bruderer et al. 2012; van der Marel et al. 2015, 2016; Kama et al. 2016; Schwarz et al. 2021) and without large dust cavities (e.g., Schwarz et al. 2016; Pinte et al. 2018; Calahan et al. 2021). The temperature of the (outer) disk midplane is derived from the location of the snow lines of major species such as H$_2$O and CO (Mathews et al. 2013; Qi et al. 2013, 2019; van ’t Hoff et al. 2017, 2018; Leemker et al. 2021). Additionally, rotational diagrams are used to derive the temperature of intermediate layers in disks (e.g., Schwarz et al. 2016; Loomis et al. 2018; Pegues et al. 2020; Terwisscha van Scheltinga et al. 2021). In this work we study the rarely observed $J = 6$–5 transition of $^{13}$CO ($E_u = 111.1$ K) in two transition disks, LkCa15 and HD 169142, which have spatially resolved ALMA data. The combination of this high transition with the more commonly observed $^{12}$CO $J = 2$–1 ($E_u = 15.9$ K) transition allows us to study the temperature and column density in the cavities of two transition disks and link them to the rest of the disk. The very high resolution of the $^{13}$CO $J = 6$–5 data provides a unique opportunity to study the gas temperature in these disks in detail.

The sources and observations are discussed in Sect. 2. Next, the continuum and molecular line emission across the cavities of LkCa15 and HD 169142 are presented in Sect. 3. The relevant equations for the temperature analysis are summarized and applied to the data in Sect. 4, where we derive the temperature, column density, and optical depth using CO isotopologs. We put the derived temperature structure in context using a representative thermochemical model in Sect. 5. Finally, we discuss and summarize our findings in Sects. 6 and 7, respectively.

2. Observations

In this paper, we analyze ALMA observations of CO isotopologs in the LkCa15 and HD 169142 disks. An overview of the stellar parameters is given in Table 1 and an overview of the observations is presented in Table 2. The sources and data reduction are discussed in this section.

2.1. The sources

LkCa15 is a transition disk with a large dust cavity up to 68 AU radius. The system is located at 157.2 ± 0.7 pc (Gaia Collaboration 2018). The disk surrounding the K3 type T Tauri star LkCa15 is inclined by ∼50–55° (Wolk & Walter 1996; van der Marel et al. 2015; Facchini et al. 2020). High resolution
Table 1. Source properties.

| Disk   | RA J2016 | Dec J2016 | $M_*$ ($M_\odot$) | $M_*$ yr$^{-1}$ | $L_*$ (L$_\odot$) | Spectral type | Age (Myr) | Distance (pc) | $v_{\text{sys}}$ (km s$^{-1}$) | Incl. (°) | PA (°) | Refs. |
|--------|----------|-----------|-------------------|-----------------|------------------|---------------|-----------|--------------|---------------------|----------|--------|-------|
| LkCa15 | 04:39:17.79 | 22:21:03.39 | 1.3 | $10^{-9.2}$ | 1.1 | K3 | ~5 | 157.2 | 6.25 | 50 | 62 | 1–5 |
| HD 169142 | 18:24:29.78 | −29:46:49.33 | 1.7 | $10^{-7.4}$ | 4.0 | F1 | ~6 | 114.9 | 6.9 | 13 | 5 | 1, 6–13 |

References. (1) Gaia Collaboration 2018, (2) Donati et al. 2019, (3) Wolk & Walter 1996, (4) this work, (5) Facchini et al. 2020, (6) Blondel & Dijet 2006, (7) following Fedele et al. 2017, based on the optical and UV extinction (Malfait et al. 1998) and the new Gaia distance, (8) Gray et al. 2017, (9) Grady et al. 2007, (10) Fedele et al. 2017, (11) Raman et al. 2006, (12) Panić et al. 2008, and (13) Guzmán-Díaz et al. 2021.

Table 2. Molecular line and continuum observations used in this work.

| Disk   | Transition | Int. flux$^{(1)}$ (Jy km s$^{-1}$) | Channel width (km s$^{-1}$) | Channel rms (mJy beam$^{-1}$) | Beam | MRS$^{(2)}$ | Robust | Project code | PI |
|--------|------------|---------------------------------|-----------------------------|--------------------------------|------|----------|--------|--------------|----|
| LkCa15 | $^{12}$CO = 2–1 | 16 ± 2 | 0.04 | 8.9 | 0′′34 × 0′′25 (~9.7′′) | 3′′7 | ~2.0 | 2018.1.01255.S | M. Benisty |
|        | $^{13}$CO = 2–1 | 1.4 ± 0.2 | 0.17 | 4.4 | 0′′17 × 0′′13 (~13.7′′) | 0′′5 | nat.$^{(4)}$ | 2018.1.00945.S | C. Qi |
|        | $^{13}$CO = 2–1 | 5.8 ± 0.6 | 0.33 | 3.1 | 0′′35 × 0′′25 (26.6′′) | 4′′0 | ~2.0 | 2018.1.00945.S | C. Qi |
|        | $^{13}$CO = 6–5 | 7.5 ± 0.8 | 0.5 | 2.8 | 0′′08 × 0′′05 (~18.6′′) | 1′′2 | 0.5$^{(5)}$ | 2017.1.00727.S | J. Szulágyi |
|        | $^{13}$CO = 6–5 | 8.2 ± 0.9 | 0.44 | 25 | 0′′32 × 0′′30 (~31.2′′) | 2′′1 | 0.5 | 2017.1.00727.S | J. Szulágyi |
|        | C$^{18}$O = 2–1 | 1.0 ± 0.1 | 0.33 | 3.9 | 0′′36 × 0′′27 (26.6′′) | 4′′0 | ~2.0 | 2018.1.00945.S | C. Qi |
|        | 0.45 mm cont. | 0.16 | 0′′071 × 0′′048 (~23.5′′) | 1′′2 | 0.5 | 2017.1.00727.S | J. Szulágyi |
| HD 169142 | $^{12}$CO = 2–1 | 9.3 ± 0.9 | 0.17 | 1.7 | 0′′05 × 0′′029 (78.8′′) | 0′′6 | 0.5 | 2016.1.00344.S | S. Pérez$^{(3)}$ |
|        | $^{13}$CO = 2–1 | 4.3 ± 0.4 | 0.17 | 2.3 | 0′′054 × 0′′035 (78.4′′) | 0′′6 | 0.5 | 2016.1.00344.S | S. Pérez$^{(3)}$ |
|        | $^{13}$CO = 6–5 | 6.1 ± 0.7 | 0.44 | 12 | 0′′055 × 0′′054 (86.2′′) | 0′′6 | 0.0 | 2017.1.00727.S | J. Szulágyi |
|        | C$^{18}$O = 2–1 | 2.0 ± 0.2 | 0.17 | 1.4 | 0′′052 × 0′′031 (78.6′′) | 0′′6 | 0.5 | 2016.1.00344.S | S. Pérez$^{(3)}$ |
|        | 0.45 mm cont. | 0.52 | 0′′038 × 0′′037 (~72.0′′) | 0′′6 | 0.5$^{(5)}$ | 2017.1.00727.S | J. Szulágyi |
|        | 1.3 mm cont. | 0.022 | 0′′036 × 0′′018 (73.0′′) | 0′′6 | ~0.5 | 2016.1.00344.S | S. Pérez$^{(3)}$ |

Notes. $^{(1)}$ Integrated flux calculated from the region within the Keplerian mask. The error includes the 10% absolute flux calibration error but not any uncertainty due to resolved-out large-scale emission. $^{(2)}$ The maximum recoverable scale (MRS) is estimated as $\sim 0.983 \lambda/L_\odot$, with $\lambda$ the wavelength and $L_\odot$ the fifth percentile baseline of the configuration. $^{(3)}$ Data first presented by Pérez et al. 2019. $^{(4)}$ Natural weighting with a $\lambda/15$ uv taper. $^{(5)}$ ALMA image for which high and intermediate spatial resolution ALMA data are combined. $^{(6)}$ Product data.

ALMA Band 6 observations reveal that, in addition to the cavity, the dust is highly structured with multiple narrow rings observed at high resolution (Facchini et al. 2020). Small grains, traced by scattered light observations, have been seen out to $\sim 30$ AU radius inside the millimeter-dust cavity, suggesting that gas is present in this disk region (Thalmann et al. 2016; Oh et al. 2016). Furthermore, ALMA observations have revealed that the dust cavity is not completely devoid of millimeter grains as the continuum intensity in the dust cavity peaks at $73.7 \pm 6.9$ μJy beam$^{-1}$ (Facchini et al. 2020). Here we present the first ALMA observations of a gas cavity in the LkCa15 disk. Previous observations by van der Marel et al. (2015) do not have the spatial resolution to resolve this gap in the gas. Furthermore, CO ro-vibrational lines at 5 μm also indicate a low CO gas column in the inner 0.3 AU of the LkCa15 disk (Salyk et al. 2009).

The dust in HD 169142 is highly structured, similar to the LkCa15 disk (Fedele et al. 2017; Pérez et al. 2019). Yet, HD 169142 is a Herbig F1 star (Gray et al. 2017) with a mass of 1.7 $M_\odot$ (Blondel & Dijet 2006) at 114.9 ± 0.4 pc (Gaia Collaboration 2018) with its surrounding disc seen almost face-on ($i = 13 \pm 1^\circ$, Raman et al. 2006; Panić et al. 2008). A small ($\sim 0.3$ AU) and variable near-IR inner dust disk has been observed in HD 169142 (Wagner et al. 2015; Chen et al. 2019). This inner dust disk has also been detected in high resolution ALMA observations (Pérez et al. 2019). The HD 169142 disk not only has structures in the dust, but also in the gas with rings and gaps. A gas cavity is seen in CO isotopologs, and DCO$^+$ is found to have an inner component and a ring at $\sim 50$–230 AU (Fedele et al. 2017; Carney et al. 2018).

2.2. Data

In this work, we used new ALMA observations of the $^{13}$CO $J = 6$–$5$ transition in the LkCa15 and HD 169142 disks (2017.1.00727.S; PI: J. Szulágyi) as well as archival ALMA observations of the CO, $^{13}$CO, and C$^{18}$O J = 2–1 lines (see Table 2). The continuum images were used to identify the dust cavity in both disks. All CO transitions for LkCa15 are consistent with a source velocity of 6.3 km s$^{-1}$. For HD 169142, a source velocity of 6.9 km s$^{-1}$ is found. The line ratio of the $^{13}$CO $J = 6$–$5$ to the $J = 2$–$1$ transition was used to constrain the temperature across the cavities of both disks, and the optical depth of the $J = 2$–$1$ transition was determined from the ratio with the C$^{18}$O $J = 2$–$1$ transition. Finally, we also used the brightness temperature of optically thick lines as a temperature probe. Subtracting the continuum may remove line flux from the CO isotopologs as the continuum and the molecular lines may be optically thick in these disks. In this case, the continuum flux at...
the frequencies of the CO isotopolog emission is overestimated as it is absorbed by the CO isotopologs (Isella et al. 2016; Weaver et al. 2018). Hence, we did not subtract the continuum for the calculation of the peak brightness temperatures, but we did subtract it for the ratios of not very optically thick lines.

