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## High angular resolution studies of protoplanetary discs

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## CHAPTER 6

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# Comparing molecular gas and dust in discs around T Tauri stars

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As protoplanetary discs evolve, their gas content is expected to decrease and the dust particles settle to the midplane. Observational constraints on the gas-to-dust mass ratio ( $g/d$ ) in discs around T Tauri stars are essential to follow this process. We investigate the relative amounts of gas and dust in the discs around a sample of six T Tauri stars. Using the Combined Array for Research in Millimeter Astronomy and archival data from the Owens Valley Radio Observatory, we study the  $J=1-0$  line of  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{HCO}^+$ , as well as the dust continuum at 2.7 mm towards a sample of six discs around T Tauri stars at a spatial resolution of  $5''$ - $10''$ . We use simple disc models and a molecular excitation and radiative transfer code to model the line and continuum emission. We test our best-fit dust continuum models against the observed line emission. Our 2.7 mm data combined with 1.3 mm data from the literature indicate dust emissivity spectral slopes of  $\beta=0.7-1.8$  in our sources. Using a maximum dust emissivity we derive lower limits on the disc dust masses of  $0.7-4.5 \times 10^{-4} M_{\odot}$  or total masses of  $0.7-4.5 \times 10^{-2} M_{\odot}$  assuming a standard value  $g/d = 100$ . With prior knowledge of the disc radius and inclination, the models that fit the dust continuum also reproduce the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra within a factor two in intensity. To obtain exact fits to the line data,  $^{12}\text{CO}$  depletion factors 10–100 are required in DM Tau and CQ Tau, likely due to efficient freeze-out and/or photodissociation. Sources AA Tau and Haro 6-5 B have optically thick lines, and require the emission to originate from layers warmer by factors close to two compared to the disc midplane. The spectral profiles towards DL Tau and RY Tau are not well defined, but the line intensity is consistent with  $g/d = 100$  and no  $^{12}\text{CO}$  depletion.

## 6.1 INTRODUCTION

The gas and dust content of discs around young stars has been studied in great detail over the last decade, in particular using submillimetre interferometers that enable us to disentangle the emission of the disc from that of the surrounding cloud material. The Taurus-Auriga cloud complex is our closest test-ground for star formation and the brightest discs around young low-mass stars (T Tauri stars) like DM Tau, LkCa 15 and GM Aur have been spatially resolved in both gas and dust millimetre emission (Piétu et al. 2007; Qi et al. 2003; Dutrey et al. 2008; Hughes et al. 2009). These studies have allowed to understand the radial and vertical structure of these discs better. The most commonly used gas tracer in submillimetre regime is  $^{12}\text{CO}$ , with the strongest line emission, followed by the gas tracers  $\text{HCO}^+$ , CN and HCN (Dutrey et al. 1997; van Zadelhoff et al. 2001; van Dishoeck et al. 2003; Thi et al. 2001; Greaves 2004; Chapillon et al. 2008). The estimates of the main disc property - its mass - have relied almost exclusively on the dust thermal continuum emission yielding disc masses in the range from 0.001 to 0.1  $M_{\odot}$  (e.g., Beckwith et al. 1990; Osterloh & Beckwith 1995; Mannings & Sargent 1997; Andrews & Williams 2005, 2007). The conversion from the estimated dust mass to the total (gas and dust) disc mass is done assuming the gas-to-dust mass ratio  $g/d=100$ , poorly constrained in discs. Most observations done so far have been biased towards the brightest sources, which are often those with the largest discs.

We study six T Tauri stars located in Taurus star-forming region and known to possess discs. Our source sample and some of the basic stellar properties are listed in Table 6.1. Besides including some of the well-known bright sources like DM Tau and CQ Tau, we include less well studied sources DL Tau, RY Tau, AA Tau and Haro 6-5 B. The presence of the circumstellar material around these sources is seen in Hubble Space Telescope images (Padgett et al. 1999; Grady 2004) and molecular gas observations at millimetre wavelengths (DM Tau: Guilloteau & Dutrey (1994); Handa et al. (1995); Saito et al. (1995); Guilloteau & Dutrey (1998); Thi et al. (2001); Dartois et al. (2003); Piétu et al. (2007), DL Tau: Koerner & Sargent (1995); Simon et al. (2000), RY Tau: Thi et al. (2001); Koerner & Sargent (1995), CQ Tau: Thi et al. (2001); Mannings & Sargent (1997); Chapillon et al. (2008), Haro 6-5 B: Dutrey et al. (1996); Yokogawa et al. (2002)). The masses of our stars range from 0.25 to 1.8  $M_{\odot}$  and their spectral types range from late A to early M. All sources have the class II spectral energy distribution (SED) characteristic of a circumstellar disc (Kenyon & Hartmann 1995; Chiang et al. 2001; Doucet et al. 2006), but Haro 6-5 B lacks the near- and mid-infrared SED information for proper classification (Kenyon & Hartmann 1995). Evidence of grain growth is found in discs around RY Tau and CQ Tau (Isella et al. 2009; Testi et al. 2003). The most massive star in our sample, CQ Tau, has properties at the border between T Tauri and Herbig Ae stars and is sometimes referred to as an Herbig Ae star. This is also the oldest star in our sample, with estimated age close to 10 Myr (see Chiang et al. 2001; Testi et al. 2003, and references therein) and low far-infrared excess indicative of a relatively flat disc structure (Doucet et al. 2006, and references therein). We investigate to what extent the molecular line emission differs from one source to another, considering that all our sources appear similar in their thermal dust emission (i.e., dust mass). Both low- $J$  molecular line emission and the thermal dust emission at the millimetre wavelengths

probe the bulk of the disc material, located up to several hundreds of AU from the central star, and are particularly well suited to address the global differences between the gas and dust contents of the discs.

To investigate the discs around our young T Tauri stars we use interferometric observations of  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{HCO}^+$  line emission, and dust continuum observations, and draw a comparison between the disc gas and dust content. In Sect. 2 we describe our observations of the molecular lines and dust continuum, while the results are shown in Sect. 3. In Sect. 4 we analyse the observed continuum and line emission using simple parametric models. Section 5 gives a brief summary of our conclusions regarding the maximum amount of  $^{12}\text{CO}$  gas and minimum dust mass, as well as the minimum temperature at which the observed line emission arises.

## 6.2 OBSERVATIONS

$^{12}\text{CO}$  and  $\text{HCO}^+$   $J=1-0$  line emission, at 115.271204 GHz and 89.188518 GHz respectively, was observed using the Owens Valley Radio Observatory (OVRO) <sup>1</sup> between September 2002 and January 2003. The spectral resolution of the observations is 127 kHz ( $0.33 \text{ km s}^{-1}$ ) for  $^{12}\text{CO}$  and 125 kHz ( $0.42 \text{ km s}^{-1}$ ) for  $\text{HCO}^+$  and the spatial resolution of  $5''$ - $10''$  (Table 6.1). The sources were observed in pairs, sharing 8-hour tracks, with approximately three hours on-source time for each individual source. The bandpass was calibrated using a boxcar fit to an internal noise source modified by a second order polynomial fit to the observations of the quasars 3C84, 3C454.3, 3C345, 3C279 and 3C273. The flux density scale was established with observations of the same quasars using fluxes bootstrapped with measurements of Neptune and Uranus. Bandpass, phase, and flux calibration were applied to the data with the MMA software package (Scoville et al. 1993). Further data reduction and image analysis was done using the MIRIAD data reduction software (Sault et al. 1995). We re-reduce and analyse the OVRO data, previously presented in Kessler-Silacci (2004). Kessler-Silacci (2004) also presents the observations of  $^{12}\text{CO}$  and  $\text{HCO}^+$   $J=1-0$  towards Haro 6-5 B, and  $\text{HCO}^+$   $J=1-0$  from CQ Tau. However, calibrated data for these observations are no longer available and are omitted from our analysis.

The dust continuum at 2.7 mm was observed in May 2007 using Combined Array for Millimetre Astronomy (CARMA) <sup>2</sup>. The interferometer was in compact configuration providing spatial resolutions  $4''$ - $6''$ . The shared track duration was 7 hours for DM Tau and DL Tau with on-source integration times of 2.2 and 2.4 hours, respectively. RY Tau and CQ Tau shared a 5.6-hour track, with on-source integration times of 2.2 hours per source. AA Tau and Haro 6-5 B were observed in a 4-hour track, and

<sup>1</sup>OVRO was operated by the California Institute of Technology with support from the National Science Foundation.

<sup>2</sup>Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

their on-source integration times are 1.6 and 1.4 hours, respectively. Flux and band-pass calibration were done using the 0530+135 calibrator, adopting a flux of 4.6 Jy for this source, and the MIRIAD software was used for all data processing. Simultaneous to the dust continuum at 2.7 mm, the  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$   $J=1-0$  lines were observed, at 110.201354 GHz and 109.782173 GHz respectively, with a spectral resolution of 122 kHz ( $0.33 \text{ km s}^{-1}$ ). Tables 6.1 and 6.2 list the synthesized beam sizes, noise levels and results of the observations.

