Warm gas in protoplanetary disks

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The structure of disks around Herbig Ae/Be stars as traced by CO ro-vibrational emission.

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Abstract

Aims We study the emission and absorption of CO ro-vibrational lines in the spectra of intermediate mass pre-main-sequence stars with the aim to determine both the spatial distribution of (molecular) gas and its physical properties. We also aim to correlate CO emission properties with disk geometry.

Methods Using high-spectral-resolution spectra containing fundamental and first overtone CO ro-vibrational emission, observed with CRIRES on the VLT, we probe the physical properties of the circumstellar gas by studying its kinematics and excitation levels.

Results We detect and spectrally resolve CO fundamental ro-vibrational emission in 12 of 13 stars observed, and in two cases in absorption. Keeping in mind that we study a limited sample, we find that the physical properties and spatial distribution of the CO gas correlate with disk geometry. Flaring disks show highly excited CO fundamental emission up to \( v = 5-4 \), while self-shadowed disks show (much) less highly excited CO. Rotational temperatures range between 250-2500 K, the highest values are found for self-shadowed disks. The \(^{13}\text{CO}\) rotational temperatures are always lower than those of \(^{12}\text{CO}\). The vibrational temperatures in self-shadowed disks are similar to or slightly below the rotational temperatures, suggesting thermal excitation of these lines. In flaring disks the vibrational temperatures range between 5000 and 10000 K.
4. The structure of disks around HAEBE stars as traced by CO emission.

suggesting fluorescent pumping. Using a simple kinematic model shows that the CO inner radius of the emitting region is 10 AU for flaring disks and ≤ 1 AU for self-shadowed disks.

Comparison with hot dust and other gas tracers shows that CO emission from the disks around Herbig Ae/Be stars, in contrast to T Tauri stars, does not necessarily trace the circumstellar disk up to, or inside the dust sublimation radius. Rather, the onset of the CO emission starts from $R_{\text{subl}}$ for self-shadowed disks, to tens of $R_{\text{subl}}$ for flaring disks. Dust settling may provide a qualitative explanation for the observed behavior of CO as a function of disk geometry.

4.1 Introduction

Proto-planetary (PP) disks around young stars are currently one of the most widely studied phenomena in astronomy. These gas- and dust-rich disks form as a result of the conservation of angular momentum in a collapsing cloud core. During the accretion of the cloud on the star, the disk is in the so-called active accretion phase. Once the active accretion stops, the disk slowly dissipates during the so-called passive phase. The evolution, and ultimately the method of dispersion of these passive disks, hold the key to many open questions related to planet formation.

PP disks have historically been studied predominantly using dust, which presents only 1% of the total circumstellar mass but carries most of the opacity. Whereas dust emission dominates the IR spectra of PP disks, and plays an important role in the evolution of PP disks, gas and dust do not necessarily evolve co-spatially and on similar timescales. Hence, gas observations are both complementary to, and essential for, our understanding of PP disks. With the advent of 10 meter class telescopes, increasing amounts of gas tracers become available to study the PP disks. Each of these tracers is sensitive to a different set of physical parameters, and we can tie these parameters to a specific radial location in the disk by using the kinematic information in the line profiles: from inside the dust sublimation radius ($\approx$ 0.1 AU) up to far in the outer disk (100s of AU), and from the mid-plane to the disk atmosphere. For a review on the diagnostic power of gas tracers, see e.g. Carmona (2010).

Carbon monoxide (CO) is the second most abundant molecule in the universe after $H_2$, and commonly detected in emission from disks (e.g. Najita et al., 2003; Blake & Boogert, 2004; Brittain et al., 2007; Salyk et al., 2009). In contrast to $H_2$, the ro-vibrational transitions of CO are much stronger, and hence CO is easier to detect. CO is a very versatile tracer, because it is sensitive to the cold outer disk at typically 100s of AU via the rotational ($\Delta v$
4.2 Sample description

= 0, sub-mm) transitions, the hot (T > 2000 K) gas close to the star via the ro-vibrational first overtone (Δv=2, 2.3 μm) transitions, and the warm (T ≈ 1000 K) gas in the inner disk and disk surface via the ro-vibrational fundamental (Δv =1, 4.6 μm) transitions.

Many recent studies of PP disks have focused on the so-called Herbig Ae/Be (HAEBE) stars, because their disks are often more massive and more extended than the disks around their lower-mass counterparts, T Tauri pre-main-sequence stars. In recent years, it has become clear that passive disks around these HAEBE stars come in two varieties: 'flaring'(group I) and 'self-shadowed'(group II) disks (Meeus et al., 2001). This classification is based on the topology of the dust in the PP disk, and the amount of small dust grains in direct view of the central star that can reprocess stellar light to IR photons, and so cause the SED IR excess. Disks around HAEBE stars have a 'puffed up' inner rim that casts a shadow over the outer disk. In flaring disks, the dust in the outer disk eventually rises out of this shadow, while the dust in self-shadowed disks does not.

In this chapter, we use the CO fundamental and first overtone ro-vibrational transitions as a tool to trace the inner disk (inner tens of AU) regions of thirteen PP disks surrounding young intermediate-mass stars. We present the studied sample, the observations, and the data reduction method in Sections 4.2 and 4.3, and show the results in Section 4.4. In Section 5 we discuss the found correlations between disk shape and CO excitation conditions in the context as a probe for the influence of disk structure on the emission properties of the molecular gas, and we summarize our conclusions in Section 6.

4.2 Sample description

The observed sample consists of 12 HAEBE stars and one F8 star (HD 135344B) from the Thé et al. (1994) catalogue. It has been selected to be homogeneous in mass of the central star and disk accretion activity (all have passive disks; $\dot{M} < 10^{-7} \ M_\odot \ yr^{-1}$), but to be heterogeneous in disk structure (4 flaring disks and 9 self-shadowed disks). The stellar parameters of the program stars are listed in Table 4.1. Because the group I/II classification of the disk structure is based on the shape of the mid-IR emission, it is sensitive to the dust-emission from the circumstellar disks. Hence the presence of a disk hole, or in lesser extent a disk gap, may influence this classification. HD 141569 has a large inner dust hole extending up to 30 AU (e.g. Marsh et al., 2002), and therefore we do not classify it as a group I/II source. HD 100546 and HD 135344B are known to have disk gaps. The gap around HD 100546 extends between a
few and \( \approx 13 \) AU (Grady et al., 2005; Benisty et al., 2010), but because this disk shows ample of signs for a flaring disk structure, we maintain the group I classification. Based on its SED, the disk around HD 135344B is also flaring. However, because of the large (\( \approx 45 \) AU Brown et al., 2007) inner gap, and because of the late spectral type (F8, the flaring / self-shadowed classification only applicable to HAEBE stars), we do not classify it as a group I/II source.