The spatial resolutions of the data for LkCa15 range from ~0′′.07 to 0′′.36. The ~0′′.07 data resolves the dust cavity with ~12 beams along the major axis of the bright ring in the Band 9 continuum, but 0′′.36 resolution is comparable to the minor axis of the dust cavity, causing the flux of the outer disk to be smoothed into the dust cavity. All data in the HD 169142 disk have a high spatial resolution of ~0′′.05 used in this work, resolving the dust cavity fully with ~9 beams within the first ring in the Band 9 continuum. The Band 9 data for LkCa15 were taken in two different ALMA configurations. The first one had a very high spatial resolution of ~0′′.05 and a small maximum recoverable scale (MRS) of 0.6′′, and the second one had an intermediate spatial resolution of ~0′′.3 and a larger MRS of 2′′.1. The latter data were self-calibrated using two rounds of phase calibration and one round of phase and amplitude calibration. We refer to these data as the intermediate resolution data. These self-calibrated data were also combined with the high resolution data to create a combined high resolution image with a large MRS. We refer to this as the combined high resolution image. Following the works of Czekala et al. (2021) and Öberg et al. (2021), we applied the Jorsater & van Moorsel (1995) (JvM) correction (∅ = 0.20 for the 13CO J = 6–5 transition, and ∅ = 0.23 for the continuum) to the residuals to correct for the difference between the dirty and clean beams. Other data sets where both high and intermediate spatial resolution data are available were not combined, instead they were imaged separately. None of the other images were self-calibrated, but all images were corrected for the primary beam response.

For HD 169142, only the high spatial resolution scheduling block was observed. Similar to the intermediate spatial resolution data for LkCa15, we self-calibrated the data covering the 13CO J = 6–5 transition using two rounds of phase calibration and one round of phase and amplitude calibration. For the continuum, we used the product data from the ALMA archive as these data were taken during excellent weather conditions and the maximum possible bandwidth was used for the product data, leading to a very good signal-to-noise ratio.

To constrain the temperature in the cavities of both disks, we not only need the 13CO J = 6–5 transition, but also a lower J transition, as this provides a good lever arm in upper energy levels. Both disks have suitable archival ALMA observations of the J = 2–1 transition of CO isotopologs. Therefore, we compared the 13CO J = 6–5 transition (E_{min} = 111.1 K) to the J = 2–1 transition (E_{min} = 15.9 K). For HD 169142, we reimaged the data presented in Pérez et al. (2019) and for LkCa15, we use two different data sets. One covers 12CO at a moderate spatial resolution of ~0′′.35, and the other one covers 13CO and C^{18}O at moderate (~0′′.35) and high spatial resolution (~0′′.15). The high spatial resolution of the latter data set lowered the signal-to-noise ratio greatly compared to the intermediate spatial resolution images. Therefore, the high resolution 13CO J = 2–1 transition was imaged using natural weighting and an 0′′.15 uv taper. This enhanced the signal-to-noise ratio while still resolving the gas cavity.

All observations were imaged using multiscale in the tclean function within the Common Astronomy Software Applications package (CASA) version 5.4.0. (combined image of 13CO J = 6–5 for LkCa15), 5.6.0 (self-calibration) or 5.7.0 (all lines except the combined image of 13CO J = 6–5 for LkCa15) (McMullin et al. 2007; Cornwell 2008). For each image, we chose the robust parameter that provides the best balance between the signal-to-noise ratio and the angular resolution. In order to compare the gas cavity with the outer disk, it is crucial to resolve the inner gas cavity. Therefore, we favored high angular resolution over a high signal-to-noise ratio. Each cube is imaged both before and after continuum subtraction, with the former image used to find the brightness temperature and the latter used for the other data products.

A Keplerian mask\(^1\) was used to create a mask for the data while cleaning. The robust parameters, resulting disk integrated fluxes, beam sizes, sensitivities, and MRSs can be found in Table 2 for the observations in the LkCa15 and HD 169142 disks. The integrated flux of the high resolution 13CO J = 2–1 transition in LkCa15 is a factor of 5 smaller than the intermediate resolution counterpart because most of the flux at scales larger than 0′′.5 (79 AU diameter) is resolved out in the high resolution data set. The integrated fluxes of the 13CO, 12CO, and C^{18}O J = 2–1 transitions for HD 169142 are 34–49% lower than those reported in Fedele et al. (2017), due to the smaller MRS of the data used in our work. The shortest baseline of the J = 2–1 data used in this work is 41.1 m, which is identical to the shortest baseline of the data set covering the 13CO J = 6–5 transition in the HD 169142 disk. Furthermore, the MRS of our two data sets are both 0′′.6 (35 AU radius), and therefore the J = 6–5 and J = 2–1 data sets are expected to have a similar sensitivity to larger scales. The MRSs of the data used in this work are typically smaller than the size of the LkCa15 and HD 169142 disks. Therefore, the brightness temperatures may be underestimated at radii similar to the MRSs. The line ratios may also be affected by the MRSs causing small differences, for example, between the 13CO J = 6–5 to J = 2–1 line ratio at (combined) high spatial resolution and that at intermediate spatial resolution in the LkCa15 disk. This is because the MRS of the combined high resolution 13CO J = 6–5 image is larger than that of the high resolution J = 2–1, whereas the opposite is the case for the intermediate resolution data. Therefore, the 13CO J = 6–5 to J = 2–1 line ratio of the (combined) high resolution will be slightly higher than that of the intermediate resolution data.

Finally, the data were imaged to specific beam sizes to compare the 13CO J = 6–5 data to the corresponding 13CO J = 2–1 transition. For LkCa15, a common restoring beam parameter of 0′′.36 × 0′′.30 (26.6″) was used to compare the azimuthally averaged radial profiles of different transitions and isotopologs. This procedure increased the beam size by at most 0′′.05. Similarly, a 0′′.057 × 0′′.054 (88.6″) restoring beam was used for the Band 6 and Band 9 data for HD 169142. As the combined high resolution 13CO J = 6–5 data for LkCa15 is a combined data product, these were not convolved using the restoring beam parameter but a 0.5″ taper was applied. This resulted in a cube with a 0′′.15 × 0′′.13 (12.2″) beam, which was then smoothed using the imsmooth function in CASA to match the 0′′.17 × 0′′.13 (13.7″) beam of the high resolution 13CO J = 2–1 data.

To improve the signal to noise in the moment 0 and peak intensity maps and on the azimuthally averaged radial profiles we used the same Keplerian mask that was also used during the cleaning process to mask any pixels that are not expected to contribute based on the Keplerian rotation of the disk. The noise on the azimuthally averaged radial profile is calculated from the channel rms using error propagation. First, the noise

\(^1\)https://github.com/richteague/keplerian_mask
on the moment 0 map, $\sigma_{\text{mom0}}$ (in mJy km s$^{-1}$ beam$^{-1}$), was calculated using the noise in one channel, $\sigma_{\text{chan}}$ (in mJy beam$^{-1}$), the number of channels included for each pixel in the moment 0 map, $N_{\text{chan}}$, and the velocity resolution $\Delta V$ (in km s$^{-1}$):

$$
\sigma_{\text{mom0}} = \sigma_{\text{chan}} \sqrt{N_{\text{chan}} \Delta V}.
$$

Then we averaged this over an annulus and corrected for the number of independent measurements using the beam size

$$
\sigma_{\text{azimuthal average}} = \sqrt{\frac{1}{N_{\text{beams}}} \sum_{\text{pix}} \sigma_{\text{mom0}}^2},
$$

where $N_{\text{beams}}$ is the number of independent calibration beams per annulus, restricted to be $\geq 1$. The 10% absolute calibration error was not included in these estimates, but it was included in the error on the total flux.

In summary, both the Band 9 and Band 6 LkCa15 data have spatial resolutions of ~0.07–0.36, with the 0.36 beam similar to the size of the dust cavity. The potential effects of this are discussed in Sect. 4.2. The data for HD 169142 have a much higher angular resolution of ~0.05. Therefore, the dust cavity in the HD 169142 disk is fully resolved with ~9 beams inside the first ring in the Band 9 continuum data and 5 beams inside the ring in the $^{12}$CO $J = 6$–5 data.

3. Results
The (combined) high resolution Band 9 continuum and the $^{12}$CO $J = 6$–5 and $J = 2$–1 Keplerian masked integrated intensity maps are presented in Fig. 1. The Band 9 continuum data show a very clear dust cavity in both disks. This is in contrast to the $^{13}$CO $J = 6$–5 and $J = 2$–1 transitions that clearly peak inside the cavity seen in the dust, as shown in Fig. 2. Channel maps of the $^{13}$CO 6–5 data are presented in Figs. A.1 and A.2 and the deprojected azimuthally averaged radial profiles of the $^{12}$CO and C$^{18}$O $J = 2$–1 transitions in Fig. A.3.

3.1. Dust
The Band 9 continuum is compared to the Band 6 continuum in both disks in Fig. 3. The Band 6 continuum in the LkCa15 disk (left-hand panel) is the fit from Facchini et al. (2020) and shows two narrow bright rings at 69 and 100 AU and a weaker
Integrated intensity (mJy beam$^{-1}$)

Fig. 2. Deprojected azimuthally averaged radial profiles of the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ transitions and the scaled 0.45 mm continuum in the LkCa15 (left) and HD 169142 disks (right). We note that, in the left-hand panel, the $^{13}$CO $J = 6 - 5$ line intensity is roughly constant in the inner ~30 AU in the LkCa15 disk, whereas the 0.45 mm continuum shows a dust cavity. The intensity outside the MRS of the observations is shown in a lighter shade of the corresponding colors. The position of the star is indicated by the black star in the bottom-left corner, and the beam sizes are indicated by horizontal bars in corresponding colors. Furthermore, the rings in the dust are indicated with the vertical black lines. We note that the MRS of the $^{13}$CO $J = 2 - 1$ line is small compared to the beam size due to the $uv$ taper applied to this data set.

Fig. 3. Deprojected azimuthally averaged profiles of the (combined) high resolution Band 9 continuum (black) in the LkCa15 (left) and HD 169142 disks (right). The intensity outside the MRS of the observations is shown in a lighter shade of the corresponding colors. For comparison, the fit to the LkCa15 Band 6 continuum by Facchini et al. (2020) (multiplied by 10 for the ease of comparison) and the observed HD 169142 Band 6 continuum (multiplied by 19 to match the Band 9 absolute intensity) are shown in orange. The beams are indicated in corresponding colors in the top-right corner, and the position of the star is marked with the black star in the bottom-left corner. We note that the Band 6 continuum in the LkCa15 disk is highly structured, whereas the Band 9 continuum shows a single ring.

ring at 47 AU. The Band 9 data on the other hand only show a broad single ring at 68 AU, regardless of the similar beam compared to the Band 6 data, suggesting that the Band 9 continuum is highly optically thick, hiding variations in the column density. Alternatively, the larger grains could be trapped in pressure traps whereas the somewhat smaller grains are not (e.g., Pinilla et al. 2016).

In contrast, the morphologies of the very high resolution 0.45 mm and 1.3 mm continuum for HD 169142 are very similar and only differ by a constant factor of 19 in intensity across the disk (right-hand panel Fig. 3). This factor of 19 in intensity is 2.3 times larger than what is expected for optically thick emission. The great similarity in morphology indicates that the trapping mechanism is more efficient in the HD 169142 disk than in the LkCa15 disk. Both the Band 6 and Band 9 continuum observations in the HD 169142 disk peak at very similar radii of 27 AU and 25 AU, respectively. The three rings seen at 57, 64, and 76 AU in the high resolution Band 6 data (Pérez et al. 2019) are observed as two marginally separated rings at 59 AU and 75 AU in the Band 9 data. The fact that we do not see three individual rings is likely due to the slightly larger beam size of our data set. Finally, we note that the high resolution data have some emission with negative intensity between the bright rings. This is likely due to the very high angular resolution, which results in a MRS smaller than the disk. The continuum data will be analyzed in more detail in a future paper.
3.2. Gas

3.2.1. Radial profiles

The $^{13}$CO $J = 6\rightarrow 5$ and $J = 2\rightarrow 1$ transitions in the LkCa15 disk (top row in Fig. 1 and left panel in Fig. 2) show very different morphologies compared to the 0.45 mm continuum and to each other. The $^{13}$CO $J = 6\rightarrow 5$ data have a roughly constant integrated intensity in the inner ~30 AU, whereas the continuum and the $J = 2\rightarrow 1$ data both show a clear cavity. The $^{13}$CO $J = 2\rightarrow 1$ gas cavity is marginally resolved at our spatial resolution. These data suggest that there is still some gas in the dust cavity. Furthermore, they show that the line ratio of the $^{13}$CO $J = 6\rightarrow 5$ to the $J = 2\rightarrow 1$ line increases steeply inside the dust cavity, highlighting that molecular excitation, controlled by the gas temperature, and the gas surface density play a role in the molecular line emission.