### 6.3 RESULTS

We detect 2.7 mm continuum emission towards all our sources (Table 6.1). Only the dust emission from the disc around DL Tau is spatially resolved with the synthesized beam size of  $4''.68 \times 3''.79$  (corresponding to approximately 600 AU resolution at 140 pc distance). Figure 6.1 shows the correlated flux as a function of the  $uv$ -distance for each source, averaged in concentric annuli in the  $uv$ -plane. The maps of the continuum emission are shown in Fig. 6.2. The sensitivity of the continuum images is  $1 \text{ mJy beam}^{-1}$ , with detections exceeding  $6\sigma$  level and centered on the the locations of our sources. The total integrated flux at 2.7 mm, listed in Table 6.1, is measured by fitting the clean map of the emission with a point source, except in case of DL Tau where a gaussian distribution provides a better fit. The deconvolved aspect ratio of the gaussian of  $2''.4/2''.7$  is consistent with the inclination the  $35^\circ$  inclination inferred for the DL Tau disc (Simon et al. 2000). Table 6.1 lists the pointing coordinates of our observations.

Based on the 2.7 mm continuum fluxes and the 1.3 mm fluxes from the literature (also listed in Table 6.1) we calculate the wavelength dependence of the millimetre flux,  $\alpha = \log[(2.7 F_{1.3}) / (1.3 F_{2.7})] / \log(2.7/1.3)$ . Values range from 3.7 to 4.8 (Table 6.1). The slope of the millimetre dust emissivity  $\beta$  is obtained assuming optically thin emission. Following (Beckwith et al. 1990) we adopt  $\beta = \alpha - 3$ , yielding values that range from  $1.8 \pm 0.9$  to  $0.7 \pm 0.9$ . While the former value suggests very small, ISM-type dust (AA Tau and Haro 6-5 B) the latter corresponds to dust that has undergone grain growth (see Draine 2006, their Fig. 3). However, due to the large errors in our estimates of  $\beta$ , we can not constrain the type of dust nor the emissivity in our sample. Our derived  $\beta$  slopes are consistent with more precise estimates of Rodmann et al. (2006), within the errors. In the Section 6.4.1 we use the millimetre continuum fluxes to estimate the minimum mass of the dust in the discs.

The  $^{12}\text{CO}$   $J=1-0$  line emission is firmly detected in DM Tau and AA Tau (corresponding to  $12\sigma$  and  $4\sigma$  respectively in the maps of the velocity integrated emission), and marginally towards RY Tau and CQ Tau ( $3\sigma$ ). Table 6.2 summarises the observed line intensities and upper limits. The spectra of the observed  $^{12}\text{CO}$  lines are shown in Figure 6.5 (black line) integrated over a region centered on the source position. The  $^{12}\text{CO}$  emission is observed at the  $V_{\text{LSR}} = 4-8 \text{ km s}^{-1}$  typical of the sources in the Taurus star-forming region, and is spatially coincident with the continuum detection. Figure 6.3 shows the integrated intensity images of the molecular line emission for our unresolved sources. Only the  $^{12}\text{CO}$   $J=1-0$  line emission from DM Tau is resolved spa-

Table 6.1: Source sample and dust continuum observations.

| Source                  | RA<br>(J2000) | Dec<br>(J2000) | Sp. type <sup>a</sup> | $M_{\star}^b$<br>( $M_{\odot}$ ) | Synthesized beam<br>(" $\times$ ") | $F_{2.7}^c$<br>(mJy) | $F_{1.3}^d$<br>(mJy) | $\alpha$      |
|-------------------------|---------------|----------------|-----------------------|----------------------------------|------------------------------------|----------------------|----------------------|---------------|
| DM Tau                  | 4:33:48.77    | 18:10:09.78    | M1                    | 0.6                              | 4.70 $\times$ 3.86                 | 13.6 $\pm$ 1.4       | 109 $\pm$ 13         | 3.8 $\pm$ 0.8 |
| DL Tau                  | 4:33:39.07    | 25:20:38.14    | K7                    | 0.6                              | 4.68 $\times$ 3.79                 | 29.7 $\pm$ 2.8       | 230 $\pm$ 14         | 3.8 $\pm$ 0.6 |
| RY Tau                  | 4:21:57.42    | 28:26:35.66    | F8-K1                 | 1.7                              | 5.67 $\times$ 4.13                 | 33.1 $\pm$ 3.8       | 229 $\pm$ 17         | 3.7 $\pm$ 0.9 |
| CQ Tau                  | 5:35:58.50    | 24:44:54.32    | A8-F2                 | 1.8                              | 5.35 $\times$ 4.08                 | 23.5 $\pm$ 2.5       | 162 $\pm$ 2          | 3.7 $\pm$ 1.0 |
| AA Tau                  | 4:34:55.43    | 24:28:53.11    | K7-M0                 | 0.7                              | 5.86 $\times$ 4.33                 | 6 $\pm$ 1            | 88 $\pm$ 9           | 4.7 $\pm$ 0.7 |
| Haro 6–5 B <sup>e</sup> | 4:22:00.70    | 26:57:32.67    | –                     | 0.25                             | 5.85 $\times$ 4.37                 | 8.5 $\pm$ 1.0        | 134 $\pm$ 6          | 4.8 $\pm$ 0.9 |

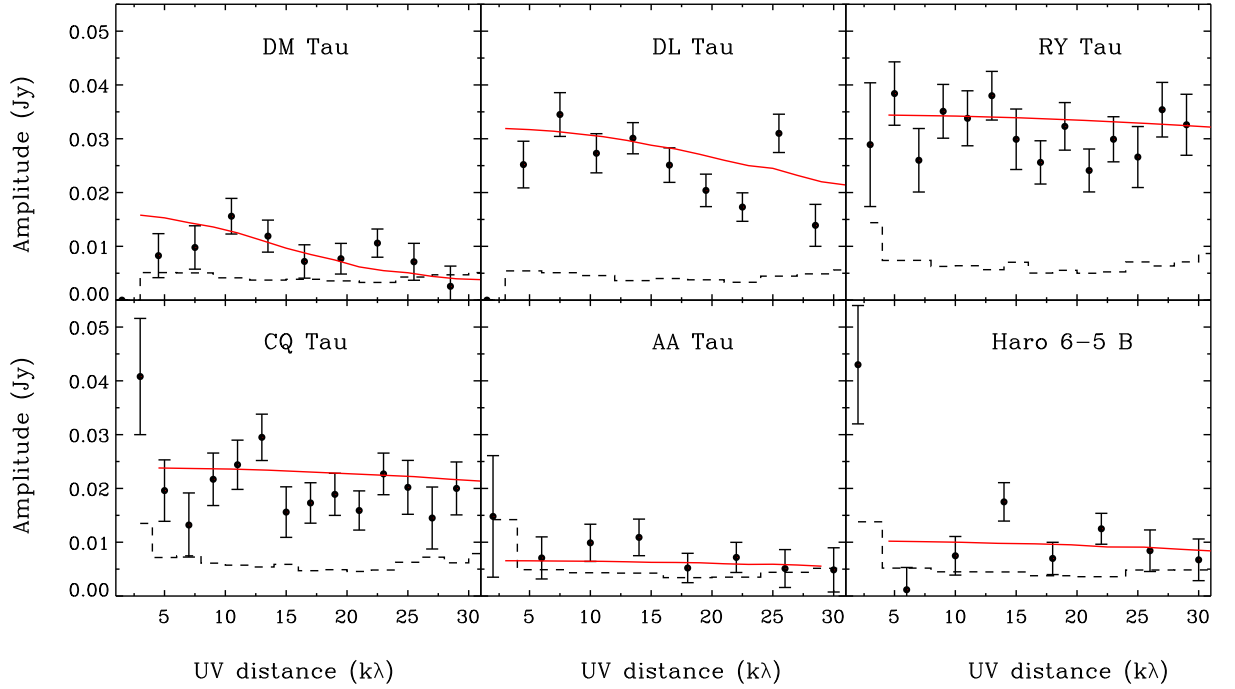
<sup>a</sup> Simon et al. (2000), Mora et al. (2001), Akeson et al. (2005), Beckwith et al. (1990) and references therein.

<sup>b</sup> Beckwith et al. (1990), Chapillon et al. (2008), Yokogawa et al. (2002)

<sup>c</sup> Point source fit results, except for DL Tau where the resolved flux was fit with a Gaussian of  $2''.7 \times 2''.4$  and peak intensity of  $21.6 \pm 1.6$  mJy beam<sup>-1</sup>, offset by  $\delta\text{RA}=0.5$  and  $\delta\text{Dec}=-0.2$  from the pointing position.

<sup>d</sup> Beckwith et al. (1990), Koerner & Sargent (1995), Chapillon et al. (2008), Osterloh & Beckwith (1995).

<sup>e</sup> Also known as FS Tau B.



**Figure 6.1:** Correlated 2.7 mm continuum flux as a function of  $uv$ -distance (black dots with the error bars corresponding to the variance in the annular averaging in the  $uv$ -plane). The zero-signal expectation value is plotted with the dashed black line. Our best fit models described in Section 6.4.1 are shown with the full lines.

tially, as can be seen in the visibility data shown in Fig. 6.6. The strongest  $^{12}\text{CO}$   $J=1-0$  source, DM Tau, is also the largest disc in our sample, with the outer radius of 890 AU (Piétu et al. 2007). The extent of the emission can be seen in Fig. 6.4 where the integrated intensity and intensity-weighted velocity map characteristic of disc rotation are shown. At  $2\sigma$ , the  $^{12}\text{CO}$  extends to  $8''$  or 1100 AU from the star. RY Tau, CQ Tau and AA Tau are unresolved in  $^{12}\text{CO}$ , limiting the size of these discs to  $\leq 840$  AU (the synthesized beam size of approximately  $6''$  at 140 pc distance).