### 4.3 Observations and data reduction

High-spectral-resolution (\( R \approx 94000 \), determined from telluric lines) spectra were taken with the VLT Cryogenic high-Resolution InfraRed Echelle Spectrograph (CRIRES\(^1\), Käufl et al. (2004)) between June 14\(^{th}\) and June 16\(^{th}\) 2007 and July 2\(^{nd}\) and July 5\(^{th}\) 2008. We also use archival data (programme ID: 079.C0860, P.I. E. Pantin) for Figure 4.15. Adaptive Optics were used to optimize the signal-to-noise and spatial resolution of the observations. The observations cover the wavelength ranges between 2.011 - 2.138 and 2.199 - 2.450 \( \mu \text{m} \) (covering the CO first overtone ro-vibrational emission), and between 4.588 - 4.899 and 4.905 - 5.094 \( \mu \text{m} \) (covering many fundamental ro-vibrational transitions of the CO molecule). The observations were made with a slit width of 0.2", and with the slit rotated along the parallactic angle. The data were reduced using the CRIRES pipeline V1.7.0\(^2\), which performs wavelength calibration, background subtraction and flatfield correction. For the targets without spatially resolved CO emission, we have used the "optimal" extraction method, which uses a weighing function dependent on a fit to the spatial profile. Because this method does not correctly account for extended emission, we have used the rectangular extraction method for the spectra of the spatially resolved disks around HD 97048, HD 100546, and HD 141569.

To correct for telluric absorption we have observed a telluric standard directly after each science observation. Each standard was chosen to be as close as possible on the sky so that their spectra are affected by similar atmospheric conditions, and compared to an appropriate Kurucz (1991) stellar atmosphere model to determine the instrumental response. The optical depth of the telluric lines of the standard was scaled to that of the science target, and the two were ratioed using a manually determined sub-pixel wavelength shift to reduce telluric residuals (i.e. spikes due to minor wavelength mismatches). Some telluric absorption lines are fully saturated, causing problems with the division of the spectra. In the further data reduction, we will disregard these areas. We identify the CO lines using the line list of Chandra et al. (1996), and show

\(^1\)http://www.eso.org/sci/facilities/paranal/instruments/crires/
\(^2\)http://www.eso.org/sci/data-processing/software/pipelines/index.html
Table 4.1: Astrophysical parameters of the programme stars. The references for the values for the effective temperature of the central star log $T_{\text{eff}}$, the observed bolometric luminosity log $L_{\text{bol}}$, and the distance $d$ can be found in Acke et al. (2005) and references therein, unless indicated otherwise. * Inclination in degrees from face-on. ♣ Derived from the PAH 8.6 $\mu$m image of Lagage et al. (2006). † We do not classify this source in group I/II (Section 4.2). ‡ Some ambiguity about the distance exists (Blondel & Tjin A Djie, 2006).

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4. The structure of disks around HAEBE stars as traced by CO emission.

Figure 4.1: Example of CRIRES spectra of our targets in the between 4650 - 4673 nm, and 4988 - 4996 nm. The continuum in all spectra was normalized to 1 and subsequently vertically shifted for clarity. The spectra of HD 95881 and HD 150193 have been omitted from the left panel because of problems with the telluric correction.
4.4 Results

Typical spectra for all sources with the CO centered on its rest wavelength in Fig. 4.3. We flux-calibrate the data using their respective 4.77 μm flux, as determined with a spline interpolation to the M band data points, from e.g. Kilkenny et al. (1985); Hillenbrand et al. (1992); de Winter et al. (2001) (see Table 4.1). We have determined the line flux and FWHM of the emission lines both manually and with a Gaussian fit. Note that the 0.2" slit of CRIRES may obscure parts of the emitting region of the spatially resolved disks. CO emission, extended out to many tens of AU has been detected around HD 97048 (van der Plas et al., 2009, Chapter 3), HD 100546 (van der Plas et al., 2009, Chapter 3; Brittain et al., 2009), and HD 141569 (Goto et al., 2006). The observed line fluxes from these stars are thus a lower limit.

4.4 Results

4.4.1 General description of the spectra

Twelve out of thirteen surveyed HAEBE stars show spectrally resolved fundamental 12CO emission, eight show fundamental 13CO emission, and one shows first overtone 12CO emission. There is a large spread in line widths and in distribution of CO molecules over vibrational transitions. The v = 1-0 bands in all stars but HD 141569 are rotationally excited up to high (J \(_{upp} > 30\) ) transitions (Table 4.2). We have been unable to characterize the spectra of two stars for which we have detected CO emission. The combination of broad lines (FWHM = 80 km/s) and multiple (at least 5: 12CO v = 1-0, 2-1, 3-2 and 4-3, and 13CO v = 1-0) vibrational transitions in the spectrum of HD 101412 caused the emission lines to be highly blended. A combination of poor SN and telluric absorption partially overlapping with the CO emission made it possible to identify CO in the spectrum of HD 104237, but we have been unable to reliably measure line fluxes.

The CO emission in HD 97048, HD 100546, HD 141569, and R CrA has been spatially resolved, and the 4.6 μm continuum emission has been resolved in HD 97048, HD 100546, and HD 179218. We discuss detected CO absorption towards HD 97048 and R CrA in Section 4.4.5, and the detected emission lines other than CO in Section 4.4.6.

4.4.2 CO rotational temperature

The strength and ratio of all rotational transitions within and between vibrational bands dictates an unique temperature of the gas via the Boltzmann equation. We can estimate the total amount of warm CO gas (N\(_{tot}\)) and the rotational temperature (T\(_{rot}\)) using this Boltzmann equation in the following...
4. The structure of disks around HAEBE stars as traced by CO emission.

Table 4.2: Detected CO lines, their radial velocities with a typical error of 2 km s\(^{-1}\) as determined in Section 4.4.3, and the stellar radial velocities derived from photospheric absorption lines in column 1-3. References for the stellar radial velocity are:

- Acke et al. (2005),
- van der Plas et al. (2008, Chapter 2), and
- Reipurth et al. (1996). Emission lines are listed in the upper panel, and absorption lines in the lower.

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Note: Observations marked with an asterisk (*) indicate that no observations are available. No observations were detected in 206 of the 209 sources in this survey. For all spectra that we do not detect these CO transitions in our spectra, they have been marked and absorption lines in the lower. For more information, refer to the paper "A survey of 209 HAEBE stars."
way:
\[
\frac{F_{ij}}{g_i \nu_{ij} A_{ij}} = \frac{1}{4 \pi d^2} \frac{\hbar B N_{\text{tot}}}{T_{\text{rot}}} e^{E_i/kT_{\text{rot}}}. \tag{4.1}
\]

Where \( F_{ij} \) is the line flux, \( \nu_{ij} \) the frequency of the transition, \( A_{ij} \) the Einstein \( A \)-coefficient, \( g_i \) the degeneracy of the upper level, \( d \) the distance to the source, \( B \) the rotational constant, and \( E_i \) the energy of the transition. If we assume that the CO gas is [1] optically thin; [2] of a single temperature; and [3] in Local Thermodynamic Equilibrium (LTE), a plot of the normalized line flux, \( \ln(F_{ij}/(g_i \nu_{ij} A_{ij})) \), versus the energy each transition in Kelvin, \( E_i/k \), traces a linear line with slope \(-1/T_{\text{rot}}\). We show our data in a so-called “Boltzmann plot” in Figure 4.2, where we have normalized the energy scale to the minimum of each vibrational band. Inspection of Figure 4.2 shows that some rotational transitions, most notably those of the \(^{12}\text{CO} \nu = 1-0\) vibrational bands, deviate from linearity, and curve upwards for lower energies. This behavior is observed frequently (see e.g. Najita et al., 2003; Blake & Boogert, 2004; Salyk et al., 2009), and is commonly explained by either a radial gradient in the CO temperature, or by optically thick gas. Fitting our data with a two-temperature model yields acceptable fits, but produces for the cold component both low temperatures (\(\approx 65\) K), and a CO column that is over 17 orders of magnitude larger that the amount of CO needed to explain the warmer CO. This is incompatible with the (much broader) observed linewidths (see Salyk et al. (2009) for comparable results for T Tauri stars). We assume in our further analysis that the curvature in the Boltzmann plots is due to opacity effects, and derive a \( T_{\text{rot}} \) and \( N_{\text{tot}} \) from the linear part of the slope for the Boltzmann plots with curved slopes. We are unable to determine \( T_{\text{rot}} \) for HD 101412, but since multiple vibrational bands of both CO fundamental and 1st overtone emission are detected, we estimate a lower limit to \( T_{\text{rot}} \) of 2000 K. The derived \( T_{\text{rot}} \) and \( N_{\text{tot}} \) are listed in Table 4.3 for \(^{12}\text{CO}\) and in Table 4.4 for \(^{13}\text{CO}\).