The C$^{18}$O emission for LkCa15 decreases with decreases in radius between 50 and 100 AU but there appears to be some emission inward of 50 AU (see Fig. A.3). This is likely due to the low signal-to-noise ratio and due to beam dilution of the gas cavity as the major axis of the C$^{18}$O beam is comparable to the minor axis of the dust cavity. Accordingly, C$^{18}$O emission from the region just outside the dust cavity is smoothed into the cavity, which affects our further analysis in Sect. 4.2. Therefore, we proceed to treat this as a $3\sigma$ upper limit on the C$^{18}$O emission inside the dust cavity.

In the case of the HD 169142 disk, the $^{13}$CO $J = 6\rightarrow 5$ and $J = 2\rightarrow 1$ lines peak ~10 AU inside the dust ring and just inside the ring seen in scattered light (Tschudi & Schmid 2021). Both $^{13}$CO lines show a clear gas cavity inward of 10 AU, similar to the structure seen in other transition disks, such as DoAr44, IRS 48, HD 135344B, HD 142527, and PDS 70 (Bruderer et al. 2014; Perez et al. 2015; van der Marel et al. 2015, 2016, 2018; Facchini et al. 2021). Finally, the $^{13}$CO $J = 2\rightarrow 1$ transition is detected out to much larger radii than the $J = 6\rightarrow 5$ transition and the continuum data in both disks.

3.2.2. Brightness temperatures

The brightness temperatures of the two $^{13}$CO and the $^{12}$CO $J = 2\rightarrow 1$ transition are presented in Fig. 4. First, we highlight the difference between the Rayleigh-Jeans approximation (dotted lines) and the full Planck curve (solid lines). The results are different because the Rayleigh-Jeans approximation is only valid if $\nu < kT$, which results in $T \gg 32$ K for the $^{13}$CO $J = 6\rightarrow 5$ and $T \gg 11$ K for the $^{12}$CO and $^{13}$CO $J = 2\rightarrow 1$ transitions. This criterion is not met for these observations except for the $J = 2\rightarrow 1$ data in the HD 169142 disk. Therefore, care should be taken when using the Rayleigh-Jeans approximation for high frequency observations and observations with low peak intensities.

Comparing their brightness temperatures directly shows that the disk around the Herbig star HD 169142 is warmer than that around the T Tauri star LkCa15. The brightness temperature of $^{13}$CO is highest in both disks as this line becomes optically thick highest up in the disk and hence traces a warmer layer closer to the surface of the disk. The $^{13}$CO $J = 2\rightarrow 1$ transition traces a lower and hence colder layer due to its lower optical depth (see Fig. B.1). The brightness temperature of both $^{13}$CO $J = 6\rightarrow 5$ lines is lower than that of the $^{12}$CO $J = 2\rightarrow 1$ lines. This is due to the lower optical depth of the $J = 6\rightarrow 5$ transition and due to its lower spectral resolution. This lower resolution lowers the peak flux by 6–13 K (40–60%) in LkCa15 and by 10–15 K (10–30%) in HD 169142 (see Appendix A.3). All CO lines may become more optically thin in the outer disk and in the gas cavities, which lowers their brightness temperature. In the case of LkCa15, the gas inside the dust cavity may be similarly warm as in the HD 169142 disk, but this cannot be determined from the brightness temperatures presented here due to beam dilution and, optical depth effects in the inner disk.

For HD 169142, the $^{12}$CO line indicates gas as warm as 170 K. The brightness temperature of the $^{13}$CO $J = 6\rightarrow 5$ transition for HD 169142 is somewhat lower than the corresponding $^{13}$CO $J = 2\rightarrow 1$ transition, which is not what is expected. $J = 2\rightarrow 1$ emission is optically thick (see also Fig. B.1), and hence its brightness temperature traces the kinetic temperature in the disk layer where its optical depth equals 1. For these temperatures, the molecular excitation is such that the optical depth of the $J = 6\rightarrow 5$ line is comparable to or larger than that of the $J = 2\rightarrow 1$ line. Therefore, the $J = 6\rightarrow 5$ transition should trace a higher layer and warmer temperatures. The reason that we do not observe this is likely due to the small MRS of 0′6 (35 AU).
radius) of the high resolution data, which resolves out some of the flux inside this radius. Furthermore, the shortest baseline of the $^{13}$CO $J = 6 - 5$ data is longer than that of the $ = 2 - 1$, causing the $J = 6 - 5$ data to be less sensitive to larger spatial scales. This is not reflected in the MRS of 0.6, because the MRS is calculated using the 5th percentile of the baseline distribution and is calculated assuming that the morphology of the emission resembles a uniform disk. Our observations show that the morphology of the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ lines is different. Therefore, the low $^{13}$CO $J = 6 - 5$ brightness temperature may be partially due to the small MRS. Finally, we note that the $^{13}$CO $J = 6 - 5$ transition is not spectrally resolved for radii larger than ~30 AU, lowering the peak flux and hence the brightness temperature by 10–15 K (~10–30%; see Appendix A.3).

### 3.2.3. Spectra

The azimuthally averaged radial profiles discussed in the previous section show a very clear difference between the morphology of the $^{13}$CO $J = 6 - 5$ transition and the $J = 2 - 1$ transition for LkCa15. The spectra extracted from the Keplerian masked images of these two transitions are presented in Fig. 5.

Both disks clearly show that the $^{13}$CO $J = 6 - 5$ line profile is broader than that of the $J = 2 - 1$ line. This is another indication that the $J = 6 - 5$ transition is brighter than the $J = 2 - 1$ transition in the inner disk, as the innermost regions of the disk are rotating at the highest Keplerian velocity:

$$R = GM_\ast \left( \frac{\sin(i)}{V_{\text{Kepl}}} \right)^2,$$

with $G$ the gravitational constant, $M_\ast$ the mass of the star, $i$ the disk inclination, and $V_{\text{Kepl}}$ the Keplerian velocity of the gas.

Bosman et al. (2021) used this principle to derive the surface brightness of molecular line emission in the innermost disk regions with a spatial resolution smaller than the beam. Using this kinematics fitting program, we are able to reconstruct the surface brightness of the molecular line emission in the innermost regions of the LkCa15 and HD 169142 disks. A 1′′/0 region was used to extract the spectrum for LkCa15 and a 0′/5 region for HD 169142. No Keplerian mask was applied. Furthermore, the spectral resolution of the model was set to the native spectral resolution of the data and the spectra were modeled out to ±60 km s$^{-1}$ from the velocity corresponding to the peak flux density. The surface brightness is fitted up to 80 AU (LkCa15) and 25 AU (HD 169142). Finally, ≥2 (LkCa15) and ≥3 (HD 169142) velocity resolution elements per model fitting point were used for the surface brightness. The model fitting points are separated by ≥6 AU (LkCa15) and ≥2 AU (HD 169142), effectively increasing the signal-to-noise ratio in the LkCa15 disk.

The resulting radial profiles for the $^{12}$CO, $^{13}$CO, and C$^{18}$O $J = 2 - 1$ and the $^{13}$CO $J = 6 - 5$ lines are presented in Fig. 6. The dashed lines indicate the detection limit for each radial profile in corresponding colors. In the LkCa15 disk, all transitions except for $^{12}$CO $J = 2 - 1$ drop below their detection limit around 20 AU. This is consistent with the azimuthal averages presented in Fig. 2 but now resolving the emission to a smaller spatial scale than what is obtained with the traditional azimuthally averaged radial profiles presented in Fig. A.3. The $^{12}$CO $J = 2 - 1$ line is detected down to 12 AU, as $^{12}$CO has the highest column density and hence the highest signal-to-noise ratio in the line wings, making it easier to detect than the less abundant isotopologs. As no steep increase in the surface brightness in the inner disk is detected in any of the lines presented here and the turnover of each line at 10–20 AU is significant compared to the corresponding detection limit, the results from the kinematically derived radial profiles can be interpreted as a ~10 AU cavity in the gas in the LkCa15 disk. Notably, this is significantly smaller than the cavity seen in the dust that peaks at 68 AU.

In the HD 169142 disk, the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ transitions both drop below the detection limit at ~10–12 AU, similar to what is seen in the traditional azimuthally averaged radial profiles. The C$^{18}$O $J = 2 - 1$ emission is only detected from 17 AU outward due to its low signal-to-noise ratio. On the other hand, $^{13}$CO $J = 2 - 1$ is detected down to the smallest radius of 5 AU, similar to LkCa15. This is supported by the signal-to-noise ratio in the line wings (right-hand panel Fig. A.5), where the $^{12}$CO $J = 2 - 1$ transition is detected out to the largest velocities. As all lines quickly drop below their detection limits and
their turn overs are significant, the results from the kinematically derived radial profiles in the HD 169142 disk can be understood as a deep gas cavity at \( \sim 5 \)–10 AU.

In summary, the derived gas cavity radii in the LkCa15 and HD 169142 disks are smaller by \( \sim 15\)–60 AU than their dust cavity radii, consistent with models of planet-disk interaction and formation of dust traps (e.g., Pinilla et al. 2012; de Juan Ovelar et al. 2013). Furthermore, the brightness temperature indicates that the gas in the dust cavity in the HD 169142 disk is warmer than that in the outer disk. This is not seen in the brightness temperature in the LkCa15 disk due to beam dilution that lowers the peak intensity inside the dust cavity. The gas temperature inside these regions will be further constrained in the next section.

4. Analysis

To analyze the data in terms of physical quantities, we first briefly reiterate the relevant equations to derive the temperature, column density, and estimates of the optical depth using CO line ratios and assuming that all levels are characterized by a single excitation temperature, that is, the common assumption that the lines are emitting from the same layer in the disk. Next, we apply this to the observations to investigate the differences between the cavities and the outer disks of LkCa15 and HD 169142.

4.1. Temperature and column density determination

The temperature structure inside and outside the dust cavity can be found by analyzing the \(^{13}\text{CO} \ J = 6 \rightarrow 5\) and \(^{12}\text{CO} \ J = 2 \rightarrow 1\) transitions, as these transitions are far apart in upper energy level \( (E_u = 15.9 \text{ K vs. } E_u = 111.1 \text{ K})\). The column density structure can then be derived using the less optically thick \(^{18}\text{O} \ J = 2 \rightarrow 1\) emission together with the temperature structure from the \(^{13}\text{CO} \) analysis.