Interestingly, one of the sources with the largest continuum flux, DL Tau, is not detected in the  $^{12}\text{CO}$  line. As will be discussed in Sect. 6.4.3, this is likely due to the absorption by the foreground cloud (noted by Simon et al. 2000).

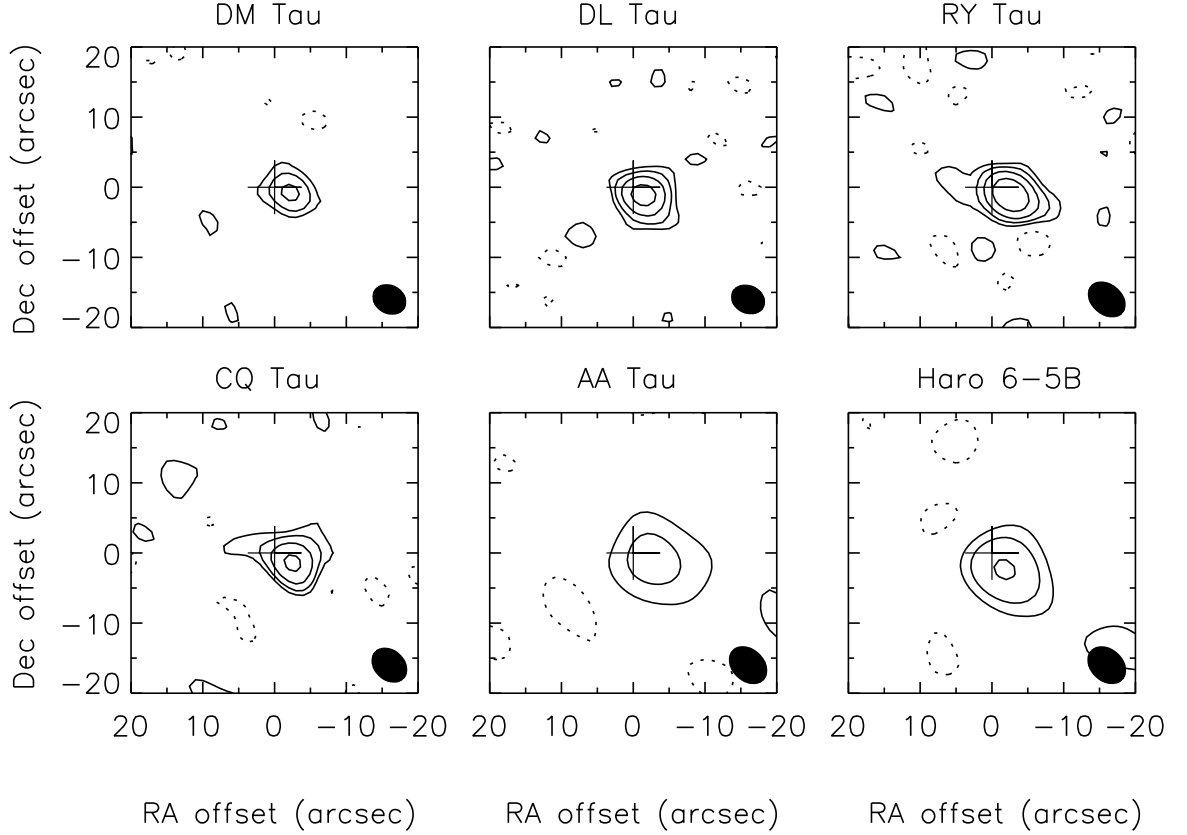
As shown in Figs. 6.3 and 6.5, we detect the  $^{13}\text{CO}$   $J=1-0$  line emission from DM Tau and Haro 6-5 B, at  $V_{\text{LSR}}=5-7$  km s $^{-1}$ . These detections are at  $8\sigma$  and  $4\sigma$ , respectively, in the integrated emission maps. The emission is unresolved and arises from the source positions (see Fig. 6.3). We detect  $\text{HCO}^+$  towards DM Tau at a  $12\sigma$  level at  $V_{\text{LSR}} \approx 5-7$  km s $^{-1}$ . The measured line intensities are shown in Table 6.2. The  $\text{HCO}^+$  emission is marginally spatially resolved, and coincident with the source position (see Fig. 6.3). None of our sources is detected in  $\text{C}^{18}\text{O}$   $J=1-0$  line with an rms of 0.2-0.3 Jy beam $^{-1}$ . In Table 6.2 we report upper limits on the line intensity.

**Table 6.2:** Molecular line results.

| Source     | Synthesized<br>beam<br>( $" \times "$ ) | I <sup>a</sup><br>(Jy/beam) | $\int I dv$<br>(Jy/beam km/s) |
|------------|-----------------------------------------|-----------------------------|-------------------------------|
|            |                                         | <sup>12</sup> CO (1–0)      | OVRO                          |
| DM Tau     | 6.59×6.07                               | 2.09±0.17                   | 3.63±0.16 <sup>b</sup>        |
| DL Tau     | 11.02×7.74                              | <0.46                       | –                             |
| RY Tau     | 6.20×6.25                               | 0.36±0.10                   | 0.40±0.14                     |
| CQ Tau     | 9.20×6.25                               | 0.86±0.25                   | 0.80±0.25                     |
| AA Tau     | 5.64×4.21                               | 0.43±0.13                   | 0.58±0.15                     |
|            |                                         | <sup>13</sup> CO (1–0)      | CARMA                         |
| DM Tau     | 4.44×3.97                               | 0.39±0.12                   | 0.77±0.11                     |
| DL Tau     | 4.48×3.90                               | <0.24                       | –                             |
| RY Tau     | 4.88×3.90                               | <0.28                       | –                             |
| CQ Tau     | 4.82×4.05                               | <0.26                       | –                             |
| AA Tau     | 4.97×3.88                               | <0.26                       | –                             |
| Haro 6-5 B | 4.97×3.88                               | 0.76±0.12                   | 0.95±0.21                     |
|            |                                         | C <sup>18</sup> O (1–0)     | CARMA                         |
| DM Tau     | 4.64×4.16                               | <0.26                       | –                             |
| DL Tau     | 4.68×4.07                               | <0.24                       | –                             |
| RY Tau     | 5.13×4.10                               | <0.26                       | –                             |
| CQ Tau     | 5.06×4.25                               | <0.26                       | –                             |
| AA Tau     | 5.17×4.01                               | <0.32                       | –                             |
| Haro 6-5 B | 5.20×4.04                               | <0.32                       | –                             |
|            |                                         | HCO <sup>+</sup> (1–0)      | OVRO                          |
| DM Tau     | 5.02×3.67                               | 0.30±0.08                   | 1.12±0.10 <sup>b</sup>        |
| DL Tau     | 5.30×3.99                               | <0.10                       | –                             |
| RY Tau     | 4.87×4.06                               | <0.10                       | –                             |
| AA Tau     | 13.27×7.08                              | <0.24                       | –                             |

<sup>a</sup> Upper limits are given by  $2\sigma$ .<sup>b</sup> Integrated flux measured using a gaussian fit for DM Tau.