Some important trends can be noted from Tables 4.3 and 4.4. First, the derived temperatures of all disks but one (HD 141569) are between \(\approx 900\) and \(2500\) K. Second, the \(^{12}\text{CO} \) temperatures are always higher than the \(^{13}\text{CO} \) temperatures. And third, the derived temperatures for the CO gas in the self-shadowed disks are higher than those for the CO gas in the flaring disks.

**CO Vibrational temperatures**

The temperature of a gas in LTE dictates the distribution of its emission over the various rotational transitions and vibrational bands. The temperatures derived via the Boltzmann equation from the fractional distribution between the different rotational transitions within each vibrational band \( T_{\text{rot}} \),
4. The structure of disks around HAEBE stars as traced by CO emission.

Figure 4.2: Boltzmann plots for detected $^{12}$CO (red/black), and if detected, $^{13}$CO (green), emission. The best fit for the rotational temperature $T_{rot}$ is shown with a dotted line, and the disk classification (group I/II) is noted on the top right. The Boltzmann plots for HD 101412 and HD 104237 are absent for reasons described in section 4.4.1.
4.4 Results

Figure 4.3: Vibrational temperatures for all targets with at least two detected vibrational bands. Overplotted are a fit to the vibrational temperature (solid red line), and the LTE population over the various vibrational bands assuming the averaged rotational temperature (scaled to the $v = 1-0$ population, dotted red line). The corresponding temperatures are also shown. The plot of HD 141569 is an adaptation of Figure 10 from Brittain et al. (2007), with the y axis in units of N(CO) cm$^{-2}$, in contrast to the total CO number density for the other panels.

The temperature derived from the ratio of the total population of each vibrational band ($T_{\text{vib}}$), are the same for gas in LTE. Deviations between these two temperatures point to a non-LTE (de)excitation mechanism. Sub-thermal vibrational level populations are expected in low-density environments, where the higher J rotational transitions are depopulated relative to LTE, and super-thermal level populations can be caused by e.g. UV fluorescence, which has been reported to play a role in at least two of our sources (HD 141569, Brittain et al. (2007) and HD 100546, Brittain et al. (2009)). UV fluorescence is the process where stellar UV radiation pumps CO in the ground electronic state ($X^3\Sigma^+$) to an excited electronic state ($A^1\Pi$), which thereafter decays back into an excited vibrational band in the ground electronic state (Krotkov et al.,
4. The structure of disks around HAEBE stars as traced by CO emission.

1980). The distribution over the various vibrational bands, and thus the vibrational temperature in case of UV fluorescence is equal to or lower than the black body temperature of the stellar UV field. This depends on the dilution of the stellar UV field, which diminishes the influence of the UV pumping over the LTE de-excitation. The rotational levels within each vibrational band are thermalized at densities as low as n(H$_2$) = 10$^6$ cm$^{-3}$ (Brittain et al., 2007), and we expect them to reflect the kinetic temperature of the gas. Comparing the rotational and vibrational temperatures is thus a good exercise to investigate the CO gas excitation mechanism. In Figure 4.3, we show the vibrational populations as a function of vibrational band of each source for which we have derived at least the T$_{\text{rot}}$ and N$_{\text{CO}}$ for the v = 1-0 and 2 vibrational bands, together with the derived vibrational temperature.

We find [1] that T$_{\text{vib}}$ > T$_{\text{rot}}$ for the flaring disks, [2] that T$_{\text{vib}}$ ≲ T$_{\text{rot}}$ for the self-shadowed disks, and conclude that fluorescence is only observed in flaring disks.

4.4.3 Kinematics

The shape of an emission line originating from a circumstellar disk is determined by the mass of the central star, the disk inclination, and the radial location of the emitting gas. Thus, a spectrally resolved emission line is an indicator for the distribution of the emitting gas throughout the disk. Comparing the line shape and width both for the rotational transitions within a vibrational band (ΔE ≈ 10 K ), and between the vibrational bands (ΔE ≈ 1000 K ) is a useful exercise to constrain the location of the emitting gas over a large range of excitation conditions.

As a proxy for line shape, we have measured the FWHM of each ro-vibrational line as function of $J_{\text{up}}$ (and thus excitation energy) both manually and using a Gaussian fit. We show this in Figure 4.4, and list the average Gaussian FWHM values for low ($J_{\text{up}}$≤10), medium (10 <$J_{\text{up}}$≤20) and high ($J_{\text{up}}$>20) in Tables 4.3 and 4.4. The FWHM of the low ($J_{\text{up}}$ ≤ 15) rotational transitions is constant within the error bars, and we construct composite line profiles for each detected vibrational band of these lines with sufficient S/N, to compare the line shapes. To construct these composite profiles we have subsequently centered each emission line at its line center, re-gridded it on a velocity grid, subtracted the continuum, and scaled the line maximum to 1. We show the composite profiles in Figure 4.5. The line profiles of HD 100546 and HD 97048 v = 3-2, and HD 150193, HD 179218 and R CrA v = 1-0, have been made using the high ($J_{\text{up}}$ > 20) ro vibrational transitions, because no suitable low J lines were available.

To determine the radial velocity of the CO emission, we fit a two-dimensional
Table 4.3: Derived physical properties (N_{12CO}, T_{rot}, and FWHM) for the \(^{12}\)CO emission in our sample. (h) means the column is derived from a fit to the higher J values only, and thus is a lower limit.