If the emission is optically thin, the column density is proportional to the integrated intensity (e.g., Goldsmith & Langer 1999):

\[
N_u^{\text{thin}} = \frac{4\pi F_\nu \Delta V}{A_{\text{tot}} \Omega c},
\]

with \(N_u^{\text{thin}}\) the column density of the upper level \((u)\), \(F_\nu \Delta V\) the integrated intensity, \(A_{\text{tot}}\) the Einstein A coefficient, \(\Omega\) the emitting region, \(h\) the Planck constant, and \(c\) the speed of light. If the emission is optically thick, a correction factor needs to be applied:

\[
N_u = N_u^{\text{thin}} C_T, \quad (5)
\]

where the correction factor is defined as

\[
C_T \equiv \frac{\tau_v}{1 - e^{-\tau_v}}. \quad (6)
\]

We note that this expression approaches 1 for \(\tau \ll 1\), such that \(N_u\) approaches \(N_u^{\text{thin}}\). On the other hand, if the emission becomes optically thick, this correction factor scales with \(\tau\), whose precise value is uncertain in this regime.

The estimate of the column density of the upper state can also be related to the total column density assuming local thermodynamic equilibrium (LTE):

\[
\frac{N_u}{\bar{\rho}_u} = \frac{N_{\text{tot}}}{Q(T_{\text{rot}})} e^{-E_u/kT_{\text{rot}}}, \quad (7)
\]

with \(Q(T_{\text{rot}}) \approx kT_{\text{rot}}/(hB_\nu) + 1/3\) the partition function of CO at a rotational temperature \(T_{\text{rot}}\) with rotational constant \(B_\nu\), and \(k\) is the Boltzmann constant. Local thermodynamic equilibrium excitation is a valid assumption for \(^{13}\text{CO} \ J = 6 \rightarrow 5\) and \(J = 2 \rightarrow 1\) line emission in protoplanetary disks as the critical density is \(\sim 10^6 \text{ cm}^{-3}\) for the two lines, respectively, which is easily reached even in higher layers. This equation can be solved for the temperature (and column density) as we have observations of both \(^{13}\text{CO} \) and \(^{12}\text{CO} \) emission.

The result of this analytical analysis is shown in Fig. 7. If the emission is optically thin, the line ratio is linearly proportional to the rotational temperature for \(T \gtrsim 25\) K. If, on the other hand, the emission is optically thick, the line ratio is only very weakly dependent on the temperature. The predicted line ratio only increases from 8 to 8.5 between temperatures of 90–200 K. For higher temperatures, the line ratio approaches \((v_{\text{LS}}/v_{\text{LS}})^2 = 9\), complicating the determination of the temperature.

The line ratio analysis requires that both \(^{13}\text{CO} \) lines emit from the same disk layer. The emitting surfaces of molecular line emission in inclined protoplanetary disks can actually be inferred directly from the channel maps, as emission from an elevated
layer appears offset compared to the disk center (Pinte et al. 2018; Law et al. 2021; Paneque-Carreño et al. 2021). The upper surface in the disk was traced within hand-drawn masks in each channel containing line emission. For each position along the disk major axis, the locations where the emission peaks in the near and far side of the disk were converted to an emitting height using their offset compared to the disk center, the Keplerian velocity and the parameters listed in Table 1. Subsequently, the resulting emitting surface was binned in radius to increase the signal-to-noise ratio.

4.2. Results for LkCa15

The observed line ratio for LkCa15 is presented in Fig. 8, where the lines used for the ratio were convolved to the same beam of 0\'\'36 × 0\'\'30 (26.6\') or 0\'\'17 × 0\'\'13 (13.7\') in case of the intermediate and (combined) high resolution observations, respectively. The line ratio of the 13CO J = 6−5 to J = 2−1 transition decreases with radius in the outer disk. This is expected as the temperature of the gas decreases with radius. Furthermore, the data show an increase in the slope inside the dust cavity compared to outside the dust cavity, driven by the drop in 13CO J = 2−1 inside 40 AU. Whether this indicates an actual increase in the temperature in the dust cavity or if it is just an optical depth effect is investigated below. The line ratio found from the (combined) high resolution data is consistent with the intermediate resolution data outside 45 AU, within the limitations of the data. The line ratio of the 12CO J = 6−5 transition presented in van der Marel et al. (2015) and the 12CO J = 2−1 transition in a common beam of 0\'\'35 × 0\'\'25 (37.5\') is similar in value and trend with radius to the intermediate resolution line ratio of the 13CO isotopolog.

The optical depths of the 13CO J = 6−5, J = 2−1 and the 18O J = 2−1 transitions at moderate spatial resolution were derived using Eq. (B.5) and using a 3σ upper limit on the integrated C18O intensity inside the dust cavity (≤68 AU; see Fig. B.1) as the radial profile derived from the kinematics clearly suggests a much smaller gas cavity of only ∼10 AU. The optical depth 13CO J = 2−1 and C18O J = 2−1 transition differ by their isotopolog ratio as this is one of the assumptions used to find the optical depth. The C18O J = 2−1 emission is marginally optically thick in the outer disk with an optical depth between ∼0.1 and ∼0.4 between 70 AU and 200 AU. Consequently, the 13CO J = 2−1 emission is optically thick throughout the same disk region. Inside the dust cavity, the optical depths of ≤2 for the 13CO and ≤0.3 for the C18O J = 2−1 are upper limits. The optical depth of the 13CO J ≥ 6−5 transition follows from the line ratio analysis and lies typically between the optical depth from the aforementioned transitions in the outer disk. Inside the dust cavity, an upper limit on the 13CO J = 6−5 optical depth is given. The 13CO and C18O lines could be close to optically thin inside the dust cavity, and thus their brightness temperatures are only lower limits to the kinetic temperature.

The rotational temperature is presented in the left-hand panel of Fig. 9 and increases toward the dust cavity. For comparison, the 13CO J = 2−1 brightness temperature is also shown. This transition is surely optically thick outside the dust cavity so the brightness temperature traces the kinetic temperature in the emitting layer of the outer disk. This brightness temperature is 5–10 K higher than the rotational temperature of 13CO in the outer disk. In the inner disk, the line ratio steeply increases toward the star, indicating a steep increase in the gas temperature.

The (combined) high resolution data for LkCa15 do not have an C18O J = 2−1 counterpart. Therefore, the optical depth cannot be determined following the same method as for the intermediate resolution data. Still, the steep increase in the line ratio in the dust cavity and the upper limit on the 13CO J = 2−1 optical depth of ~2 in the dust cavity at moderate spatial resolution suggest that the gas in the dust cavity is likely optically thin in the two 13CO and the C18O J = 2−1 lines. In this case, the temperature derived from the line ratio (blue dotted line in Fig. 9) is very similar to the rotational diagram analysis on the moderate spatial resolution data.

The hypothesis that the 13CO J = 6−5 and J = 2−1 transitions emit from inside the disk region can be supported by the emitting surfaces presented in Fig. 10. First, we note that the LkCa15 disk is very flat with z/r ~ 0.1 for the 13CO J = 2−1 transition similar to, for example, AS 209, HD 163296, and MWC 480 (Law et al. 2021). At radii smaller than 85 AU, the emitting surfaces of these two transitions measured from the high resolution data are consistent within the error bars. Moreover, their brightness temperatures are very similar (Fig. 4), which is as expected if the same layer is traced. Outside this radius of 85 AU, the 13CO J = 6−5 and 13CO J = 2−1 lines emit from a similar layer at z/r ~ 0.2−0.3, whereas the 13CO J = 2−1 line emits from a lower layer at z/r ~ 0.1. This is the first time that we derive directly from the data that the 13CO J = 6−5 line indeed emits from a higher layer than the 13CO J = 2−1 line.

Finally, the total hydrogen column density in the LkCa15 disk is derived using the rotational temperature and the absolute integrated C18O intensity at intermediate resolution, assuming a CO abundance of 10−4 with respect to the total number of hydrogen atoms. As the C18O emission is marginally optically thick throughout the outer disk, the optical depth of the line is explicitly taken into account. The total column density, presented in

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including optical depth constraints (solid lines), for LkCa15 (left; (combined) high and intermediate resolution data) and HD 169142 disk (right). The rings in the continuum and the radius where the $^{13}$CO $J = 2–1$ transition peaks are indicated with the vertical black lines. The horizontal dotted black line indicates the theoretical maximum line ratio if both lines are optically thick and emit from the same disk region. The beam is indicated with the horizontal bar in the top-right corner. The gray shaded region shows the 10 % absolute calibration error. The line ratio is not shown for radii where the $^{13}$CO $J = 6–5$ or the $J = 2–1$ integrated intensity is below 1.5σ. Furthermore, the intensity outside the MRS of the observations is shown in a lighter shade of the corresponding colors.

Fig. 9. Temperature derived from the line ratio analysis. The rotational temperature (red) is derived from the $^{13}$CO $J = 6–5$ to $J = 2–1$ line ratio, including optical depth constraints (solid lines), for LkCa15 (left) and HD 169142 (right). The dotted lines in corresponding colors indicate the rotational temperature inside the dust cavity if the emission were optically thin. For comparison, the brightness temperature of the optically thick $^{13}$CO $J = 2–1$ transition (green) is shown. We note the difference in the vertical temperature axes. In the case of LkCa15, the dotted blue line shows the rotational temperature assuming optically thin emission for the (combined) high resolution observations. The downward triangles indicate the upper limit on the rotational temperature due to the upper limit on the integrated C$^{18}$O $J = 2–1$ intensity in the dust cavity. The intensity outside the MRS of the observations is shown in a lighter shade of the corresponding colors.

Fig. 11, increases toward the central star up to $\sim 75$ AU. However, the exact radius where the gas column density peaks is smaller as argued in Sect. 3.2.3. Inside the dust cavity, the C$^{18}$O upper limit gives an upper limit of $5 \times 10^{22}$ cm$^{-2}$ at 15 AU, consistent with the value of $1.3 \times 10^{23}$ cm$^{-2}$ in the inner 0.3 AU using the CO column density derived by Salyk et al. (2009), and with the modeling result found by van der Marel et al. (2015). Furthermore, the derived drop in gas column density inside the dust cavity is a factor of $\geq 2$, consistent with the modeling by van der Marel et al. (2015). Finally, we note that the total hydrogen column density in the LkCa15 disk may be higher than the values derived here depending on whether CO is transformed to other species resulting in a CO abundance lower than the assumed value of $10^{-4}$ (Sturm et al., in prep.).

4.3. Results for HD 169142

The fact that $^{13}$CO $J = 6–5$ is detected just inside the dust cavity, but drops steeply inward of $\sim 15$ AU indicates that the gas cavity is likely very depleted in gas (Figs. 2, 6). Therefore, we focus on the region outside $\sim 10$ AU. The line ratio of $^{13}$CO $J = 6–5$ to $^{13}$CO $J = 2–1$ for HD 169142 increases to a value of $\sim 13$ at the inner edge of the gas cavity and rapidly decreases further out in the disk (Fig. 8).

The results of the line ratio analysis are shown in the right-hand panels of Figs. 9 and B.1. The optical depths of the lines are comparable to the values found for LkCa15, that is to say, the $^{13}$CO $J = 2–1$ transition has an optical depth of a few. Furthermore, the temperature in the outer disks of HD 169142 and
LkCa15 are similar at ~30 K as derived from the line ratio. This derived temperature in the outer disk of HD 169142 is likely very low due to the small MRS of the Band 6 and Band 9 data, which lowers the $^{12}$CO $J = 6−5$ and $J = 2−1$ integrated intensities in the outer disk outside ~35 AU. Furthermore, at the location of the bright continuum rings, the temperature from the line ratio may be affected by the continuum subtraction of the $^{13}$CO $J = 6−5$ and $J = 2−1$ lines used for the line ratio. The bright rim just inside the dust cavity of the HD 169142 disk is warm and (marginally) optically thick in $^{13}$CO $J = 6−5$. The line ratio analysis predicts an increase to ~50 K compared to the outer disk, but the uncertainty on the line ratio and optical depth are large. In contrast with the LkCa15 case, the $^{12}$CO $J = 2−1$ brightness temperature suggests that the dust cavity is much warmer, up to 170 K, compared to the outer disk (~100 K).