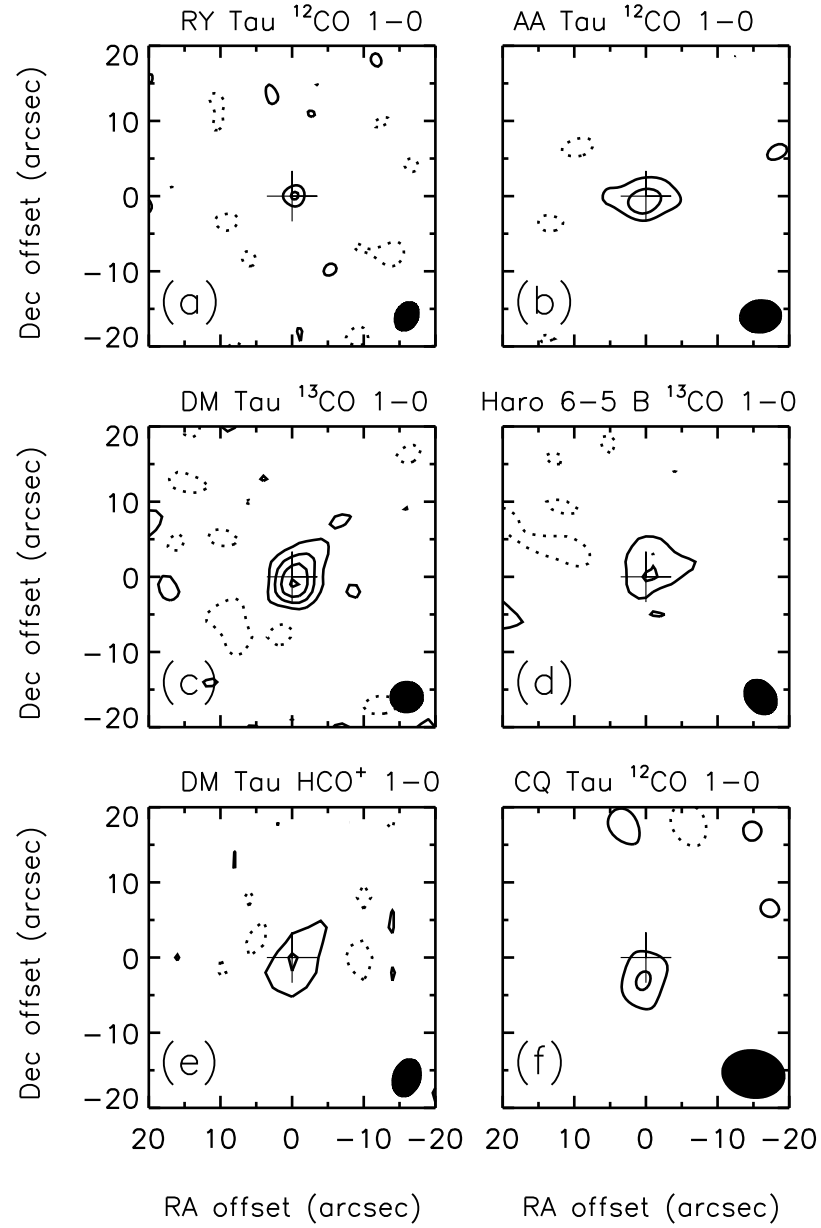


**Figure 6.2:** 2.7 mm continuum maps. The rms level of the maps is  $1 \text{ mJy beam}^{-1}$  and the contour levels are  $-2, 2, 4, 8, 16, 32 \text{ mJy beam}^{-1}$  in all panels.

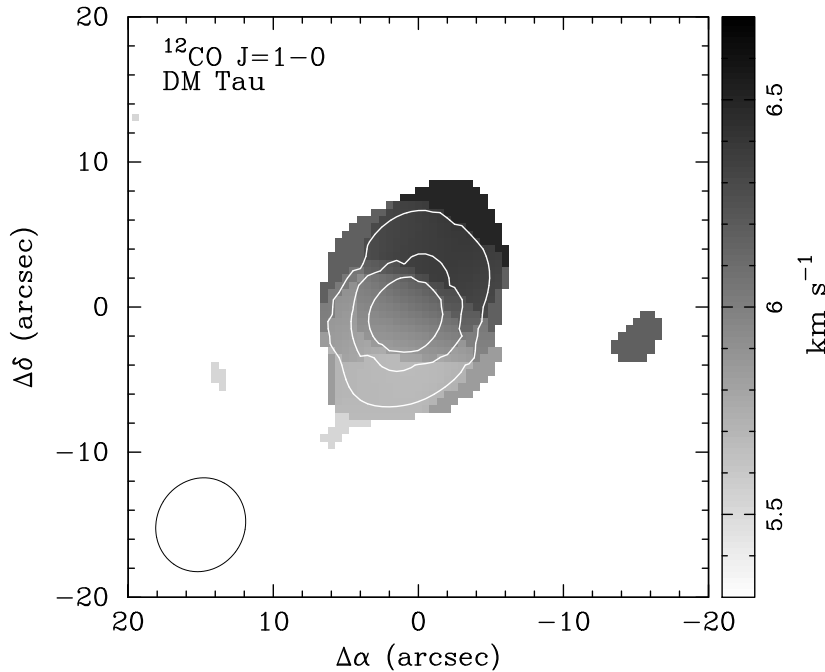
## 6.4 DISCUSSION

### 6.4.1 Modelling the millimetre continuum emission

The dust thermal continuum emission in the millimetre wavelength range is optically thin in discs of dust masses close to  $10^{-4} M_{\odot}$  and sizes of several hundred AU, as is the case for the sources in our sample. It is dominated by the dust located in the cold and dense disc midplane, which contains almost all of the disc dust mass. Throughout the literature, the millimetre flux is used to make disc mass estimates (e.g., Beckwith et al. 1990; Osterloh & Beckwith 1995; Mannings & Sargent 1997; Andrews & Williams 2005, 2007). The estimates are, however, heavily affected by the uncertainty in the millimetre dust emissivity that varies from roughly  $0.1$  to  $2 \text{ cm}^2 \text{ g}^{-1}$  in circumstellar discs (see Draine 2006, for a detailed discussion). A frequent assumption of a single temperature for the entire disc, neglecting the disc temperature and density structure, introduces a further uncertainty in the mass estimates. In our analysis we make simple assumptions of the disc radial structure, relying on the results from the literature, and use a radiative transfer code to calculate the observed millimetre fluxes. We adopt the



**Figure 6.3:** Integrated intensity images of the spatially unresolved molecular line emission from sources with detections or marginal detections. (a): RY Tau,  $^{12}\text{CO}$   $J=1-0$  line integrated over 5.1-6.7 km/s velocity range. Contour levels  $-2,2,3 \times 172 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $0.172 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ). (b): AA Tau,  $^{12}\text{CO}$   $J=1-0$  line integrated over 4.9-9.1 km/s velocity range. Contour levels  $-2,2,4,6 \times 200 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $200 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ). (c): DM Tau,  $^{13}\text{CO}$   $J=1-0$  line integrated over 5.1-7.1 km/s velocity range. Contour levels  $-2,2,4,6,8 \times 84 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $84 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ). (d): Haro 6-5B,  $^{13}\text{CO}$   $J=1-0$  line integrated over 5.3-6.6 km/s velocity range. Contour levels  $-2,2,4 \times 157 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $157 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ). (e): DM Tau,  $\text{HCO}^+$   $J=1-0$  line integrated over 5.4-7.1 km/s velocity range. Contour levels  $-2,2,4 \times 71 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $71 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ). (f): CQ Tau,  $^{12}\text{CO}$   $J=1-0$  line integrated over 4.4-6.1 km/s velocity range. Contour levels  $-2,2,3 \times 250 \text{ mJy beam}^{-1} \text{ km s}^{-1}$  ( $250 \text{ mJy beam}^{-1} \text{ km s}^{-1} = 1 \sigma$ ).



**Figure 6.4:** First moment map of the  $^{12}\text{CO}$   $J=1-0$  emission towards DM Tau. Integrated intensity is shown with  $500 \text{ mJy beam}^{-1}$  contours (white). The synthesized beam size and orientation are indicated with the black ellipse.

highest millimetre dust emissivity expected in discs, corresponding to grain growth to millimetre sizes, and thus provide an estimate of a minimum amount of dust present in these discs. We obtain best fit models of our interferometric 2.7 mm data and the 1.3 mm flux from the literature, simultaneously.

*Disc temperature structure.* Our disc models are vertically isothermal and the expression for the temperature  $T = T_{100} (R/100 \text{ AU})^{-q}$  is based on the midplane temperature in disc models of D'Alessio et al. (2005b), for the spectral types of our sources and an age of 1 Myr. The models for 10 Myr old sources may provide somewhat different temperatures but we do not use these, considering that that our sources are all estimated to be younger. The assumption of a vertically isothermal disc structure is appropriate for the optically thin thermal millimetre emission that is heavily dominated by the cold disc midplane, as the density decreases exponentially with height while the temperature increase is roughly linear. The values of  $T_{100}$  and  $q$  are listed in Table 6.3 for each source. In some cases a single power law does not provide a good mathematical description of the midplane temperature given by the D'Alessio et al. (2005b) models, and we use different power laws for the inner and the outer disc regions to reproduce their temperature values (see Table 6.3). For DM Tau, DL Tau, AA Tau and Haro 6-5 B we use the midplane temperature given by the models of D'Alessio et al. (2005b) for a disc around a K7 star, which is approximately  $T = 16 (R/100 \text{ AU})^{-0.35} \text{ K}$  in the inner few hundred AU but levels to 10 K in the outermost disc regions where the interstellar radiation field dominates the midplane temperature. This power-law description is valid irrespective of the size of grains assumed in the D'Alessio et al. models ( $1 \mu\text{m} - 1 \text{ mm}$ ). For RY Tau we use a K1 star with a disc temperature of  $T = 28 (R/100 \text{ AU})^{-0.45} \text{ K}$  within 70 AU from the star, and  $T = 26 (R/100 \text{ AU})^{-0.4} \text{ K}$  beyond that radius. This description corresponds to micron-sized grains, while the disc model with millimetre-

sized grains has a 10% lower temperature and would yield up to 10% higher mass estimate. For CQ Tau, we use a temperature of  $T = 50 (R/100 \text{ AU})^{-0.5} \text{ K}$  corresponding to the midplane temperature of a disc around an F1 star. As in the case of RY Tau, this description corresponds to micron-sized grains. A 15% higher mass estimate may be obtained if millimetre-sized grains are assumed. As grains grow to millimetre sizes the amount of small grains decreases and thus less incident radiation is captured by the disc, since the small grains are the most effective absorbers at short wavelengths (D'Alessio et al. 2005a). However, the temperature decrease in the models we use is  $\leq 15\%$ , fraction not significant in terms of the mass estimate. We focus our dust emission analysis on deriving the lower limits on the dust mass and therefore use only the models with micron-sized grains.