<table>
<thead>
<tr>
<th>Target</th>
<th>Group</th>
<th>(v)</th>
<th>(N_{12CO}) (\times 10^{14})</th>
<th>(T_{rot}) (\text{K})</th>
<th>FWHM ((J&lt;10)) (\text{km s}^{-1})</th>
<th>FWHM ((10\leq J&lt;20)) (\text{km s}^{-1})</th>
<th>FWHM ((J\geq20)) (\text{km s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h) HD 100546</td>
<td>I</td>
<td>1-0</td>
<td>37.2(3.5)</td>
<td>1350(50)</td>
<td>14.2(1.1)</td>
<td>14.5(0.4)</td>
<td>16.0(1.6)</td>
</tr>
<tr>
<td>(h) HD 100546</td>
<td>I</td>
<td>2-1</td>
<td>4.6(0.5)</td>
<td>1440(90)</td>
<td>15.9(1.1)</td>
<td>15.0(1.6)</td>
<td>14.6(2.0)</td>
</tr>
<tr>
<td>(h) HD 100546</td>
<td>I</td>
<td>3-2</td>
<td>3.0(0.8)</td>
<td>1100(100)</td>
<td>13.9(1.7)</td>
<td>16.1(0.5)</td>
<td>13.9(2.2)</td>
</tr>
<tr>
<td>HD 100546</td>
<td>I</td>
<td>4-3</td>
<td>1.6(0.2)</td>
<td>1280(70)</td>
<td>10.0(3.6)</td>
<td>14.8(3.3)</td>
<td>16.7(3.2)</td>
</tr>
<tr>
<td>HD 100546</td>
<td>I</td>
<td>5-4</td>
<td>1.2(0.1)</td>
<td>1290(50)</td>
<td>14.3(2.4)</td>
<td>-</td>
<td>13.7(1.9)</td>
</tr>
<tr>
<td>(h) HD 97048</td>
<td>I</td>
<td>1-0</td>
<td>61.0(9.1)</td>
<td>1060(70)</td>
<td>15.2(1.5)</td>
<td>14.2(0.9)</td>
<td>13.7(0.6)</td>
</tr>
<tr>
<td>(h) HD 97048</td>
<td>I</td>
<td>2-1</td>
<td>14.3(5.0)</td>
<td>910(110)</td>
<td>15.3(1.7)</td>
<td>16.0(2.3)</td>
<td>-</td>
</tr>
<tr>
<td>HD 97048</td>
<td>I</td>
<td>3-2</td>
<td>6.2(1.2)</td>
<td>960(70)</td>
<td>17.8(3.3)</td>
<td>16.2(1.5)</td>
<td>18.7(1.7)</td>
</tr>
<tr>
<td>HD 97048</td>
<td>I</td>
<td>4-3</td>
<td>5.1(1.5)</td>
<td>910(80)</td>
<td>19.1(3.2)</td>
<td>18.0(5.6)</td>
<td>10.8(0.0)</td>
</tr>
<tr>
<td>HD 97048</td>
<td>I</td>
<td>5-4</td>
<td>3.8(1.8)</td>
<td>920(160)</td>
<td>18.1(1.2)</td>
<td>23.8(5.0)</td>
<td>16.7(7.7)</td>
</tr>
<tr>
<td>HD 179218</td>
<td>I</td>
<td>1-0</td>
<td>32.6(23.1)</td>
<td>1300(270)</td>
<td>-</td>
<td>-</td>
<td>17.4(4.0)</td>
</tr>
<tr>
<td>HD 179218</td>
<td>I</td>
<td>2-1</td>
<td>4.8(0.7)</td>
<td>1300(100)</td>
<td>17.4(1.9)</td>
<td>18.7(2.6)</td>
<td>16.7(5.3)</td>
</tr>
<tr>
<td>HD 179218</td>
<td>I</td>
<td>3-2</td>
<td>2.9(1.3)</td>
<td>1330(280)</td>
<td>-</td>
<td>18.4(14.3)</td>
<td>20.8(8.9)</td>
</tr>
<tr>
<td>HD 179218</td>
<td>I</td>
<td>4-3</td>
<td>2.6(0.6)</td>
<td>1240(110)</td>
<td>-</td>
<td>17.5(1.5)</td>
<td>23.4(1.8)</td>
</tr>
<tr>
<td>HD 141569</td>
<td>I</td>
<td>2-1</td>
<td>6464.1(646.1)</td>
<td>250(20)</td>
<td>15.8(3.0)</td>
<td>14.1(3.3)</td>
<td>-</td>
</tr>
<tr>
<td>(h) HD 190073</td>
<td>II</td>
<td>1-0</td>
<td>58.1(1.7)</td>
<td>2250(50)</td>
<td>14.2(2.4)</td>
<td>-</td>
<td>15.4(1.9)</td>
</tr>
<tr>
<td>(h) HD 190073</td>
<td>II</td>
<td>2-1</td>
<td>8.1(0.5)</td>
<td>2420(170)</td>
<td>16.0(3.5)</td>
<td>15.3(1.0)</td>
<td>15.5(3.5)</td>
</tr>
<tr>
<td>(h) HD 98922</td>
<td>II</td>
<td>1-0</td>
<td>1307.4(33.0)</td>
<td>1660(20)</td>
<td>18.2(1.1)</td>
<td>19.7(9.3)</td>
<td>27.7(2.3)</td>
</tr>
<tr>
<td>HD 98922</td>
<td>II</td>
<td>2-1</td>
<td>82.7(26.8)</td>
<td>2690(1160)</td>
<td>26.5(1.2)</td>
<td>23.2(5.1)</td>
<td>34.5(2.1)</td>
</tr>
<tr>
<td>HD 95881</td>
<td>II</td>
<td>1-0</td>
<td>23.3(2.5)</td>
<td>1840(100)</td>
<td>36.8(1.8)</td>
<td>33.5(8.0)</td>
<td>48.0(4.7)</td>
</tr>
<tr>
<td>R CrA</td>
<td>II</td>
<td>1-0</td>
<td>49.9(35.6)</td>
<td>2970(1950)</td>
<td>-</td>
<td>-</td>
<td>15.5(3.3)</td>
</tr>
<tr>
<td>(h) HD 135344B</td>
<td>II</td>
<td>1-0</td>
<td>22.0(2.4)</td>
<td>1070(50)</td>
<td>15.5(2.4)</td>
<td>14.6(1.4)</td>
<td>22.8(1.6)</td>
</tr>
<tr>
<td>HD 150193</td>
<td>II</td>
<td>1-0</td>
<td>75.6(35.4)</td>
<td>1460(230)</td>
<td>-</td>
<td>-</td>
<td>64.4(5.5)</td>
</tr>
</tbody>
</table>
Table 4.4: Continued, but for $^{13}$CO.

<table>
<thead>
<tr>
<th>Target Group</th>
<th>$v_{\text{CO}}$</th>
<th>$T_{\text{rot}}$</th>
<th>FWHM ($J &lt; 10$)</th>
<th>FWHM ($10 \leq J &lt; 20$)</th>
<th>FWHM ($J \geq 20$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 100546 I</td>
<td>1-0</td>
<td>16.2 (9.5)</td>
<td>740 (110)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HD 97048 I</td>
<td>1-0</td>
<td>30.2 (27.0)</td>
<td>720 (170)</td>
<td>17.2 (2.4)</td>
<td>14.9 (2.4)</td>
</tr>
<tr>
<td>HD 179218 I</td>
<td>1-0</td>
<td>37.7 (13.0)</td>
<td>760 (60)</td>
<td>14.6 (7.0)</td>
<td>19.3 (0.5)</td>
</tr>
<tr>
<td>HD 141569</td>
<td>1-0</td>
<td>117271.7 (11727.2)</td>
<td>200 (20)</td>
<td>10.5 (1.2)</td>
<td>14.5 (1.2)</td>
</tr>
<tr>
<td>HD 190073 I</td>
<td>1-0</td>
<td>40.3 (4.1)</td>
<td>1050 (40)</td>
<td>11.5 (0.5)</td>
<td>11.8 (1.7)</td>
</tr>
<tr>
<td>HD 98922 I</td>
<td>1-0</td>
<td>249.7 (101.9)</td>
<td>1320 (300)</td>
<td>15.9 (1.1)</td>
<td>17.2 (1.8)</td>
</tr>
<tr>
<td>HD 95881 II</td>
<td>1-0</td>
<td>10.9 (7.1)</td>
<td>1000 (240)</td>
<td>23.1 (1.1)</td>
<td>23.9 (2.6)</td>
</tr>
</tbody>
</table>

Table 4.4: Table 4.3 continued, but for $^{13}$CO.
polynomial to the offset between the telluric absorption lines in the spectra and a HITRAN synthetic atmosphere model (Rothman et al., 1992), correct for the barycentric velocity, and determine the centroid of the emission line. The so determined values are in general agreement with the stellar radial velocity determined from stellar atmosphere absorption lines (taken from literature, when available). We list these values in Table 4.2.