The total hydrogen column density, derived using the rotational temperature and the integrated C$^{18}$O intensity (purple line in Fig. 11, right panel), shows similar values at the location of the two rings detected in this disk and a few times higher than in the LkCa15 disk. The HD 169142 column density at 23 AU is a factor of 2.5 lower than that modeled by Fedele et al. (2017). This difference is due to the lower spatial resolution and larger MRS of the data used in that work. The drop in the gas column density by a factor of 40 in the gap at 56 AU found by Fedele et al. (2017) is not constrained in our work due to the small MRS. The signal-to-noise ratio and MRS of the data are not high enough to determine the expected steady decrease in gas column density in the outer disk outside of ~35 AU.

5. Thermochemical models

The analysis in Sect. 4 shows that the temperature increases inside the dust cavity compared to outside for both the LkCa15 and HD 169142 disks. Furthermore, it is found that the gas is located at smaller radii, ~10 AU, than the dust cavity and that the gas cavity is very deep (≥100× drop in gas column density) in the HD 169142 disk. The gas in the dust cavity for LkCa15 could be optically thin, but only an upper limit on the column density could be obtained due to the beam size being comparable to the dust cavity and because the line ratio exceeded the maximum possible value of 9 if both lines are optically thick. Finally, a difference between the temperature derived from the line ratio and the brightness temperature was found. Although this could be due to the MRS being smaller than the angular size of the gas and dust disk in the case of HD 169142, another explanation would be a difference in the emitting layers of the $^{13}$CO $J = 6−5$ and $J = 2−1$ transitions. This is in line with the expectation that different lines do not emit from the same disk region due to optical depth and excitation effects (e.g., van Zadelhoff et al. 2001) as also derived directly in the LkCa15 disk (see Fig. 10). In order to investigate this situation, we present some exploratory DALI models following Bruderer (2013). Then we compare our results to other sources and finally discuss the implications.

The thermochemical code DALI was used to model the line ratio of the $^{13}$CO $J = 6−5$ to $J = 2−1$ transition in the cavities of typical transition disks. A detailed description of the DALI modeling setup is given in Appendix C and in Table C.1. We do not attempt to model the individual sources, but look for trends in a set of representative disk models and study the sensitivity to parameters. The fiducial Herbig disk model is a transition disk with a gas cavity with variable gas drop inside 30 AU. The dust cavity extends to 50 AU and a small inner disk of 1 AU is present. The ALMA observations presented in this work mainly probe the region inside the dust cavity but outside the gas cavity corresponding to 30–50 AU in this model. The density and temperature structure of this model are presented in Fig. C.2. The cyan and orange lines show the $τ = 1$ surfaces of the $^{13}$CO $J = 6−5$ and $J = 2−1$ transitions, respectively. For gas density drops by factors of 0.1–0.001, both $^{13}$CO lines are (marginally) optically thin in the gas cavity. Outside the gas cavity and in the model with no gas drop in the dust cavity, both lines are optically thick and trace a slightly different layer in the disk.

The predicted $^{13}$CO $J = 6−5$ to $J = 2−1$ line ratios for this model with four different gas drops inside 30 AU are presented in the top-left panel of Fig. 12. This figure shows that the line ratio can reach up to the maximum possible value of 80 for optically thin gas in the gas cavity, due to the high gas temperatures in the gas cavity midplane and both $^{13}$CO lines being optically thin. The temperature in the gas cavity midplane increases due to the increased UV radiation field if less gas is present. We note that PAHs are present in the gas even if at small amounts and absorb the UV radiation from the star. This increased radiation field for lower gas densities also changes the chemistry in the cavity by photodissociating CO, the major coolant at a height of ~1 AU inside the gas cavity. Therefore, the gas inside 30 AU in the models with a deep gas cavity, cools less efficiently than in the full gas disk model. This results in an increased midplane temperature inside 30 AU with deeper gas cavity depth (compare 0.1–0.001× drops in Fig. 12, right-hand panel). In these models with a gas density drop (≥10×), the line ratio is a direct probe of the temperature.

Outside the gas cavity but inside the dust cavity and in the outer disk ($R > 30$ AU), the line ratio is larger than 9, which is the maximum theoretical value that is expected when the emission is optically thick. This is because the $J = 6−5$ line emits from a layer with a higher temperature than the $J = 2−1$ line (bottom panel, Figs. C.2 and 12, top-right panel), increasing the line ratio with respect to the $J = 2−1$ transition up to 20 in the outer disk. In summary, the line ratio analysis can be used if both lines are emitting from the same disk region. If the lines become optically thick, their emitting regions will deviate, and the brightness temperature becomes a good probe of the temperature of that layer.

The effect of the host star is investigated as LkCa15 is a 1.1 $L_⊙$ T Tauri star and HD 169142 is a 10 $L_⊙$ Herbig star. The higher luminosities of the Herbig star heats the surrounding disk to higher temperatures as shown in the left two panels of Fig. 13. One of the main heating agents in the disk is molecular hydrogen
Fig. 11. Total hydrogen column density (purple) derived from the $^{13}$CO $J = 6−5$ to $J = 2−1$ line ratio, the integrated C$^{18}$O $J = 2−1$ line intensity, and the optical depth for LkCa15 (left) and HD 169142 (right). The dotted line indicates the rotational temperature and column density inside the dust cavity if the emission were optically thin. The purple downward triangles in the left panel indicate the upper limit on column density due to the upper limit on the integrated C$^{18}$O $J = 2−1$ intensity in the dust cavity. The green bars with downward triangles in the right panel indicate the 3σ upper limit on the hydrogen column density derived from the non-detection of $^{12}$CO $J = 2−1$ in this region and assuming a temperature of 100 K and 300 K, respectively.

Fig. 12. Predicted line ratio (left) and gas temperature (right) at the height where the $^{13}$CO $J = 6−5$ (solid) and $J = 2−1$ (dotted) transitions become optically thick for different gas cavity depths (no drop to a factor of 0.001, colors) in the Herbig disk models (top) and T Tauri models (bottom). We note the different temperature scales for the two types of stars. If the transitions are optically thin, the midplane temperature is shown, as that is the region that optically thin CO lines trace in the gas cavity. The dotted horizontal line in the left panels indicates the theoretical maximum value for the line ratio if both $^{13}$CO lines are optically thick and emit from the same disk layer.
that is vibrationally excited by the absorption of a far-UV photon. The collisional de-excitation then releases this energy to the gas causing it to heat up. This process is most effective in the gas cavity midplane, and at $z/r \sim 0.1$ for radii >30 AU. The disk midplane in the T Tauri model is colder than the corresponding region in the Herbig model because the main heating agents, far-UV pumped H$_2$ and the photoelectric effect on small grains and PAH, are less effective due to the weaker far-UV field and lower luminosity in the T Tauri model.

The line ratio and temperature at the $r = 1$ surface for the T Tauri models are presented in the bottom row of Fig. 12. The line ratios in the T Tauri disk models are smaller than the values in the Herbig disk models. This is due to the lower gas temperature in the T Tauri models (Fig. 12, right-hand panel). Another difference between the Herbig and the T Tauri models is the temperature of the emitting layers. In the outer disk of the Herbig models, the temperature of the $^{13}$CO $J = 6-5$ layer is ~1.3–2x higher than in the $J = 2-1$ layer, but in the T Tauri models the layers have nearly the same temperature of 50–100 K. Inside the dust cavity, the temperatures of the $J = 6-5$ and $J = 2-1$ layers differ from each other except within the 30 AU gas cavity for the models with a deep gas cavity (drop >0.01), as the layers become optically thin in this region. The effects of the PAH abundance, the presence of a dusty inner disk, and the effects of grain growth are investigated in Appendix C.2.

The exploratory DALI models show that the UV field and the amount of gas in the gas cavity are important for the temperature of the gas cavity. The disk models by Bruderer et al. (2009, 2012), Bruderer (2013), and Alarcón et al. (2020) do not distinguish between a gas and dust cavity or gap and show that the gas in this region is warmer than the gas outside the cavity or gap. In contrast, the models by Facchini et al. (2017, 2018) show lower temperatures. The main difference between these models are the heating and cooling rates that are taken to be independent of grain sizes and gas-to-dust ratios in the cavities and gaps in the models by Bruderer (2013), whereas they are dependent on grain sizes in the models by Facchini et al. (2017) and in this work. In our models, we show that the gas temperature not only depends on these choices, but also on the stellar luminosity (Fig. 13). In our T Tauri models with a gas cavity the emitting layer of $^{13}$CO $J = 6-5$ and $J = 2-1$ inside the dust cavities (10–50 AU) have a temperature similar to or colder than the outer disk, whereas in the Herbig disk models, we find that the temperature of the emitting layers is generally warmer than the outer disk.

6. Discussion

6.1. Comparing models and observations

The DALI models show that the $^{13}$CO $J = 6-5$ to $J = 2-1$ line ratio is a sensitive tracer of the gas temperature in the gas cavity of transition disks if the emission is optically thin. Outside the gas cavity and in the outer disk regions of the models, the two $^{13}$CO lines are optically thick, complicating the line ratio analysis, but in this case the brightness temperature can be used to constrain the temperature. The line ratio inside the gas cavity is especially sensitive to the amount of gas in the gas cavity, the presence of a dusty inner disk, the abundance of small grains and PAHs in the gas cavity, as these are all important parameters to set the temperature. A higher line ratio points toward a low PAH abundance, no dusty inner disk, and grain growth.

Our ALMA observations in the HD 169142 disk trace the disk region outside the gas cavity but inside the dust cavity (from 30 to 50 AU in the models and from 5–10 to 25 AU in the data). In this region, the line ratio is not very sensitive to the amount of gas in the gas cavity due to optical depth effects and because its temperature structure is not affected much when a gas cavity is introduced. In contrast, the line ratio in this disk region is affected by the presence of a dusty inner disk, the abundance of PAHs and grain growth similar to the disk region inside the gas cavity. Therefore, the ALMA line ratio in the HD 169142 disk mainly traces the effects of these parameters rather than the amount of gas in the gas cavity.

The $^{12}$CO brightness temperature indicates that the gas is 170 K in this region in the HD 169142 disk, which is consistent with the 80–300 K temperature range predicted by the DALI models inside the dust cavity but outside the gas cavity. Similarly, the observed brightness temperature of ~100 K in the outer disk of HD 169142 is consistent with the typical temperature of the $^{13}$CO emitting layers in the fiducial Herbig disk model.

In the case of LkCa15, the gas cavity of ~10 AU is unresolved by ALMA observations. Therefore, the observed line ratio likely traces a combination of all effects (gas cavity depth, abundance of PAHs, presence of a dusty inner disk and grain growth) discussed above, complicating the interpretation of the observations. The T Tauri models have a typical temperature of 50–100 K in the outer disk at their $r = 1$ heights, which is higher than the typical temperature of 20–30 K in the outer disk of LkCa15. Still, the models predict a steep increase in the gas temperature inside the gas cavity. This is likely also traced by our
observations, but the large beam smears this out to larger radii up to the dust cavity radius.