*Disc surface density distribution.* The disc dust mass  $M_{\text{dust}}$  is our free fit parameter and the surface density  $\Sigma \propto R^{-p}$  is distributed with a radial slope  $p=1$ . This slope, representative of a steady state viscous disc (Hartmann et al. 1998; D'Alessio et al. 1998, 1999; Calvet et al. 2002) is consistent with the observationally constrained values in some well-studied discs (Wilner et al. 2000; Pinte et al. 2008). Andrews & Williams (2007) report a median value of  $p=0.5$  based on the SEDs and submillimetre continuum observations of a sample of 24 discs, but stress that this estimate is closely related to the assumptions of the disc temperature structure, and that a steeper median slope of  $p=1$  is more reasonable. In their recent study of the dust distribution in T Tauri discs using high-resolution millimetre data, Isella et al. (2009) show that a power-law disc surface density distribution modified by an exponential taper is a good description of disc structure, also proposed by Hughes et al. (2008). However, our assumption of a single power-law is a good approximation for the overall disc structure at scales of several hundred AU, especially considering the limited spatial resolution of our data.

We use the vertical density distribution of a disc in hydrostatic equilibrium, calculated for the assumed temperature and surface density at a given radius. The inner radius of the disc is irrelevant for the disc millimetre emission, and its value is set to an arbitrary value of 0.6 AU. We adopt values for the outer radius and the disc inclination as determined through spatially resolved submillimetre interferometric observations of our sources in the literature, listed in Table 6.3. A good determination of  $R_{\text{out}}$  is essential for the interpretation of the spatially unresolved continuum and line emission in the submillimetre, dominated by the outer disc regions. We use the radiative transfer code RATRAN (Hogerheijde & van der Tak 2000) to calculate the 1.3 and 2.7 mm continuum flux, adopting the dust emissivity  $\kappa = \kappa_{1.3 \text{ mm}} (\lambda/1.3 \text{ mm})^\beta$ . We use  $\beta$  as derived in Sect. 6.3 (see Table 6.1), and a dust emissivity of  $\kappa_{1.3 \text{ mm}} = 2 \text{ cm}^2 \text{g}^{-1}$ . These emissivities are not necessarily the same as those used in the SED modelling to derive the disc temperature structure (see above). The millimetre continuum emission is dominated by the properties and emissivity of the grains in disc midplane regions where the density is the highest and grain growth is most efficient. Conversely, the SED modelling is sensitive to the small dust population in the disc (Meijer et al. 2008), and to the disc layers at some height above the midplane due to optical thickness of the infrared emission. Vertical stratification of grain sizes (and thus emissivity) caused by grain growth and settling was found in some sources (e.g., T Tauri star IM Lup, Pinte

et al. 2008). Therefore, there is no inconsistency in our assumption of different dust emissivities for the upper and midplane layers.

We fit the 1.3 and 2.7 mm continuum flux simultaneously, and derive the minimum dust masses of  $(0.7-4.5) \times 10^{-4} M_{\odot}$ , shown in Table 6.3. Figure 6.1 shows the synthetic visibilities from our best fit models compared to the 2.7 mm visibilities observed with CARMA. In a recent study of spatially resolved submillimetre continuum emission in discs, Andrews & Williams (2007) use similar parametrisations for disc structure and simultaneously fit to the SED and submillimetre emission for a number of discs. Their results are consistent with our lower limits in Table 6.3 for AA Tau, DL Tau and RY Tau. However, for DM Tau they derive a dust mass of  $1.4_{-0.2}^{+0.3} \times 10^{-4} M_{\odot}$ , lower than our minimum dust mass of  $2.5 \times 10^{-4} M_{\odot}$ , probably due to their assumption of a disc radius of  $150_{-100}^{+250}$  AU, much smaller than the outer disc radius derived from other spatially resolved observations of this source ranging from 650 AU to 890 AU (Simon et al. 2000; Dartois et al. 2003; Piétu et al. 2007). In a smaller disc, the bulk of the disc mass located in the outermost disc regions is at a comparably higher temperature than in a larger disc. This means that the submillimetre flux measurement (dominated by the outer regions) yields a lower mass estimate in a smaller disc. This is valid for optically thin submillimetre emission. Our minimum dust mass estimates correspond to the total disc mass of  $(0.7-4.5) \times 10^{-2} M_{\odot}$  when a gas-to-dust mass ratio of  $g/d=100$  is assumed.

## 6.4.2 Modelling the $^{12}\text{CO}$ and $^{13}\text{CO}$ $J=1-0$ emission

### Comparison with the dust disc models

We use the disc models described in Sect. 6.4.1 (*dust disc models* hereafter), with the derived minimum dust masses and a gas-to-dust mass ratio of  $g/d=100$ , to analyse the  $^{12}\text{CO}$  and  $^{13}\text{CO}$   $J=1-0$  emission. We adopt a  $^{12}\text{CO}$  gas phase abundance  $[^{12}\text{CO}]=10^{-4}$  with respect to  $\text{H}_2$  (Frerking et al. 1982; Lacy et al. 1994) and a  $[^{12}\text{C}]/[^{13}\text{C}]$  isotopic ratio of 77 (Wilson & Rood 1994), constant throughout the disc. A more realistic disc model requires including the freeze-out of  $^{12}\text{CO}$  and its isotopologues onto dust grains, through a decreased  $^{12}\text{CO}$  abundance in the cold midplane regions. For the purpose of a simple comparison of gas and dust emission we neglect this process. In Sect. 6.4.3, we fit the line spectra and derive molecular abundances, providing estimates of  $^{12}\text{CO}$  depletion factors. We calculate the molecular line emission using the molecular excitation and radiative transfer code RATRAN. The velocity field is given by Keplerian rotation (see Table 6.1 for stellar masses used). We sample the synthetic line emission in the  $uv$ -plane according to our obtained interferometric data and derive synthetic images and spectra using the MIRIAD data reduction package.

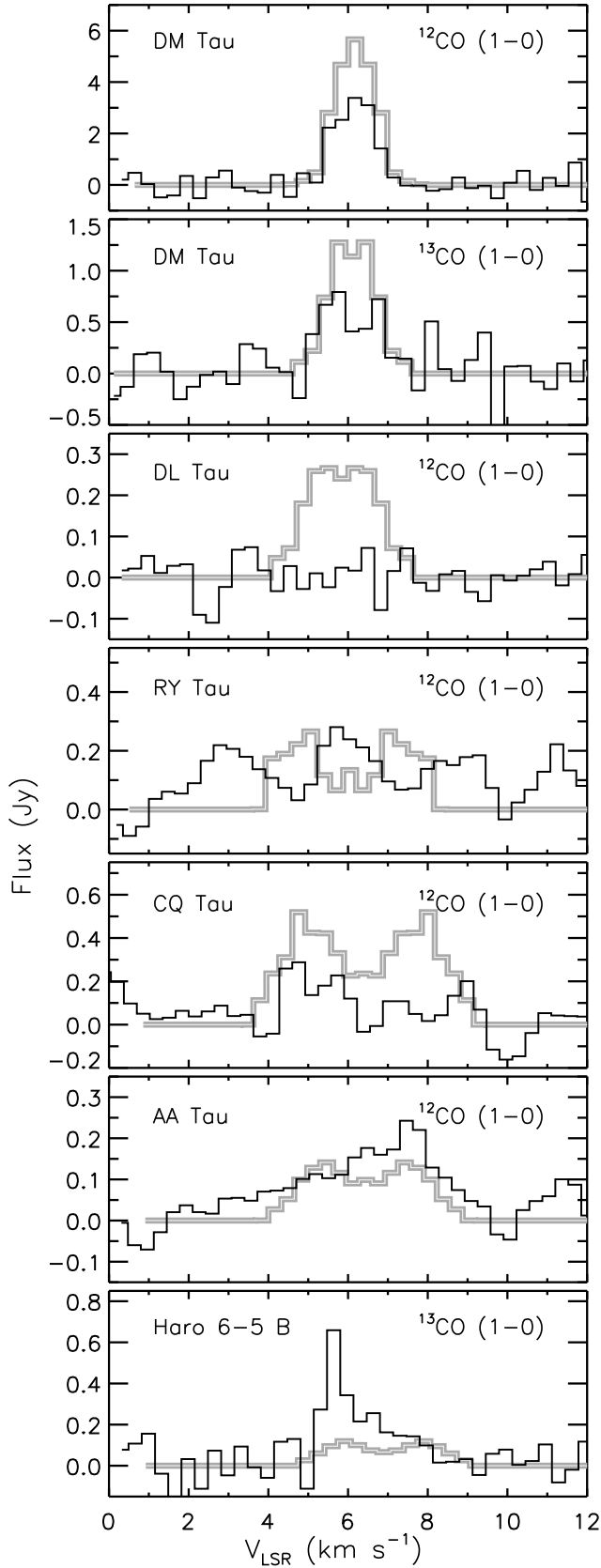
The comparison between the modelled and observed spectra is shown in Fig. 6.5, where the line intensity is summed over a several arcseconds wide region centered at the position of the source. An important first conclusion is that, without adjusting any parameters, the modelled line intensity differs by at most a factor of two to three from the observed line intensity. In the sources where we firmly detect the  $^{12}\text{CO}$  and/or  $^{13}\text{CO}$   $J=1-0$  line (DM Tau, AA Tau and Haro 6-5 B), the modelled line shape matches