Naively one would expect that line widths correlate with line excitation, the higher excitation lines originating from closer to the star and so showing broader lines. Surprisingly, only two stars in our sample, HD 98922 and HD 135344B show this trend (Figure 4.4). In HD 100546, there is no such change in line width between the different vibrational bands, but the line shape of the $^{12}\text{CO} v = 1-0$ transitions becomes more flat-topped with increasing excitation levels. In the remaining stars of our sample we could find no correlation between line excitation and line shape, nor between self-shadowed and flaring disks. For all stars with self-shadowed disks the $^{13}\text{CO}$ line width (FWHM) is smaller than that of the corresponding $^{12}\text{CO}$ lines (Figure 4.4). This is not seen in the flaring disks. We will return to these trends in Section 4.5.3.

### 4.4.4 Spatially resolved CO and continuum emission

The CO emission in HD 97048, HD 100546 and HD 141569 is spatially resolved and shows equally resolved red- and blue-shifted components on spatially opposite sides of the star (see Figures 4.15 and 4.16), compatible with gas in Keplerian rotation. Furthermore, the 4.6 μm continuum emission has been resolved in HD 97048 and HD 100546 (see van der Plas et al. (2009, Chapter 3) for details), and in 179218 with a FWHM of $0.209'' \pm 0.005''$, compared to the FWHM of the unresolved PSF of the telluric standards observed directly before (0.194'' $\pm 0.005''$) and after (0.192'' $\pm 0.006''$), which yields a size of $0.078'' \pm 0.003''$, or 19 ± 1 AU after deconvolution. The spatially resolved CO emission in HD 97048 and HD 100546 remains discernible above the background up to projected radii of 50 and 40 AU on the reduced, combined 2D spectra. Because our observations were not made with the slit aligned to the disk major axis, we correct for the misalignment of the slit with the disk major axis. This yields a FWHM continuum size of 23 ± 2 AU for HD 179218, 26 ± 4 AU for HD 97048 and 13 ± 2 AU for HD 100546, and deprojected CO outer radii of 60 and 51 AU for HD 97048 and HD 100546.

The CO emission in R CrA in contrast is only resolved in one spatial direction, and blueshifted with 10 km/s with respect to the surrounding Corona Australis molecular cloud (c.f. Section 4.4.5). This suggests the CO emission in R CrA is likely to originate from an outflow.
4. The structure of disks around HAEBE stars as traced by CO emission.

Figure 4.4: FWHM as a function of rotational quantum number J of $^{12}$CO (red/black) and $^{13}$CO (green). The large dots represent the FWHM of a Gaussian fit to the emission line, the dotted line a linear best fit to these. The small dots are manually determined FWHM values. The disk classification (group I/II) is noted on the top right, and the velocity scale differs only between targets.
Figure 4.5: Averaged, normalized composite line profiles for all detected vibrational transitions that have sufficient signal (as described in Section 4.4.3). The composite profiles of different isotope or vibrational bands of the same target are presented below each other, the disk classification (group I/II) is noted on the top right, and the velocity scale of the most right column differs with each panel. The line profile for HD 101412 is a mix of the $^{13}$CO $v = 1-0$ R(23) and $^{12}$CO $v = 4-3$ R(35) lines.
4.4.5 CO absorption

We detect CO absorption in the spectra of R CrA and HD 97048. In R CrA, we detect the $^{12}\text{CO}\ v = 0 - 1$ and $v = 0 - 2$, and $^{13}\text{CO}\ v = 0 - 1$ bands in the spectrum. We show an absorption line, together with the line widths and a Boltzmann plot in Figure 4.6.

The absorption lines in R CrA are spectrally resolved, and the radial velocity of the $^{12}\text{CO}\ v = 1 - 0$ emission is blue shifted with -10 km/s in respect to the $^{12}\text{CO}\ v = 0 - 1, v = 0 - 2$, and $^{13}\text{CO}\ v = 0 - 1$ absorption. The CO isotope ratio of $^{12}\text{CO}\ v(0-2) / ^{13}\text{CO}\ v(0-1)$ towards R CrA is 142, and their temperature ratio is $57 \pm 1 \text{ K} / 44 \pm 1 \text{ K} = 1.3$. These values are comparable to values found toward local molecular clouds (Goto et al., 2003), and suggest that the absorption lines are formed in the Corona Australis molecular cloud.

We detect $^{12}\text{CO}$ and $^{12}\text{CO}\ v = 0 - 1$ in the spectrum of HD 97048. The absorption lines in HD 97048 are unresolved and blended with emission lines, making it difficult to reliably determine the line strengths. The radial velocity of the absorption and emission is similar.

4.4.6 Other lines

All targets but HD 101412 with detected CO emission also show the HI recombination lines Pf$^\beta$ and Hu$^\epsilon$, much wider than the CO lines (Figure 4.3).

We detect the neutral Na I D doublet (2.206 and 2.209 $\mu$m, 4p$^2P_0^0$ - 4s$^2S$) in emission in the spectrum of HD 190073, with a FWHM of 34$^{+3}_{-1}$ km s$^{-1}$, and a 2.206 $\mu$m / 2.209 $\mu$m line ratio of $\approx 2$. The Na I radial velocity in HD 190073 is -3$^{+3}_{-1}$ km s$^{-1}$, and in agreement with the radial velocity of the central star and the CO emission. The low first ionization potential of neutral sodium (5.1 eV, 243 nm), makes a non-thermal excitation mechanism such as fluorescent pumping by 330.3 nm photons (Thompson & Boroson, 1977), or ionization and subsequent recombination likely. This doublet is more often detected in early-type high-luminosity stars (McGregor et al., 1988), as well as in EXor stars in concert with CO first overtone $v = 2 - 0$ emission, and in those cases is explained by disk emission (Lorenzetti et al., 2009). We note that CO first overtone emission is not detected in HD 190073.

HD 98922 has an unidentified emission line at 4.7485 $\mu$m, similar in line shape, but with a FWHM of 14 km/s slightly narrower than the CO emission lines.

4.4.7 Summary of observed trends in the CO emission

We have detected ro-vibrational fundamental $^{12}\text{CO}$ emission in 12 out of 13 surveyed HAEBE stars. The temperature of the CO gas in these objects
varies - with the exception of HD 141569 - between 900 and 2500 K. We have also detected $^{13}$CO emission in 8 of these objects, with temperatures between 720 and 1600 K, all lower than that of the $^{12}$CO gas in the same disks. The $T_{\text{rot}}$ of the CO gas in the self-shadowed disks is higher than that in the flaring disks, and there is a correlation between line shape and excitation temperature in at least 2 stars, but also a surprising lack of this correlation in the higher vibrational bands in the 3 flaring disks where we expect the line broadening to be the most prominent. In the flaring disks, the CO fundamental emission is exited high up the vibrational ladder, at least up to $v = 5-4$, but no CO overtone emission is detected. We have spatially resolved the 4.6 $\mu$m continuum emission in all flaring disks, and the CO emission in the two out of three flaring disks, with outer radii for the CO emission of at least 60 AU for
4. The structure of disks around HAEBE stars as traced by CO emission.