6.2. Comparison to other sources

The temperature structure of few other sources has been studied in detail. Recent work on the temperature structure in the transition disk GM Aur has shown that an additional increase of a factor of up to 10 in the gas temperature in the surface layers in the inner disk, inside its dust cavity at 40 AU, compared to the thermochemical model prediction is needed to fit the observed intensities (Schwarz et al. 2021). In contrast, that same model overpredicts the gas temperature in the outer disk by a factor of 2. The increase in temperature inside the GM Aur dust cavity is similar to the steep increase in gas temperature inside the dust cavity found in the LkCa15 and HD 169142 disks. One of their proposed explanations is that the PAH abundance in the surface layer is too low in the GM Aur models. Our models confirm that the abundance of PAHs is important together with the UV field to effectively heat the gas through the photoelectric effect. On the other hand, a high PAH abundance also shields the gas from stellar UV radiation causing a lower gas temperature in the emitting layer. The disk region inside the inner most beam for LkCa15 may even be warmer than what we derived using the \(^{13}\)CO \(J = 6–5\) to \(J = 2–1\) line ratio, because of beam dilution. This effect is less relevant for HD 169142 as its gas cavity is very depleted in gas.

High resolution \(^{13}\)CO \(J = 6–5\) observations probing the inner few AU in the TW Hya disk are not available. The temperature in the outer disk of TW Hya, derived using a similar method to this work, is also consistent with excitation temperature derived from formaldehyde and methyl cyanide emission (Schwarz et al. 2016; Loomis et al. 2018; Pegues et al. 2020; Terwisscha van Scheltinga et al. 2021). As all of these temperatures are similar to each other, the molecules used likely emit from similar disk regions as the disk is very flat. This situation is similar to our case for LkCa15, which has similar outer disk temperatures as the TW Hya disk and also a shallow vertical temperature gradient.

Modeling by Fedele et al. (2016) shows that the temperature in four Herbig disks depends on their vertical structure (flaring and scale height) as well as the dust distribution (gas-to-dust ratio and dust settling). Comparing the temperature of the HD 169142 disk to the temperatures found in Herbigs using Herschel observations of the CO ladder shows that HD 169142 is \(\sim 50–100\ K\) warmer than the HD 163296 disk at the emitting heights. Furthermore, HD 169142 falls within the range of all four Herbig disks analyzed in Fedele et al. (2016).

6.3. Implications for the cause of the gas cavity

Our results have shown that temperature plays a role in lowering the low-\(J\) lines. One of the most popular alternative explanations for cavities and rings in protoplanetary disks are planets. The deep gas cavity in the HD 169142 disk could be carved by a massive companion. The high signal-to-noise ratio of the \(^{12}\)CO \(J = 2–1\) transition constrains the total hydrogen column density in the inner 10 AU to be \(\lesssim (3–7) \times 10^{20} \text{ cm}^{-2}\) using a 3\(\sigma\) upper limit on the integrated \(^{12}\)CO \(J = 2–1\) intensity and assuming an average gas temperature of 100–300 K, respectively.

This upper limit shows that the deep gas cavity that is depleted by at least a factor of \((2–5) \times 10^{2}\), with respect to the bright ring seen in the gas. If this cavity is carved by a massive companion, its mass can be estimated using the following equation (Zhang et al. 2018):

\[
K = \frac{q}{24} \times 0.001 \left( \frac{h/r}{0.07} \right)^{2.81} \left( \frac{\alpha}{10^{-3}} \right)^{-0.38},
\]

where \(q\) is the mass ratio of the companion to the star, \(\alpha\) the viscosity, and \(h/r\) the scale height of the disk. The \(K\) is a dimensionless parameter that describes the depth of the gas cavity, \(\delta\), as \(\delta = 1 - CK^0\). The values of \(C = 0.002\) and \(D = 2.64\) are the best fitting parameters to the hydro simulations of both the gas and the dust performed by Zhang et al. (2018). Fedele et al. (2017) find from models that the disk scale height \(h/r\) is 0.07, independent of radius. Assuming a typical disk viscosity of \(10^{-3}\) constrains the mass of the potential companion to be \(\gtrsim 8.0\ M_J\) for a gas temperature of 100 K in the gas cavity and \(\gtrsim 5.5\ M_J\) for 300 K. The mass of the potential planet and the disk viscosity are degenerate. Therefore, a lower disk viscosity of \(10^{-4}\), results in the mass of the potential planet to be \(\gtrsim 3.3\ M_J\) (100 K) or \(\gtrsim 2.3\ M_J\) (300 K). A cartoon of the proposed scenario is presented in Fig. 14. It is also possible that multiple smaller planets carve the cavity seen in the gas (Dodson-Robinson & Salyk 2011).

LkCa15 may be hosting multiple low mass planets, as the gas cavity (\(\sim 10\ AU\)) is much smaller than the dust cavity (68 AU). In LkCa15, the gas column density drops by at least a factor of 2 inside the dust cavity, though the exact drop cannot be inferred from the observations due to large beam of the \(^{13}\)CO data. Still, the CO column density inside 0.3 AU derived by Salyk et al. (2009) constrains the total drop in gas column density inside the gas cavity with respect to the outer disk to be a factor of 24. The gas detection up to \(\sim 10\ AU\) points to the presence of multiple low mass planets that are massive enough to carve a cavity in the dust up to 68 AU but not (yet) in the gas (Dong et al. 2015 and see our Fig. 14).

Another possible mechanism to create cavities in transition disks is internal photoevaporation. In this case, low accretion rates of \(\lesssim 10^{-9}\ M_\odot\ yr^{-1}\) are expected since the gas is evaporated from the cavity, preventing it from being accreted onto the central star (Owen et al. 2011; Picogna et al. 2019; Ercolano et al. 2021). The mass-accretion rate of \(10^{-9}\ M_\odot\ yr^{-1}\) for LkCa15 can be consistent with internal photoevaporation, but we find that the gas cavity of \(\sim 10\ AU\) is much smaller than the dust cavity of 68 AU, which is inconsistent with what is expected for a cavity carved by photoevaporation (Donati et al. 2019). These models predict that small grains are removed from the cavity together with the gas, while the larger grains remain present (Franz et al. 2020), such that the cavity seen in gas and small
dust is larger than the cavity seen in large dust grains. This
is the opposite of what is observed in the LkCa15 disk as the
millimeter-sized grains peak at larger radii (68 AU) than the
micron-sized grains (56 AU; Thalmann et al. 2014) and our gas
data (10 AU). In the case of the HD 169142 disk, the mass accre-
tion rate of $10^{-7.4} \ M_\odot \ yr^{-1}$ (Guzmán-Díaz et al. 2021) is at least
one order of magnitude larger than what can be explained by
photoevaporation models.

Dead zones can also cause a drop in the gas column density
in the inner disk, but the drops due to dead zones are expected
to be on the order of a factor of a few (Lyra et al. 2015). The
deep drops in the gas column density inside the dust cavities
of LkCa15 and HD 169142, together with the presence of gas well
inside the dust cavity points to the presence of one or more lower
mass planets that are hard to detect. Moreover, multiple planets
can produce a gap that has a similar width to a gap with a massive
planet, making their detection even more challenging.

7. Conclusions

In this work we have used the observed $^{13}$CO $J = 6−5$ to
$J = 2−1$ line ratio to determine the temperature in the cavities
for LkCa15 and HD 169142 with ALMA. The line ratio in the
LkCa15 and HD 169142 disks steeply increases inside the dust
cavity toward the position of the star in the (combined) high
resolution data. Outside the dust cavity, both disks have a rela-
tively low ratio of $<6$. The temperature is derived from the
line ratio and brightness temperature analysis. Also, DALI mod-
els are used to investigate the effect of a drop in the dust and
gas column density in the dust and gas cavity on the line ratio.
Furthermore, we also investigated the effect of the stellar spec-
trum, PAH abundance, grain growth, and a dusty inner disk on
the line ratio as these parameters affect the local UV field. Our
conclusions are summarized as follows:

1. The gas cavity is smaller than the dust cavity for both disks.
Based on the kinematically derived radial profiles, we find
that the gas in the LkCa15 disk extends down to at least
10 AU, much farther than the dust ring at 68 AU. The results
for HD 169142 are consistent with a $\sim 5−10$ AU gas cavity
and a dust ring at 25 AU;

2. The integrated intensity of the $^{13}$CO $J = 6−5$ transition
is relatively flat in the dust cavity of the LkCa15 disk, whereas
the $J = 2−1$ transition shows a steep decrease. Therefore,
gas is present inside the dust cavity, and the excitation is
important for determining its column density. The molecular
excitation can be constrained directly by the $^{13}$CO $J = 6−5$
to $J = 2−1$ line ratio if both lines are optically thin;

3. The line ratio of $^{13}$CO $J = 6−5$ to $J = 2−1$ reaches a high
value of 13 at the inner rim of the HD 169142 gas (15 AU)
disk, and it steeply increases toward the position of the star
inside the dust cavity of the LkCa15 disk. This indicates that
these disk regions are warm compared to the dusty outer
disk. The dust cavity of the LkCa15 disk (up to 65 K) is
warmer than the outer disk ($\sim 20−30$ K), based on the line
ratio analysis. For HD 169142 this analysis is not possible as
the lines are optically thick;

4. The brightness temperature of optically thick lines is a good
alternative probe of the temperature across the cavity for
HD 169142 and indicates that the gas in the dust cavity is
warmer, up to 170 K, than in the outer disk, up to $\sim 100$ K.
For LkCa15, the brightness temperature is only a good probe
of the temperature in the outer disk due to beam dilution;

5. The factor of $(2−5) \times 10^2$ drop in gas column den-
sity in the HD 169142 cavity indicates that a massive
$(\geq 2.3−8.0 \ M_\odot)$ planet may be present in this region. For
LkCa15, the extended gas-rich region inside the dust cavity
may be indicative of several lower mass planets;

6. The DALI models show that the $^{13}$CO $J = 6−5$ and $J = 2−1$
transitions emit from different layers in the disk if the lines
are optically thick. Their line ratio in the cavities of transition
disks can reach high values, up to the theoretical maximum
value of 80, depending on the model. In general, models
with a high luminosity, a low PAH abundance, no dusty inner
disk, and a large fraction of large grains predict the highest
temperatures and line ratios;

7. The vertical structure inferred from the channel maps in
the LkCa15 disk is very flat, with a typical scale height of
$z/r \sim 0.1$ for the $^{13}$CO $J = 2−1$ transition. Furthermore,
the $^{13}$CO $J = 6−5$ transition emits from a higher disk layer
($z/r \sim 0.2−0.3$) than the $^{13}$CO $J = 2−1$ transition, consistent
with thermochemical models.

In summary, the brightness temperature is a good probe of
the disk temperature if the (low-J) CO lines are optically thick
(e.g., for HD 169142). If the lines are optically thin, the
$^{13}$CO $J = 6−5$ to $J = 2−1$ line ratio is a sensitive probe of the gas
temperature. The intermediate case, where these lines are marginally
optically thin or not very optically thick, the analysis is more
difficult (e.g., for LkCa15). The line ratio analysis in LkCa15
clearly shows that an intensity drop in a low-J CO line does not
necessarily require a drop in the CO column density. This work
also highlights that resolving the cavities with more than one
beam and with good sampling of the relevant scales is crucial
for the analysis. High spatial resolution ALMA observations of
high-J CO isotopologs (both optically thick and thin) of a much
larger sample of transition disks is needed to nail down the com-
bined temperature and column density structure of the gas inside
dust cavities and thus, ultimately, the mechanism responsible
for carving them.

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Appendix A: Observations

Appendix A.1: Channel maps \(^{13}\)CO \(J = 6 - 5\)

The channel maps of the \(^{13}\)CO \(J = 6 - 5\) transition in the LkCa15 and HD 169142 disks are presented in Figs. A.1 and A.2, respectively.