**Table 6.3:** Adopted model parameters and derived minimum dust mass.

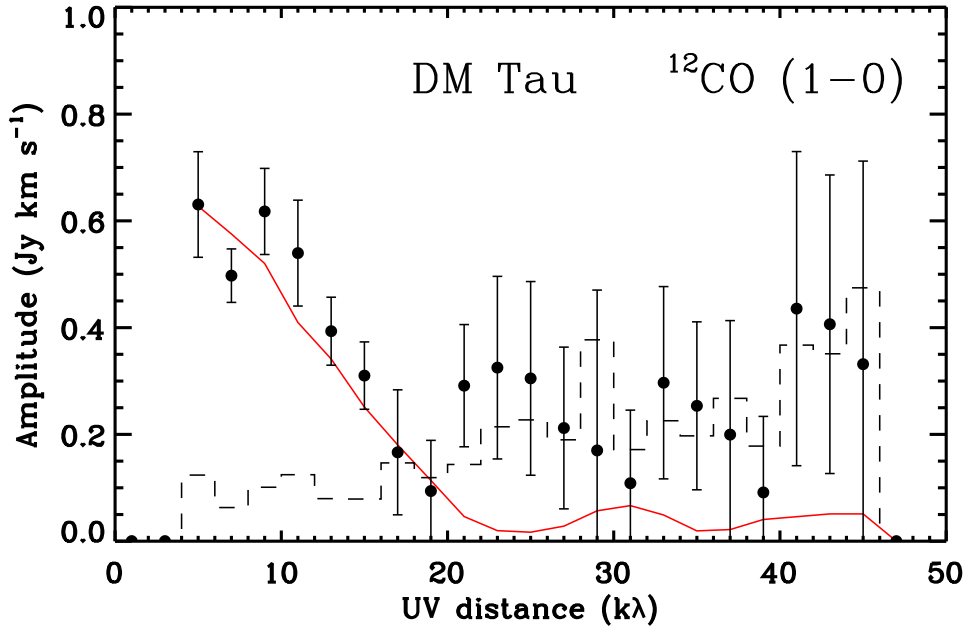
| Source     | $R_{out}^a$<br>(AU) | $i^a$<br>(°) | $T_{100}$<br>(K)     | $q$                             | $M_{dust}(min)^b$<br>( $10^{-4} M_{\odot}$ ) |
|------------|---------------------|--------------|----------------------|---------------------------------|----------------------------------------------|
| DM Tau     | 890                 | 32           | 16                   | 0.35 (if $T < 11$ then $T=11$ ) | 2.5                                          |
| DL Tau     | 400                 | 35           | 16                   | 0.35 (if $T < 10$ then $T=10$ ) | 4.5                                          |
| RY Tau     | 150                 | 25           | 28 (26 beyond 70 AU) | 0.45 (0.4 beyond 70 AU)         | 1.9                                          |
| CQ Tau     | 200                 | 29           | 50                   | 0.5                             | 0.65                                         |
| AA Tau     | 300                 | 70           | 16                   | 0.35                            | 2.0                                          |
| Haro 6–5 B | 300                 | 75           | 16                   | 0.35                            | 3.7                                          |

<sup>a</sup> Disc size and inclination from interferometric imaging (Piétu et al. 2007; Simon et al. 2000; Koerner & Sargent 1995; Chapillon et al. 2008; Pinte & Ménard 2005) or assumed relying on near-infrared imaging (Grady 2004; Padgett et al. 1999)

<sup>b</sup> Calculated using  $\kappa_{230} = 2 \text{ cm}^2 \text{ g}_{dust}^{-1}$  and  $\alpha$  given in Table 6.1.



**Figure 6.5:** The observed  $^{12}\text{CO}$  and  $^{13}\text{CO}$   $J=1-0$  line spectra (black lines) compared to the synthetic line spectra (thick grey-white lines) from the disc models that fit the dust continuum emission, calculated without any adaptation of the model parameters. The spectra are integrated over a region centered on the source position, of the following sizes: for DM Tau  $20'' \times 20''$ , for CQ Tau  $8'' \times 8''$ , and for the remaining sources:  $4'' \times 4''$ .

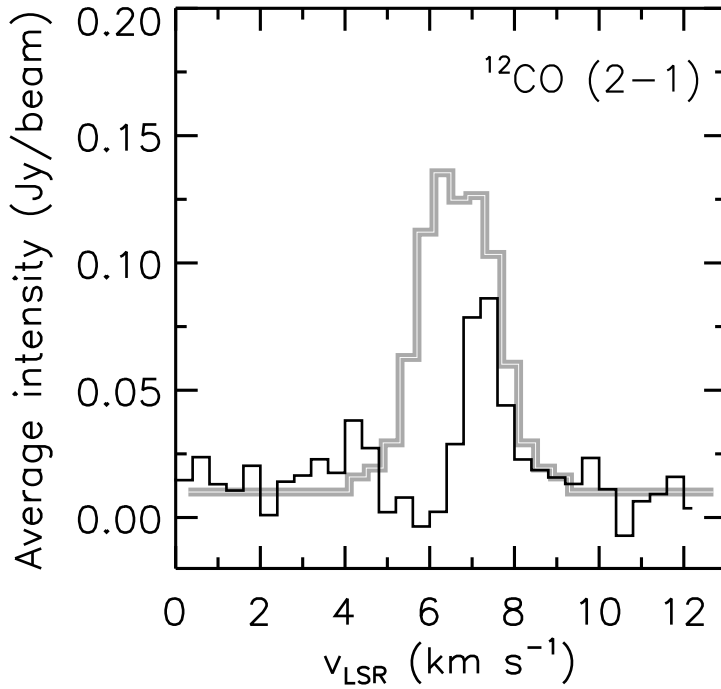


**Figure 6.6:** The vector-averaged  $^{12}\text{CO } J=1-0$  line flux from DM Tau (black symbols) integrated over the velocity range of  $5.8-7.5 \text{ km s}^{-1}$ , plotted versus the  $uv$ -distance. Dashed black lines represent the zero-signal expectation value of our line visibility data. The visibilities of our best-fit model are shown with the full line. The model corresponds to a  $^{12}\text{CO}$  depletion factor of  $f_d=10$  within 750 AU and of  $f_d=100$  between 750 AU and the disc outer radius of 890 AU. The wavy shape of the model visibilities beyond  $25 \text{ k}\lambda$  is due to the adopted sharp outer edge of the disc and step function of  $f_d$ .

the observations well. In sources with a weak detection of the  $^{12}\text{CO } J=1-0$  line, RY Tau and CQ Tau, the observed spectral profiles are not well defined because of the low signal-to-noise ratio, and cannot be compared well to the models. The dust disc model of DL Tau predicts a  $^{12}\text{CO } J=1-0$  line with a peak intensity of  $0.25 \text{ Jy}$  integrated over  $4'' \times 4''$  centered on the source ( $0.66 \text{ Jy beam}^{-1}$ ) detectable at  $3\sigma$  in our observations. However, there is no detected  $^{12}\text{CO } J=1-0$  line emission in our observations. The reason for this is confusion of the  $^{12}\text{CO}$  emission from DL Tau with the foreground cloud material in the interferometric observations, in the velocity range  $5.0-6.6 \text{ km s}^{-1}$  as discussed in Simon et al. (2000) where the  $^{12}\text{CO } J=2-1$  line observations are presented. We conclude that all  $^{12}\text{CO } J=1-0$  emission above the noise level of our observations is likely absorbed by the foreground cloud. Using data from Simon et al. (2000) we find that the emission from the dust disc model is consistent with the observed  $^{12}\text{CO } J=2-1$  emission at the velocities higher than  $6.6 \text{ km s}^{-1}$ , where the emission from the disc is unaffected by the cloud, see Fig. 6.7.

The differences between the models and observations are not large, considering the simplistic approach to the disc structure and the molecular abundances applied here. The fact that the intensities of the synthetic spectra are roughly consistent with the





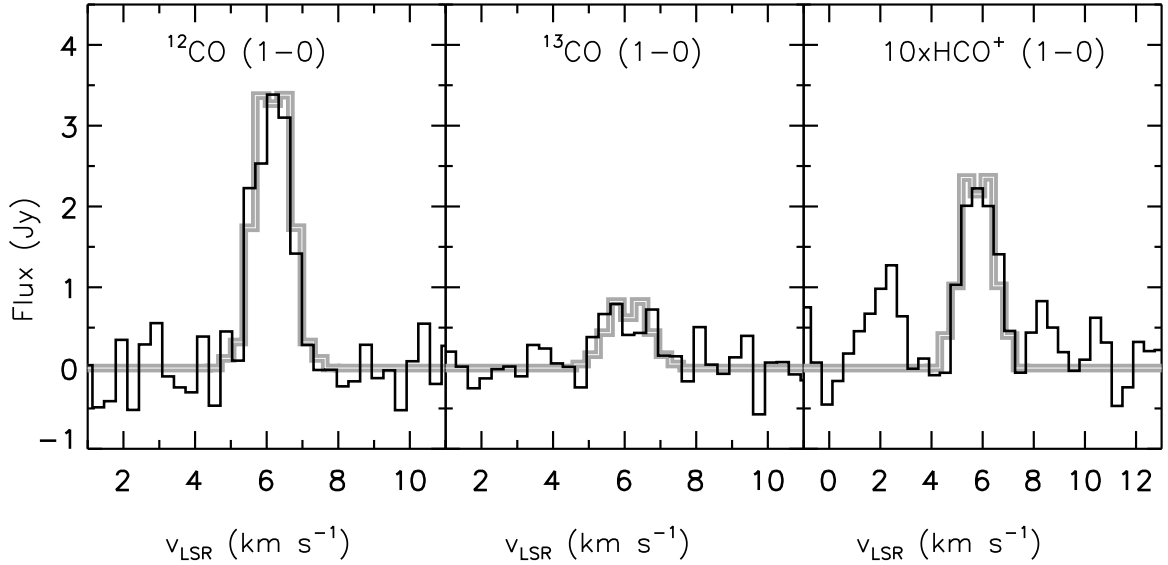
**Figure 6.7:**  $^{12}\text{CO}$   $J=2-1$  spectrum of DL Tau (Simon et al. 2000) shown in black, compared to our dust disc model of this source (thick grey-white line). The spectral region where the emission is confused with the foreground cloud is 5.0–6.6  $\text{km s}^{-1}$ .