HD 97048 and 51 AU for HD 100546. There is highly excited CO fundamental and CO overtone emission in one target with a self-shadowed disk, HD 101412, but neither the CO emission nor the continuum emission have been spatially resolved. We also detect CO absorption toward two stars.

4.5 Discussion

4.5.1 CO rotational temperature

The assumption that the curvature in the Boltzmann plots is caused by optically thick gas, but using an optical thin model to derive its physical properties, has implications both on the derived column and temperature. For instance, Najita et al. (2003) show, using spectral synthesis modeling, that, if the CO emission is moderately optically thick, the temperatures derived with the optical thin approximation overestimates the excitation temperature by several hundreds of degrees for moderately optically thick gas, and even more for increasing optical thickness. A comparison of our results to the results of other authors who show overlap with our sample (Brittain et al., 2007, 2009; Salyk et al., 2009), and who use more detailed modeling of the CO gas, show that our estimates for all three cases are about 30 % higher. This makes the interpretation of the temperature difference between the $^{12}$CO and $^{13}$CO isotopes more challenging (see Section 4.5.3). The results we present here are based on an empirical fit to the higher ro-vibrational transitions, which we assume to be in the optical thin part of a Boltzmann plot.

4.5.2 CO vibrational temperature

In the vibrational populations of HD 97048, HD 100546, HD 179218, we observe a break at $v = 2-1$ (Figure 4.3). The populations of the vibrational bands with $v \geq 2$ reflect a temperature much higher than the rotational temperature of the gas, whereas the populations of the vibrational bands with $v \leq 2$ reflect a temperature close to the rotational temperature. To show this we have overplotted the predicted vibrational populations assuming a temperature equal to the averaged rotational temperature, scaled to the $v = 1-0$ population, in Figure 4.3.

All sources from our sample with a group I (flaring) disk have $T_{rot} < T_{vib}$. In these cases, we interpret the vibrational temperature as a reflection of the (diluted) blackbody temperature of the central star, and the rotational temperature as the local gas temperature. The group I central stars have temperatures between 10000 and 10500 K, which equals the vibrational temperature for HD 97048 and HD 179218. The vibrational temperature of HD 100546 is $\approx 6600$
4.5 Discussion

K, which indicates that the fluorescing UV field is more diluted. Because the CO emission in HD 100546 is resolved, and does not originate from farther out than in HD 97048 (c.f. Section 4.4.4), this could be due to the central star UV luminosity. HD 100546 has the lowest UV luminosity of the three (a factor 0.77 of the UV luminosity of HD 97048, and a factor 0.27 of the UV luminosity of HD 179218).

Both sources with $T_{\text{rot}} \geq T_{\text{vib}}$ have group II (self-shadowed) disks. These sub-thermal vibrational populations in the self-shadowed disk suggest that at least part of the CO emission originates from a region where the CO is not completely thermalized and is not exposed to the stellar UV radiation, e.g. in the low-density disk atmosphere.

4.5.3 Correlations between CO line width and temperature

The combination of the radial distance of the CO emission and temperature can be a powerful tool. We would expect the higher J and v transitions to form at higher temperatures, closer to the central star. The relatively weak lines in our sample, and the associated large errors on the FWHM determination, as well as the lack of CO emission close to the star in some cases - which makes the effect of hot/cold gas on the line widths less pronounced, can be causes that this expected behavior is not observed.

We wish to trace the CO as close as possible to its inner radius. Due to the quality of our data, it is difficult to assess where the line ends and the continuum starts. Therefore, we use the Half Width at 10% of the line Maximum (HW10M) as a compromise. We calculate the onset of the CO emission ($R_{\text{CO,10\%}}$) using this HW10M, the assumption of Keplerian rotation, and the stellar parameters from Table 4.1. In case of missing error estimates, we use an error of $\pm 10\%$ for the stellar mass, and $\pm 10^\circ$ for the inclination.

In Figure 4.7, we plot the dependence of $T_{\text{rot}}$ of the $^{12}\text{CO} \ v = 1\text{-}0$ emission on $R_{\text{CO,10\%}}$. If we disregard the disks with an inner hole (HD 141569, plot ID ‘5’) and the disk with a 45 AU gap around the T Tauri star (HD 135344B, plot ID ‘10’), there is a clear trend between the radial onset of the CO emission, and its $T_{\text{rot}}$. The CO gas is hot ($\approx 2000$ K) and located relatively close to the star for the self-shadowed disks. In the flaring disks, the CO emission comes from larger radii, and the $T_{\text{rot}}$ decreases accordingly, to $\approx 1200$ K.

$^{12}\text{CO}$ versus $^{13}\text{CO}$

The temperature difference between the $^{13}\text{CO}$ and $^{12}\text{CO}$ isotopes could be due to opacity effects, or due to a different radial location of the emitting gas. Adding kinematic information can break this degeneracy. In Figure 4.8
we compare the line widths of both isotopes, and show that the $^{13}$CO width in the flared disks is within error bars similar to the $^{12}$CO width, whereas the $^{13}$CO lines in the self-shadowed disks are more narrow, and thus originate further out. We also plot the ratio of the HW10M of both isotopes against the onset of the $^{12}$CO emission derived from the HW10M in Figure 4.9. This figure shows that the magnitude of the radial difference is a function of the onset of the $^{12}$CO emission, and that this difference decreases for increasing $R_{\text{CO,10\%}}$. We will get back to this with a qualitative interpretation in Section 4.5.5.

Figure 4.7: $^{12}$CO $v = 1-0$ rotational temperature as function of the onset of the CO emission as derived from the half width at 10% of the maximum flux. Sources are named according to column 1 from Table 4.1. Flaring disks are marked as triangles, self-shadowed disks as circles and disks with an inner opacity hole are labeled with open gray squares.
4.5 Discussion

To get an as complete census of the gas around the studied HAEBEs as possible, we complement the detected CO lines, HI recombination lines Pfβ and Huel and in one case the sodium doublet, with two other gas tracers. Here we present data on [OI] 6300 Å and Polycyclic Aromatic Hydrocarbon (PAH) emission, which both trace the PP disk surface at different radial regimes. [OI] traces the gas up to the inner disk, between ≈ 0.1 - 50 AU, and PAHs trace the outer disk, between ≈ 10 and 100 AU.

4.5.4 CO compared to other gas tracers

Figure 4.8: Correlation between the half line width at 10% of the maximum flux of $^{12}$CO and $^{13}$CO emission. Sources are named according column 1 from Table 4.1, flaring disks are marked as triangles, self-shadowed disks as circles. The 1:1 ratio is overplotted with a dotted line.
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![Figure 4.9](image)

**Figure 4.9**: Correlation between the ratio of the 10% widths and the onset of the $^{12}$CO emission as derived from the half width at 10% of the maximum flux. Sources are named according column 1 from Table 4.1, flaring disks are marked as triangles, self-shadowed disks as circles.

CO and [OI] emission

[OI] 6300 Å emission in HAEBE stars is the by-product of photo-dissociation of OH molecules. It traces those regions where FUV radiation impinges on the (OH, H$_2$O) gas in the atmosphere of circumstellar disks, and is commonly observed in HAEBE stars (Acke et al., 2005). Like fundamental CO emission, it traces the circumstellar disk from the innermost disk out to tens of AU. We interpret this emission as a tracer of the disk atmosphere, and show a comparison between the [OI] and CO emission lines in Figure 4.10. Except for HD 101412, the [OI] lines are much broader than the CO lines, with a HW10M ratio that is typically 2.5. We investigate this difference in line widths as a
function of the HW10M radii in Figure 4.11. The onset of the [OI] emission is relatively constant at 0.8 ± 0.4 AU, whereas the onset of the CO emission changes from less than 1 to 10 AU. The presence of this [OI] emission, together with the hydrogen recombination and sodium lines reported in Section 4.4.6, clearly shows that the lack of CO emission at small radii in some disks does not imply a scarcity of gas close to the star.