Appendix A.2: Azimuthally averaged radial profiles

The deprojected azimuthal averages of the CO isotopolog emission are presented in Fig. A.3.

Appendix A.3: Brightness temperature

The brightness temperature of an optically thick line was calculated using the peak flux. However, a low spectral resolution can lower this peak flux compared to the true value. In this section we quantify this effect for the \(^{13}\)CO emission. The spectral resolution of the data set covering the \(^{13}\)CO \(J = 2 - 1\) line is 0.17 km s\(^{-1}\), whereas that of the \(J = 6 - 5\) data set is 0.44 km s\(^{-1}\) in HD 169142. Therefore, the former data set better samples the line profile and hence the peak flux of the \(^{13}\)CO emission than the latter. The effect of underestimating the peak flux due to a lower spectral resolution is shown in Fig. A.4, where the brightness temperature of the \(^{13}\)CO \(J = 2 - 1\) transition is shown at two spectral resolutions: 0.17 km s\(^{-1}\) (native resolution solid orange line) and 0.44 km s\(^{-1}\) (binned, dashed orange line). This figure shows that binning lowers the brightness temperature by 10-15 K, corresponding to ~10-30%, compared to the brightness temperature at the native spectral resolution. For comparison the brightness temperature of the \(^{13}\)CO \(J = 6 - 5\), at 0.44 km s\(^{-1}\) is shown as the blue dashed line. This figure shows that the low spectral resolution of the \(^{13}\)CO \(J = 6 - 5\) data is partially responsible for the difference between the \(J = 2 - 1\) and \(J = 6 - 5\) brightness temperatures discussed in Sect. 3.2.2. Similarly, in the LkCa15 disk, the lowering the spectral resolution of the high spatial resolution \(^{13}\)CO \(J = 2 - 1\) line from 0.17 km s\(^{-1}\) to 0.5 km s\(^{-1}\) lowers the peak brightness temperature by 6-13 K or 40-60%. Therefore, the \(^{13}\)CO \(J = 6 - 5\) brightness temperature in LkCa15 is likely underestimated due to the spectral resolution.

Appendix A.4: Spectra

The signal-to-noise ratio of the spectra used for the kinematically derived radial profiles is presented in Fig. 6. The signal-to-noise ratio is the highest for the \(^{12}\)CO \(J = 2 - 1\) and \(^{13}\)CO \(J = 6 - 5\) transitions in the line wings, and therefore these lines are also detected out to the smallest radii.

Appendix B: Line ratio analysis

Appendix B.1: Temperature and column density

Rotational diagrams can be used to derive the temperature and column density of the gas observationally (e.g., Goldsmith & Langer 1999; Schwarz et al. 2016; Loomis et al. 2018; Pegues et al. 2020; Terwisscha van Scheltinga et al. 2021). The relation between the column density and rotational temperature, as discussed in Sect. 4, can best be solved in log-space:

\[
\ln \left( \frac{N_u}{g_u} \right) = \ln N_{\text{rot}} - \ln Q(T_{\text{rot}}) - \frac{E_u}{kT_{\text{rot}}} \quad (B.1)
\]

\[
\ln \left( \frac{N_u}{g_u} \right) + \ln C_T = \ln N_{\text{rot}} - \ln Q(T_{\text{rot}}) - \frac{E_u}{kT_{\text{rot}}} \quad (B.2)
\]

where we used the correction factor for the optical depth in the last line. The optical depth is discussed in the next section.

Appendix B.2: Optical depth

The observations cover both the \(^{13}\)CO \(J = 2 - 1\) and the \(^{18}\)O \(J = 2 - 1\) transitions. Therefore, the ratio of these two lines can be used to derive the optical depth of \(^{13}\)CO \(J = 2 - 1\). The equation of radiative transfer can be written as

\[
T_b = T_{\text{ex}}(1 - e^{-\tau_{\text{opt}}}) \quad (B.3)
\]

with \(T_b\) the brightness temperature obtained from the non-continuum subtracted map and \(T_{\text{ex}}\) the excitation temperature of the line. The excitation temperatures of \(^{13}\)CO \(J = 2 - 1\) and \(^{18}\)O \(J = 2 - 1\) are similar if both emit from the same region of the disk. Therefore, we can write

\[
\frac{T_{b,\text{^{13}CO}}}{T_{b,\text{^{18}O}}} = \frac{1 - e^{-\tau_{\text{opt}}}}{1 - e^{-\tau_{\text{opt}}}} \quad (B.4)
\]

As the line widths of the \(^{13}\)CO and \(^{18}\)O \(J = 2 - 1\) transitions are similar, this line ratio is similar to the ratio of their integrated intensities, \(I_v\Delta\nu\):

\[
\frac{I_{\text{^{13}CO}}}{I_{\text{^{18}O}}} = \frac{1 - e^{-\tau_{\text{opt}}}}{1 - e^{-\tau_{\text{opt}}}} \quad (B.5)
\]

Furthermore, the ratio of the optical depths of \(^{13}\)CO and \(^{18}\)O is identical to the isotopolog ratio, which we assume to be 8 (Wilson 1999). The isotopolog ratio for \(^{12}\)CO to \(^{13}\)CO is assumed to be 70 (Milam et al. 2005). The uncertainty on the optical depths is dominated by the uncertainty on the line ratio of the \(^{13}\)CO to the \(^{18}\)O \(J = 2 - 1\) transition. Assuming a 10% higher \(^{12}\)CO/\(^{13}\)CO ratio of 77, lowers the optical depths of the \(^{13}\)CO and \(^{18}\)O \(J = 2 - 1\) transitions slightly but the values remain consistent within the error bars in the disk region where \(^{18}\)O is detected inside the MRS. Therefore, the uncertainty on the isotopolog ratio is neglected.

The optical depth of the \(^{13}\)CO \(J = 6 - 5\) line cannot be estimated in this way as no \(^{18}\)O \(J = 6 - 5\) observations are available. Therefore, we used an analytical expression for the optical depth (Goldsmith & Langer 1999):

\[
\tau_v = \frac{A_u\nu^3}{8\pi^3\Delta\nu} \left( e^{\nu_0/kT} - 1 \right) N_u. \quad (B.6)
\]

This can be related to the optical depth of \(^{13}\)CO \(J = 2 - 1\), by taking the ratio of the two optical depths:

\[
\frac{\tau_{65}}{\tau_{21}} = \frac{A_{65}\nu_{21}^3\Delta\nu_{21} e^{\nu_{21}/kT_{65}} - 1}{A_{21}\nu_{65}^3\Delta\nu_{65} e^{\nu_{65}/kT_{21}} - 1} N_6 \quad (B.7)
\]

This expression can be simplified by using the Planck function, assuming that the line widths are similar, and using that the ratio of the column densities is determined by a Boltzmann distribution:

\[
\frac{\tau_{65}}{\tau_{21}} = \frac{A_{65} B_{21}(T) g_6 e^{(E_6 - E_3)/kT}}{A_{21} B_{65}(T) g_2}, \quad (B.8)
\]
with $g_J = 2J + 1$ the degeneracy of level $J$ for CO. The derived optical depths are presented in Fig. B.1. The $^{13}$CO $J = 2 \rightarrow 1$ emission outside the dust cavity is optically thick in both disks as expected, the C$^{18}$O $J = 2 \rightarrow 1$ transition is moderately optically thick. The optical depths of all transitions in the dust cavity of LkCa15 are upper limits as an upper limit on the integrated C$^{18}$O $J = 2 \rightarrow 1$ intensity was used. In the case of HD 169142, the optical depth estimates outside 35 AU may be affected by the maximum resolvable scale of these observations.

Appendix C: DALI

Appendix C.1: Model setup

The exploratory models for the $^{13}$CO $J = 6 \rightarrow 5$ to $J = 2 \rightarrow 1$ line ratio discussed in Sect. 5 and Appendix C.2 were computed using the thermochemical code DALI (Bruderer et al. 2009, 2012; Bruderer 2013). The disk gas and dust structure together with the stellar spectrum were used to calculate the thermal and chemical structure across the disk and predict the flux that can be observed by, for example, ALMA.

The radial structure of the gas and dust in DALI is based on the self-similar solution to a viscously evolving disk (Lynden-Bell & Pringle 1974; Hartmann et al. 1998):

$$\Sigma_{\text{gas}}(R) = \Sigma_c \left( \frac{R}{R_c} \right)^{-\gamma} \exp \left[ -\left( \frac{R}{R_c} \right)^{2-\gamma} \right],$$

with $\Sigma_{\text{gas}}(R)$ the gas surface density at radius $R$, $\Sigma_c$, the gas surface density at the characteristic radius $R_c$, and $\gamma$ is the power-law index, similar to the approach of Andrews et al. (2011). An overview of the gas and dust surface density structure is presented in Fig. C.1 and an overview of all model parameters is presented in Table C.1. The inner radius of the protoplanetary disk is set to the sublimation radius that can be approximated as

$$R_{\text{subl}} \approx 0.07 \text{ AU} \sqrt{\frac{L_*}{L_\odot}},$$

with $L_*$ the luminosity of the star (Dullemond et al. 2001).

The vertical structure of the gas in the disk is assumed to follow a Gaussian distribution, where the scale height of the gas at each radius is given determined by the flaring, $\phi$, of the disk:

$$h = h_c \left( \frac{R}{R_c} \right)^{\phi},$$
Fig. A.2: Same as Fig. A.1 but in the HD 169142 disk.

with \( h \) the scale height angle and \( h_c \) the scale height angle at \( R_c \). This scale height angle can be converted to a physical height above the disk midplane, \( H \), by \( H \sim hR \).

The dust is modeled using two populations of dust grains following Andrews et al. (2011): small grains (5 nm–1 \( \mu m \)) and large grains (5 nm–1 mm). Both dust populations follow the Mathis, Rumpl, and Nordseick (MRN) distribution \( (a^{-3.5} \text{ with } a \text{ the grain size}; \text{Mathis et al. 1977}) \) and the mass fraction of large grains is controlled by \( f_{ls} \). The small dust grains are assumed to be well-coupled to the gas and hence follow the same radial and vertical distribution. The larger grains are assumed to be well-coupled to the gas and hence follow the same radial and vertical distribution. The large grains are assumed to be settled to the midplane, as recent observations have shown (e.g., Villenave et al. 2020), and therefore the scale height of the large grains is reduced by a factor of \( \chi < 1 \). Finally, the total dust mass is scaled such that the global gas-to-dust mass ratio in the outer disk, \( \Delta_g/d \), matches the interstellar medium (ISM) value of 100.

The transition disk structure was parametrized as presented in Fig. C.1. The gas cavity was modeled by reducing the gas column density inside \( R_{\text{cav in gas}} \) by a factor of \( \delta_{\text{gas in}} < 1 \). The cavity in the dust was modeled in a similar way by a drop in column density controlled by \( \delta_{\text{dust out}} < 1 \) between \( R_{\text{cav in dust}} \) to \( R_{\text{cav out dust}} \). The dusty inner disk between \( R_{\text{subl}} \) and \( R_{\text{cav in dust}} \) was modeled with a factor of \( \delta_{\text{dust in}} < 1 \) with respect to the outer disk. The gas cavity is typically smaller than the dust cavity (Bruderer et al. 2014; Perez et al. 2015; van der Marel et al. 2015, 2016); therefore, we used \( R_{\text{cav out gas}} \leq R_{\text{cav out dust}} \).