observations in all our sources shows that the parametric models of dust emission at millimetre wavelengths are good starting points for the detailed modelling of molecular lines in discs around T Tauri stars. This is consistent with our finding for the intermediate-mass young stars (Herbig AeBe stars) that similar parametric models can be used to reproduce the low- $J$   $^{12}\text{CO}$  line spectra while models derived based on SED alone do not (Chapter 5 of this thesis). It is important to stress that the knowledge of  $R_{\text{out}}$  is crucial in this approach, as the submillimetre line and continuum emission are very sensitive to the outer disc regions.

### 6.4.3 Optimising the model parameters

In this section we take a step further in the modelling of the molecular lines and explore to what extent the observed emission probes the molecular abundances, the temperature in the line emitting layer, and the overall gas-to-dust mass ratio. Starting from the disc models obtained in the previous section, which are entirely based on the observed millimetre fluxes and theoretical calculations of the disc midplane temperature for the young stars of the given spectral type, and using a gas-to-dust mass ratio of 100, we vary the basic disc parameters to fit the observed spectral line profiles.

In those sources where the emission from the dust disc model exceeds the observed line intensity, DM Tau and CQ Tau, the fit to the spectral profile is obtained with the  $^{12}\text{CO}$  abundance as a free parameter. We assume that the gas temperature is the temperature of the disc midplane, the coldest disc region. This assumption is appropriate for optically thin line emission, while for the optically thick lines warmer layers above



**Figure 6.8:** The observed  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{HCO}^+$   $J=1-0$  line spectra (black) compared to our best fit model for dust and gas in DM Tau (thick grey-white line). The flux is integrated over a  $20'' \times 20''$  region centered on the DM Tau position.

the midplane dominate the line emission. Our assumption of a relatively low gas temperature results in an upper limit on the amount of gas phase  $^{12}\text{CO}$ . In these two discs, we find that  $^{12}\text{CO}$  is depleted by factors 10-100 by freeze-out and/or an overall gas dispersal.

In the sources where the dust disc model underestimates the observed line intensity, CQ Tau, AA Tau and Haro 6-5 B, the spectra are fitted by increasing the gas temperature. In this scenario, the disc is emitting optically thick  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines, relatively insensitive to the amount of gas-phase  $^{12}\text{CO}$ . The fits provide lower limits of the temperature of the disc layer where the lines are emitted.

*DM Tau.* To fit the  $^{12}\text{CO}$   $J=1-0$  spectrum of DM Tau, overestimated by the dust disc model by a factor  $\approx 2$ , we decrease the  $^{12}\text{CO}$  gas phase abundance  $[^{12}\text{CO}] = 10^{-4}/f_d$ , where  $f_d$  is the  $^{12}\text{CO}$  depletion factor. Moderate depletion of  $^{12}\text{CO}$  is reported in previous molecular line observations of this disc (Dutrey et al. 1997; Dartois et al. 2003). The assumed midplane temperature is the minimum temperature for the  $^{12}\text{CO}$  emitting layer and cannot be decreased further, therefore it is necessary to decrease the molecular abundance. The same reasoning is applied when fitting the  $^{13}\text{CO}$   $J=1-0$  spectrum, overestimated by the dust disc model that assumes the isotopic ratio  $[^{12}\text{CO}]/[^{13}\text{CO}]=77$  and the  $^{12}\text{CO}$  gas phase abundance of  $10^{-4}$ . We find that it is not possible to fit both the  $^{12}\text{CO}$  and  $^{13}\text{CO}$   $J=1-0$  spectra with a single value of  $f_d$  throughout the disc. The fit to the  $^{13}\text{CO}$   $J=1-0$  results in  $f_d=10$ , while the fit to the  $^{12}\text{CO}$   $J=1-0$  results in  $f_d=100$ . This apparent discrepancy cannot be explained by an anomalous isotopic ratio, because the isotopic fractionation, e.g., when  $^{13}\text{CO}$  is photodissociated in layers where the more abundant  $^{12}\text{CO}$  is self-shielding, causes an increase of  $[^{12}\text{CO}]/[^{13}\text{CO}]$ , and not a decrease. However, a radially increasing depletion factor, perhaps due to an enhanced

penetration of the interstellar radiation field in the outer disc regions of DM Tau can reproduce both lines. We assume  $f_d$  as a radial step function, with a break at 750 AU, the radius where  $^{13}\text{CO}$  emission in our synthetic images becomes negligible with respect to the  $^{12}\text{CO}$  emission. In this way we obtain a fit to the observed spectra with  $f_d = 10$  within 750 AU and  $f_d = 100$  beyond this distance from the star. Our fit to the spectra is shown in Fig. 6.8. Our result is consistent with that of Piétu et al. (2007) where the radially increasing depletion factor  $f_d \propto R^{-p_m}$  is derived, with  $p_m$  in the range from 3 to 5 for a set of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  low- $J$  rotational transitions. Our best fit model yields a mass of the gas phase  $^{12}\text{CO}$   $M_{^{12}\text{CO}} = 3 \times 10^{-6} M_\odot$  and of  $^{13}\text{CO}$   $M_{^{13}\text{CO}} = 4 \times 10^{-8} M_\odot$ . These values represent upper limits, as the  $^{12}\text{CO}$  mass may be lower if a higher gas temperature is assumed.

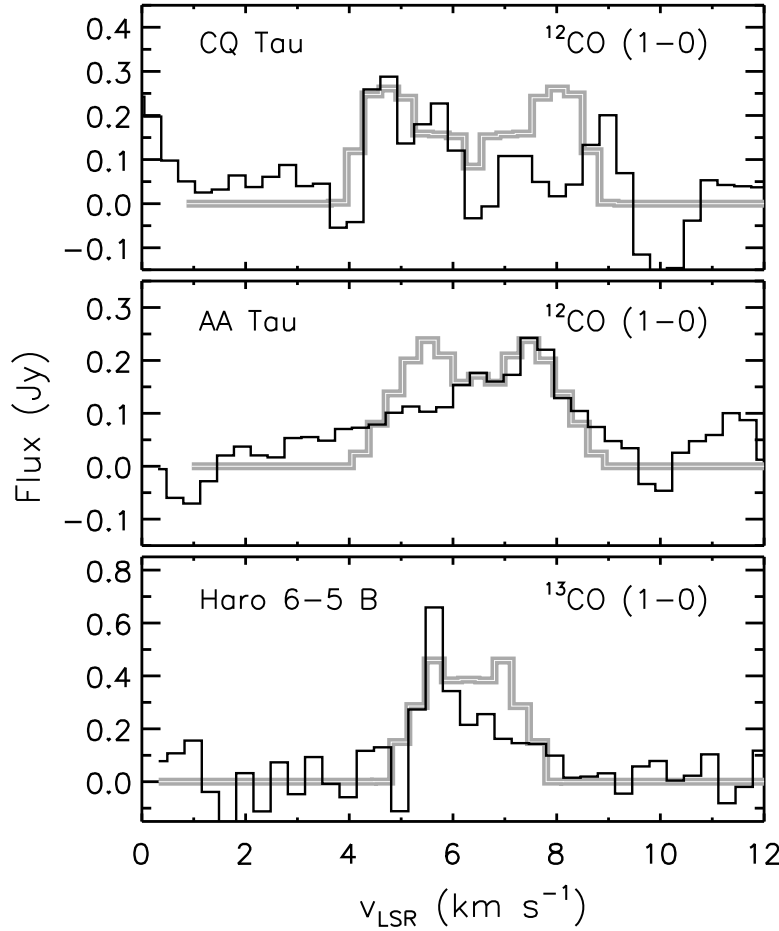
The  $\text{HCO}^+$   $J=1-0$  line observed towards DM Tau is fitted by using our dust disc model and  $\text{HCO}^+$  abundance  $[\text{HCO}^+] = 3 \times 10^{-10}$  with respect to  $\text{H}_2$ , constant throughout the disc. The fit to the spectral line is shown in Fig. 6.8. However, this model overestimates the  $\text{HCO}^+$   $J=4-3$  emission observed by Greaves (2004) by a factor  $\approx 10$ . This suggests that the  $\text{HCO}^+$  emission does not arise in the disc midplane but, as predicted by the work of van Zadelhoff et al. (2001) and Semenov et al. (2008), in a lower density layer of intermediate height. If the density of the emitting gas is  $\leq 10^{-6} \text{ cm}^{-3}$ , the  $J=4-3$  line is less efficiently excited than in the dense midplane.