**CO and PAH emission**

PAHs are often detected and spatially resolved up to 100 AU scales in the disks around HAEBE stars, and are a main contributor to the PP disk gas temperature in the upper layers of the disk due to the photo-electric heating of the gas (see e.g. Woitke et al., 2009). For a complete review of PAHs, (see e.g. Tielens, 2008). Meeus et al. (2001) first suggested a possible correlation between the strength of the PAH features and the shape of the IR SED, which was recently confirmed by Acke & van den Ancker (2004); Habart et al. (2004); Acke et al. (2010). Acke et al. (2010) find that the PAH-to-stellar luminosity ratio is higher in disks with a flared geometry, but that a few of their sources with a flattened dust disk still show relatively strong PAH emission. Because PAH molecules trace the gas disk, they suggest that while the dust in these disks has already settled, the gas disk may still be flaring. This scenario of still flaring gas but settled dust has been previously suggested for two of our targets: HD 101412 (Section 4.5.4) and HD 95881 (Verhoeff et al., 2010). This scenario was also modeled and works if dust sedimentation is the dominant process in the disk. However, dust sedimentation does not explain the general trend of increasing PAH luminosity with increased flaring, but rather the opposite (Dullemond et al., 2007). We also add HD 98922 to this group based on the similarities in the dust (SED) and gas ([OI], PAH, CO ro-vibrational) diagnostics between HD 95881 and HD 98922.

We choose the 6.2 μm PAH band as a proxy for the PAH emission because the relative luminosity of this feature displays the strongest correlation with far-IR excess. Moreover, the 6.2 μm feature is easily detectable and the underlying continuum is featureless. We use the PAH-to-stellar luminosity ratio to eliminate uncertainties in distance. We show the PAH-to-stellar luminosity ratio based on Spitzer IRS (Acke et al., 2010) and ISO-SWS (Acke & van den Ancker, 2004) spectra, in Table 4.5.

We plot the CO inner radius against the PAH-to-stellar luminosity ratio in Figure 4.12. The self shadowed disks with no PAH detections have the smallest CO inner radii, and the inner CO radius increases with increasing PAH strength. The trend between disk-shape and PAH luminosity also holds for our sample, where the flaring disks show the strongest PAH emission, the
4. The structure of disks around HAEBE stars as traced by CO emission.

Figure 4.10: 6300 Å [OI] emission in filled gray histograms, and CO $v = 1-0 J \leq 15$ average line profiles in black, together with their 10% width [OI]/CO ratio. The CO emission of HD 141569 is averaged over the $v = 2-1$ lines, and because of problems with the telluric correction, we have used the high ($J_u \geq 30$) for R CrA and HD 190073. The CO line profile plotted for HD 101412 is a blend of the $^{13}$CO $v = 1-0 R(23)$ and the $^{12}$CO $v = 4-3 R(35)$ lines. We show [OI] data of HD 97048 and HD 100546 from Acke & van den Ancker (2006), of HD 101412, HD 135344B, and HD 179218 from van der Plas et al. (2008, Chapter 2), of HD 190073 from R. van Lieshout en T. Bagnoli (Both students at the University of Amsterdam, Observed with the HERMES spectrograph (R = 85000, http://hermes.sr.kuleuven.ac.be/) at the MERCATOR telescope, private communication), and from Acke et al. (2006) for the other stars. Note that both the CO and [OI] lines have been centered at 0 velocity, and the differing velocity scale for HD 141569.

Note: There is a mix-up in the labels of the axes in the figure. The correct labels are: normalized counts vs. velocity [km/s].
Figure 4.11: Correlation between the CO and [OI] inner radii. Sources with a flaring disk marked as triangles, self-shadowed disks as circles and disks with an inner opacity hole are labeled with open gray squares. Sources are named according column 1 from Table 4.1, and the 1:1 ratio is overplotted with a dotted line.

self shadowed disks are not detected or have very low PAH emission, and the disks with still flaring gas and self-shadowed dust, show intermediate PAH emission.

If we interpret our observations in the naive context of the 3 different disk ‘stadia’, where grain growth leads to dust settling and the change of the PP disk from flaring to self-shadowed can be interpreted as an evolutionary sequence, both the PAH and CO emission are influenced by this. The PAH emission decreases in strength and the CO emission shifts closer inwards as the disks change from flaring to self-shadowed. Because of the instrumental role of PAHs in heating the gas in the PP disk, it perhaps does not surprise
4. The structure of disks around HAEBE stars as traced by CO emission.

![Figure 4.12](image-url)

**Figure 4.12**: The CO inner radius and the $L_{PAH}^{6.2 \mu m}/L_\ast$ ratio. As the PAH luminosity ratio decreases, the inner radius of the CO emission moves closer in. Sources are named according to column 1 from Table 4.1, and divided into flaring (triangles), self-shadowed (circles), and flaring gas but self-shadowed dust (diamonds). Disks with an inner opacity hole are labeled with open gray squares.

that flaring disks with strong PAH emission show warm CO up to tens of AU. However, it is not yet clear what is the cause and what is the result in the correlation between disk geometry and the presence of CO/PAH.

**The special case of HD 101412**

HD 101412 is the only HAEBE star in our sample for which we detect both fundamental and first overtone CO emission, and where the CO line width is similar to the [OI] line width. The Spitzer-IRS spectrum of HD 101412 has an unusual shape due to the presence of strong PAH emission bands,
and its SED is typical for a self-shadowed disk. However, it also displays some characteristics typical for a flaring disk, such as extended PAH emission (Fedele et al., 2008), and bright [OI] emission (Acke et al., 2005) suggesting that this disk might be transitioning from flaring to self-shadowed. Fedele et al. (2008) and van der Plas et al. (2008, Chapter 2) have investigated the dust and gas components independently via high resolution spectroscopy of the [OI] 6300 Å line, and interferometry (VLT/MIDI). The 8-12 μm emission has been resolved, and can be modeled by a ring between 0.4 and 1.9 AU, and shows signs of asymmetry. The PAH feature at 11.3 μm is more extended than the continuum emission, and the [OI] emission shows 2 components: One originating from the inner rim, and the other between 6 and several tens of AU. Both [OI] and PAH emission are thought to trace the part of the disk atmosphere that is directly exposed to the stellar UV field. Their conclusion is that the gas and dust in the disk around HD 101412 are decoupled, with a gas disk that rises out of the shadow cast by the inner rim after ≈ 6 AU.

Based on the kinematics of the fundamental and first overtone emission (both have the same radial velocity as the central star, the line widths of the fundamental and first overtone emission are similar, but the line center is more filled in for the fundamental emission), the CO emission is constrained to the inner disk region. We show the line profiles of [OI], fundamental and first overtone CO emission in Figure 4.13.

The comparable [OI] and CO line widths demonstrate that the onset of their emission in disks around HAEBE stars can be co-spatial. As discussed above, the dust and gas in the outer disk of HD 101412 are decoupled, and the [OI] emission originates from two components: A high projected velocity component from the hot inner rim, and a lower projected velocity component further out. We test this interpretation to first order by over plotting scaled [OI] emission in Figure 4.13. The high projected velocity components of both the [OI] and the CO emission are indeed co-spatial, but the low projected velocity component seen in the [OI] is not detected in the CO emission.