Polycyclic aromatic hydrocarbons are assumed to be well mixed with the gas. The abundance of PAHs was modeled as a step function where PAHs can only exist in the disk regions where the integrated far-UV flux is at most \( 10^6 G_0 \), with \( G_0 \) the interstellar radiation field. In this region where PAHs are abundant, they provide an additional source of opacity. Thus, PAHs act both as a heating agent as well as a source for attenuation of UV radiation. A more detailed discussion on the treatment of PAHs with respect to the gas can be found in Bruderer et al. (2012) and Visser et al. (2007).
The stellar spectrum was modeled as a 4000 K (10000 K) black body for a T Tauri (Herbig) star. In the case of the T Tauri star, the UV-luminosity from accretion onto the star was modeled as an additional 10000 K black body and a mass accretion rate of $10^{-8} M_\odot$ yr$^{-1}$, corresponding to a UV luminosity of 0.15 L$_\odot$. This is a typical mass accretion rate for a T Tauri type star (Francis & van der Marel 2020 and references therein).

The temperature structure in DALI was calculated in an iterative manner, starting with the dust temperature. The dust temperature was calculated using Monte Carlo continuum radiative transfer. Initially, the abundances of the species in the chemical network were calculated assuming that the gas temperature is equal to the dust temperature. The chemical network used to calculate these abundances is based on the UMIST06 network (Woodall et al. 2007) and has previously been presented in Bruderer (2013). No isotope-selective chemistry was included and the network was evaluated assuming steady state. Instead, the isotopolog abundances were scaled to their main isotopolog using their elemental ratios given in Table C.1. Finally, the heating and cooling rates, depending on the grain sizes following Facchini et al. (2017) and Facchini et al. (2018), were used to calculate the gas temperature independent of the dust temperature. The calculations of the abundances and gas temperatures were repeated until they are consistent.

Finally, the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ transitions were ray-traced using non-LTE excitation adopting the collisional rate...
difference in horizontal axes. We note the difference in horizontal axes.

The systematic velocity is indicated with the vertical red line. The vertical black lines indicate the maximal velocities where emission at that radius is expected based on the Keplerian velocity profile. We note the difference in horizontal axes.

Other parameters as listed in Table C.1.

Fig. B.1: Optical depth of the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ transitions and the C$^{18}$O $J = 2 - 1$ transition for LkCa15 (left) and HD 169142 (right). The optical depth of the $J = 2 - 1$ transitions is derived from their respective line ratio, and the optical depth of the $^{13}$CO $J = 6 - 5$ transition is derived using the line ratio analysis (see text for details).

coefficients from the LAMDA database (Botschwina et al. 1993; Flower 1999; Schöier et al. 2005). Our fiducial disk was located at 150 pc and has a face-on orientation.

Appendix C.2: DALI models for other parameters

The effect of the gas cavity depth is discussed in Sect. 5. In this section the effect of other parameters such as the abundance of PAHs, the presence of a dusty inner disk and the mass fraction of large grains is investigated.

The results for the Herbig disk model with a deep (x0.01) gas cavity and a dusty inner disk$^3$ are presented in Fig. C.3. The dusty inner disk shields the cavity from UV-radiation, and therefore the gas between 30 and 50 AU is warmer in the model without a dusty inner disk, which is also reflected in the line ratio. This effect is even more pronounced in the region inside 30 AU, where the gas density is low.

The importance of PAHs is highlighted in the two right-most panels of Fig. 13 and in the middle panel of Fig. C.3. Increasing the PAH abundance increases the gas temperature in a thin layer at $z/r \sim 0.15$, but it decreases the gas temperature in the midplane and in intermediate layers due to attenuation of UV radiation. Furthermore, the two $^{13}$CO transitions emit from higher disk layers due to this temperature change and because CO is abundant to higher disk layers. Together these two effects result in a lower line ratio of $^{13}$CO in the gas cavity, whereas the model with a lower PAH abundance of $10^{-3}$ with respect to the ISM predicts a high line ratio inside 30 AU. This is again due to the underlying temperature structure. The high abundance of PAHs in the former model effectively shields the midplane where the optically thin $^{13}$CO lines are emitting from. The lack of UV radiation is responsible for the low temperatures.

$^3$ Other parameters as listed in Table C.1.
Finally, the effect of grain growth is investigated by varying the fraction of large grains, $f_{\text{ls}}$, from 98% in the fiducial model to 85% and 0% in the models mimicking disks with smaller grains. The disk models with many small grains are colder because of the efficient shielding of UV radiation by these grains and PAHs that are abundant to larger scale heights. Therefore, heating through the photoelectric effect on PAH and far-UV pumped H$_2$ is less efficient in these regions, causing the line ratio to decrease when more grains are small.

Fig. C.1: Generic structure of the DALI models. The gas surface density is indicated in red, and the dust surface density is indicated in blue.

Fig. C.2: Gas number density (top), dust density (middle), and gas temperature (bottom) of our fiducial model for a Herbig star with a factor of 100 drop in gas density inside 30 AU. The cyan and orange contours indicate the $\tau = 1$ surface of the $^{13}$CO $J = 6 - 5$ and $J = 2 - 1$ lines, respectively. The $^{13}$CO $J = 2 - 1$ transition is optically thin inside the dust cavity, and the $J = 6 - 5$ is optically thin inside the gas cavity; hence, these lines trace the midplane at these radii. We note that the dust cavity starts from 50 AU inward and the gas cavity from 30 AU. Only the regions with a gas density above $10^7$ cm$^{-3}$ are shown. We note that the bottom panel is identical to the middle panel in Fig. 13.
Fig. C.3: Modeled line ratio for the Herbig disk model (top), where the absence of a dusty inner disk (left), the PAH abundance with respect to the ISM (middle), and the fraction of large grains (right) are compared to the fiducial Herbig disk model with a 0.01 times drop in gas density inside 30 AU (blue). The bottom row shows the temperature at the $r = 1$ surface for the $^{13}$CO $J = 6 - 5$ (solid) and $J = 2 - 1$ (dotted) transitions. Both $^{13}$CO lines are (moderately) optically thin inside the gas cavities of these models. Therefore, the midplane temperature is shown in this region. We note the difference in the temperature axes.
### Table C.1: Other DALI model parameters.

| Model parameter             | T Tauri | Herbig | Description                                                                                                                                 |
|-----------------------------|---------|--------|-------------------------------------------------------------------------------------------------------------------------------------------|
| **Physical structure**      |         |        |                                                                                                                                           |
| $R_{\text{subl}}$           | 0.07 AU | 0.2 AU | Sublimation radius, calculated as $0.07 \cdot \sqrt{\frac{L_\star}{L_\odot}}$. following Dullemond et al. (2001).                            |
| $R_{\text{cav in, dust}}$   | 1 AU    |        | Inner radius of the dust cavity.                                                                                                           |
| $R_{\text{cav out, gas}}$   | 30 AU   |        | Outer radius of the gas cavity.                                                                                                           |
| $R_{\text{cav out, dust}}$  | 50 AU   |        | Outer radius of the dust cavity.                                                                                                          |
| $R_c$                       | 100 AU  |        | Characteristic radius of the surface density profile.                                                                                     |
| $R_{\text{out}}$            | 600 AU  |        | Outer radius of the disk.                                                                                                                 |
| $\Sigma_c$                  | 0.28 g cm$^{-2}$ |        | Sets the gas surface density at the characteristic radius $R_c$.                                                                        |
| $M_{\text{disk}}$           | $1.5(-3) M_\odot$ |        | Mass of the disk.                                                                                                                         |
| $\gamma$                    | 1       |        | Power law index of the surface density profile.                                                                                           |
| $h_c$                       | 0.05    |        | Scale height angle at the characteristic radius $R_c$.                                                                                     |
| $\psi$                      | 0.05    |        | Flaring index of the disk surface density.                                                                                                 |
| PAH abundance               | $1(-3)$, $1(-1)$ |        | Abundance of PAHs w.r.t. to ISM value, in gas.                                                                                             |
| $\delta_{\text{gas, in}}$   | $1(-3)$, $1(-2)$, $1(-1)$, 1 |        | Relative drop in gas density inside the gas cavity ($R_{\text{subl}} < R < R_{\text{cav out, gas}}$).                                |
| $\delta_{\text{gas, out}}$  | 1       |        | Relative drop in gas density inside the dust cavity, but outside the gas cavity ($R_{\text{cav out, gas}} < R < R_{\text{cav out, dust}}$). |
| $\delta_{\text{dust, in}}$  | $1(-10)$, $1(-4)$ |        | Relative drop in dust density in the dusty inner disk w.r.t. the outer disk ($R_{\text{subl}} < R < R_{\text{cav in, dust}}$).           |
| $\delta_{\text{dust, out}}$ | $1(-10)$ |        | Relative drop in dust density inside the dust cavity ($R_{\text{cav in, dust}} < R < R_{\text{cav out, dust}}$).                   |
| **Dust properties**         |         |        |                                                                                                                                           |
| $\chi$                      | 0.2     |        | Settling of large grains.                                                                                                                 |
| $f_{\text{ls}}$             | $1(-10)$, 0.85, 0.98 |        | Mass-fraction of grains that is large.                                                                                                    |
| $\Delta_{\text{gas/dust}}$  | 100     |        | Global gas-to-dust mass ratio.                                                                                                             |
| **Stellar properties**      |         |        |                                                                                                                                           |
| $M_*$                       | 0.9 $M_\odot$ | 2.5 $M_\odot$ | Mass of the central star.                                                                                                                  |
| $M_*^{(2)}$                  | $1(-8)$ $M_\odot$ yr$^{-1}$ | 0 $M_\odot$ yr$^{-1}$ | Mass accretion rate of the central star.                                                                                                   |
| **Stellar spectrum**        |         |        |                                                                                                                                           |
| $L_*$                       | 1 $L_\odot$ | 10 $L_\odot$ | Luminosity of the central star.                                                                                                           |
| $L_X$                       | $1(30)$ erg s$^{-1}$ | 10000 K | X-ray luminosity of the central star.                                                                                                      |
| $T_{\text{eff}}$            | 4000 K  |        | Effective temperature of the central star.                                                                                                |
| $T_X$                       | 7(7) K  |        | Effective temperature of the X-ray radiation.                                                                                              |
| $\zeta_{\text{c.r.}}$       | 5(-17) s$^{-1}$ |        | Cosmic ray ionization rate.                                                                                                               |
| **Observational geometry**  |         |        |                                                                                                                                           |
| $i$                         | 0$^\circ$ |        | Disk inclination (0$^\circ$ is face-on).                                                                                                  |
| $d$                         | 150 pc  |        | Distance to the star.                                                                                                                     |
| **Chemistry**               |         |        |                                                                                                                                           |
| H                           | 1       |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                       |
| He                          | $7.6(-2)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| C                           | $1.4(-4)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| N                           | $2.1(-5)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| O                           | $2.9(-4)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| Mg                          | $4.2(-7)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| Si                          | $7.9(-6)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| S                           | $1.9(-6)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| Fe                          | $4.3(-7)$ |        | Abundance w.r.t. the total number of hydrogen atoms.                                                                                      |
| $^{12}\text{C}/^{13}\text{C}$ | 70     |        | Carbon isotope ratio.                                                                                                                     |
| $^{16}\text{O}/^{18}\text{O}$ | 560   |        | Oxygen isotope ratio.                                                                                                                     |

**Notes.** $a(b)$ represents $a \times 10^b$. Boldface indicates the fiducial value. Following Dullemond et al. (2001). The stellar accretion rate is converted to a $10^3$ K black body and then added to the stellar spectrum. An accretion rate of $10^{-8} M_\odot$ yr$^{-1}$ corresponds to a UV luminosity of $0.15 L_\odot$. 