*DL Tau.* As mentioned above, the  $^{12}\text{CO}$   $J=1-0$  line emission from DL Tau is heavily affected by confusion with the foreground cloud and our non-detection provides no information regarding the disc's gas content. However, the dust disc model is consistent with the detected  $^{12}\text{CO}$   $J=2-1$  emission (data from Simon et al. 2000) at high velocities, see Fig. 6.7, and suggests a  $^{12}\text{CO}$  gas mass of  $M_{^{12}\text{CO}} = 6 \times 10^{-5} M_\odot$ , obtained from our dust model assuming  $g/d=100$  and no depletion.

*RY Tau.* The  $^{12}\text{CO}$   $J=1-0$  line intensity from the dust disc model matches the observed line intensity, while the line shape is poorly defined in the marginal detection of the line emission, see Fig. 6.5. The model uses a mass of the gas-phase  $^{12}\text{CO}$  of  $M_{^{12}\text{CO}} = 3 \times 10^{-5} M_\odot$ , corresponding to  $g/d=100$  and no depletion.

*CQ Tau.* The dust disc model for CQ Tau overestimates the observed  $^{12}\text{CO}$   $J=1-0$  line emission. Following the approach used for DM Tau, we use a  $^{12}\text{CO}$  depletion factor  $f_d$  to fit the observations and derive upper limit on the mass of gas-phase  $^{12}\text{CO}$  in this disc. The fit to the observed spectrum can be seen in Fig. 6.9. A constant of  $f_d=100$  reproduces the observations well, with  $M_{^{12}\text{CO}} = 9 \times 10^{-8} M_\odot$ . Because this value is obtained using the disc midplane temperature, i.e., the lowest possible gas temperature in the disc, it represents an upper limit on the mass of the gas-phase  $^{12}\text{CO}$  in the disc.

*AA Tau.* Opposite to the cases of DM Tau and CQ Tau, for AA Tau the dust disc model underestimates the observed line emission. Our line calculations for the AA Tau dust disc model show that its  $^{12}\text{CO}$   $J=1-0$  line emission is optically thick, and insensitive to the disc mass ( $M_{\text{disc}} = 2 \times 10^{-4} M_\odot$ ). Therefore we increase the gas temperature in the disc to fit the observed line flux. By increasing the disc temperature from  $T = 16 (R/100 \text{ AU})^{-0.35}$  to  $T = 24 (R/100 \text{ AU})^{-0.35}$  we reproduce the observed  $^{12}\text{CO}$   $J=1-0$  spectrum. Our fit is shown in Fig. 6.9. However, even higher temperatures are possible if lower values for  $^{12}\text{CO}$  or  $g/d$  are allowed. Therefore we conclude that the



**Figure 6.9:** The observed  $^{12}\text{CO}$   $J=1-0$  emission of CQ Tau and AA Tau, and the  $^{13}\text{CO}$   $J=1-0$  emission of Haro 6-5 B (black), compared to the best fit models for dust and gas (thick grey-white line). The flux is integrated over a  $4'' \times 4''$  region centered on the position of each source.

$^{12}\text{CO}$  emission arises in a warm layer above the midplane, but cannot derive information about  $f_d$  or  $g/d$ . We note that the asymmetry in the spectral profile may be due to the large scale asymmetry in the disc around AA Tau, suggested by the quasi-periodic eclipses of the stellar photosphere by the circumstellar material (Bouvier et al. 1999; Pinte et al. 2008). Another possible explanation for the line asymmetry may be confusion with the foreground cloud, as in the case of DL Tau.

*Haro 6-5 B.* The  $^{13}\text{CO}$   $J=1-0$  line observed towards Haro 6-5 B is stronger than the dust disc model predicts. We find that the line is optically thick and cannot be fitted by increasing the gas mass or molecular abundance. We use the same approach as for AA Tau, i.e., we scale the temperature in the model linearly to fit the line. The best fit is obtained for a temperature of  $T = 32 (R/100 \text{ AU})^{-0.35}$ , two times larger than the disc midplane temperature. The observed narrow line width is fitted by adopting a disc inclination of  $30^\circ$  (Fig. 6.9), lower than the  $70^\circ$  obtained from the scattered light images of this source and used in the dust disc model. In Dutrey et al. (1996) the  $^{13}\text{CO}$  emission from this source was found to be well described by a qualitatively similar parametric disc model with  $R_{\text{out}}=150 \text{ AU}$  and  $i=0$ , while Yokogawa et al. (2002) derive a much larger disc size of  $R_{\text{out}}=1300 \text{ AU}$  and find the line emission consistent with

$i=70^\circ$ . Clearly, the inclination is very sensitive to the adopted outer radius, and submillimetric observations at a sufficiently high spatial resolution are necessary to constrain the disc size better. So far, the  $^{13}\text{CO}$   $J=1-0$  line emission indicates that the scattered light imaging (Padgett et al. 1999) likely does not trace the full extent of the disc, and that the disc is larger than their derived size of 300 AU. Our fit suggests that the  $^{13}\text{CO}$   $J=1-0$  line emission is dominated by a disc layer roughly two times warmer than the disc midplane. As for AA Tau, we cannot derive information about the amount of gas in the disc, or  $^{13}\text{CO}$  abundance.

## 6.5 SUMMARY AND CONCLUSIONS

We report observations of the molecular lines  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{HCO}^+$   $J=1-0$ , as well as the 2.7 mm dust continuum emission towards a sample of discs around T Tauri stars.

The 2.7 mm continuum fluxes, combined with reported fluxes at 1.3 mm, yield minimum disc dust masses of approximately  $10^{-4} M_\odot$ . We obtain very rough estimates of the dust millimetre emissivity slopes, but we cannot draw conclusions about the type of dust present in these discs. The dust mass estimates are comparable to the values found for discs around T Tauri stars in the literature (Beckwith et al. 1990).

The molecular line detections are roughly consistent with the observed millimetre fluxes, in the framework of simple parametric disc models. The  $^{12}\text{CO}$  and  $\text{HCO}^+$   $J=1-0$  line intensity is the highest in our largest disc, DM Tau with an outer radius of 890 AU.

We can divide the sources in our sample in two groups. In the first group are the sources where a  $^{12}\text{CO}$  depletion factor must be invoked to account for the low line fluxes even when the molecular line emission is assumed to arise from very low temperatures as found in the disc midplane. In these sources, substantial amounts of the  $^{12}\text{CO}$  and isotopologues are efficiently removed from the gas-phase, either through freeze-out and/or photo-dissociation resulting in  $[^{12}\text{CO}] < 10^{-4}$ , or in a significant overall gas loss with  $g/d < 100$ . The discs around DM Tau and CQ Tau fall in this category. In these sources we derive the maximum gas masses of  $^{12}\text{CO}$ . Through the comparison with the minimum dust masses that we derive in these discs, the following constraint can be placed on the depletion factor and the gas-to-dust mass ratio:

$$\frac{M_{\text{CO}}(\text{max})}{M_{\text{dust}}(\text{min})} \geq 10^{-4} \frac{m_{\text{CO}}}{m_{\text{H}_2}} \frac{g/d}{f_d}. \quad (6.1)$$

For DM Tau we obtain  $g/d f_d^{-1} \leq 9$ , and CQ Tau  $g/d f_d^{-1} \leq 1$ . We speculate that the low amount of CO gas with respect to dust in DM Tau is due to freeze-out, a process expected to be efficient in the outer regions of discs around T Tauri stars where the temperature is below 20 K. Because of the large outer radius, DM Tau has most of its mass located in these cold regions. CQ Tau, on the other hand, is warm and small. The lack of CO gas suggested by our results is likely due to the stronger stellar radiation field and age close to 10 Myr. The evidence of grain growth and dust settling reported for this disc point to a scenario of an overall gas loss. In the second group of discs are AA Tau and Haro 6-5 B, and their observed  $^{12}\text{CO}$  and  $^{13}\text{CO}$  line emission is optically thick. Therefore no information can be obtained regarding the amount of the molecular

gas from the observed lines. In these discs we find that the line emission comes from disc layers warmer than the disc midplane, by factors 1.5-2.0, and thus located at some height above the disc midplane. CO observations at a higher spatial resolution ( $\approx 1''$ ) would be useful to determine the outer radius of these two discs better, and thus test our finding.

We conclude that, while the disc structure models based on the millimetre continuum modelling (i.e., Andrews & Williams 2007; Isella et al. 2009, and this work) are good starting points for modelling the rotational emission from cold molecular gas, discs apparently similar in their cold dust emission may vary drastically in their  $^{12}\text{CO}$  gas mass content, due to freeze-out, photodissociation and/or gas dispersal. Therefore, molecular line observations are necessary to assess the disc gas content. Instead using detailed three-dimensional disc structure models with a number of free parameters to interpret the spatially unresolved millimetre dust and  $^{12}\text{CO}$  line observations, valuable constraints on  $M_{\text{dust}}$  and  $g/d f_d^{-1}$  can be obtained if the parameter uncertainties are minimised. In this paper, we show how this can be done by assuming extreme conditions (maximum emissivity, minimum temperature) in combination with a most simplistic disc model. A prior knowledge of disc outer radius and inclination is essential in deriving these information from spatially unresolved observations.

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