The detection of [OI] and non-detection of CO emission further out in the disk demonstrates that the same trend as observed at small radii - [OI] becomes, for whatever reason (dust settling, CO depletion, photo-destruction of CO), visible sooner in the inner disk - also holds further out in the disk. HD 101412 has a flaring gas ([OI], PAH) disk but settled dust disk. This suggests that the CO emission originates from deeper in the disk (closer to the dust, where it is either protected from dissociation and/or can be thermalized), and the [OI] emission - as by-product of photo-dissociation - traces those regions of the disk where the stellar UV flux impinges on OH gas.
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Figure 4.13: Composite line profiles of CO fundamental and first overtone emission in HD 101412, smoothed over 2 bins for clarity. Overplotted (dotted histogram) is the [OI] emission, scaled vertically for the high velocity components to overlap.

4.5.5 A qualitative interpretation of the observed trends

A possible qualitative interpretation of the observed trends in our sample is the degree of dust settling in the disk. Initially disks have gas and dust well mixed and no significant depletion of dust from the upper disk layers has occurred yet. These disks have flaring disk geometries, and relatively strong PAH emission. The [OI] line is strong, and the CO is excited high up the vibrational ladder by UV fluorescence, because it is emitted from the disk surface which is directly irradiated by the central star. In these disks the gas and dust in the inner disk regions are well coupled and only in the outer disk, at distances beyond 5 to 10 AU, CO temperatures in the upper disk are sufficiently higher than the dust for a large enough column to be detected. As dust begins to settle, gas and dust temperatures begin to differ also in the inner disk regions. CO emission can now be detected from the inner disk regions.

In this picture, self-shadowed disks will have higher CO rotational temperatures and have broader CO lines than flaring disks, in agreement with observations. It also explains the behaviour of $^{13}$CO, which needs larger a larger column of gas to be detected. Such a larger column is reached at larger distance from the star, and so $^{13}$CO rotational temperatures should be lower and the lines should be narrower than $^{12}$CO, as observed. This difference disappears for disks with large CO inner radii, i.e. the flaring disks.
We stress that this picture is only qualitative and needs to be underpinned by 2D radiative transfer calculations of disks with different gas/dust properties. A second point to keep in mind is that our sample is modest and must be expanded to make more robust statistical claims.

4.6 Where is the CO?

CO fundamental emission is not a direct proxy for warm gas in the disks around HAEBE stars. The CO emission around flaring disks originates from larger radii than around self-shadowed disks, and in both types of disks there is circumstellar gas present closer to the central star. There is no correlation between the 4.77 μm continuum flux and radial CO location, ruling out contrast effects.

To investigate why the CO emission is not detected in the inner part of the disk, we compare the inner radius of the CO emission, \( R_{\text{CO,10\%}} \), with the naively expected cut-off of the inner disk, the dust sublimation radius at 1500 and 2000 K, and, when available, the radius of the inner rim as traced by 2μm interferometry. We calculate the dust evaporation radius following:

\[
R_{\text{subl}} = 0.035 \sqrt{Q_R} \sqrt{\frac{L_*}{L_\odot}} \left( \frac{1500}{T_{\text{subl}}} \right)^2
\]

with \( Q_R \) the ratio of the dust absorption efficiencies for radiation at color temperature \( T \) of the incident and re-emitted field. For a star of 10000 K, \( \sqrt{Q_R} \) varies between 1 and 4.5 for grain sizes between respectively 1.00 and 0.01 μm (Monnier & Millan-Gabet (2002), Figure 2). For our calculations we adopt \( \sqrt{Q_R} = 2 \), but we note that the choice for \( \sqrt{Q_R} \) used in the literature for T Tauri stars varies between 1 and 2, and that this value increases with the color temperature of the central star. We show the HW10M radii, the dust sublimation radii for 1500 and 2000 K, the radius of the inner rim as traced by 2μm interferometry, and the PAH-to-stellar-luminosity ratio in Table 4.5.

Inspection of Table 4.5 shows that the inner rim sizes determined from the hot dust loosely agree with a dust sublimation temperature between 1500 and 2000 K, and that the CO emission starts at the largest radii for flaring disks. In the flaring disks, the CO starts far beyond the calculated dust sublimation radius, at \( \approx 16-48 \) \( R_{\text{subl}} \). The disks with a self-shadowed dust disk, but still flaring gas, have intermediate CO inner radii, and the CO onset of the self-shadowed disks without flaring gas disks is approximately similar to \( R_{\text{subl}} \).

There are two outliers to this: HD 190073 and HD 98922, but we argue that they fall within the picture described, given the uncertainty in their stellar parameters. For HD 190073, the error on the inclination of 23 ± 15°, 23°.
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Table 4.5: The references for the 2 μm inner rim sizes in the fifth column are: "Monnier et al. (2006), IOTA, H band. "Eisner et al. (2009) (Keck, K band). "Kraus et al. (2008), VLTI/AMBER, K band. "Verhoef et al. (2010), VLTI/AMBER, K band. "Benisty et al. (2010), VLTI/AMBER, K band. PAH to luminosity ratios in the last column are adapted from Acke et al. (2010) and Acke & van den Ancker (2004). The upper limits are 3 σ, a(b) represents a x 10^a, and n.s. means no spectrum is available.

| Name          | 
|---------------|---------------|
|               | R_{CO,10%}   | R_{1500K} | R_{2000K} | R_{2000K,2μm} | L_{PAH}^{k,2μm} / L_∗ |
|---------------|---------------|
| Group I       | [AU]          | [AU]      | [AU]      | [AU]          |                         |
| HD 100546     | 6.8           | 0.45      | 0.25      | 0.26          | 1.30 ± 0.13 (-3)        |
| HD 197048     | 10.1          | 0.36      | 0.20      |               | 1.29 ± 0.01 (-3)        |
| HD 179218     | 9.2           | 0.61      | 0.34      | >3.1          | 1.65 ± 0.17 (-3)        |
| Group H       | [AU]          | [AU]      | [AU]      | [AU]          |                         |
| HD 101412     | 0.6           | 0.35      | 0.20      |               | 2.57 ± 0.05 (-4)        |
| HD 190073     | 1.9           | 0.64      | 0.36      | 0.62          | 9.61 ± 2.80 (-5)        |
| HD 98922      | 4.2           | 2.09      | 1.18      | 1.25          | d.s.                    |
| HD 95881      | 1.9           | 0.33      | 0.18      | 0.37          | 9.53 ± 0.08 (-4)        |
| HD 150193     | 0.5           | 0.28      | 0.15      | 0.71          | < 5.3 (-5)              |
| HD 104237     | 0.3           | 0.41      | 0.23      | 0.20          | < 5.3 (-6)              |
| Not classified| [AU]          | [AU]      | [AU]      | [AU]          |                         |
| HD 141569     | 10.4          | 0.25      | 0.14      |               | 8.70 ± 0.10 (-5)        |
| HD 135344B    | 0.3           | 0.22      | 0.13      |               | 2.74 ± 0.12 (-4)        |

degrees is large. Eisner et al. (2004) note that their data for HD 190073 is also consistent with an almost face-on inclination, and the high derived T_{rot} of 2420 K appears inconsistent with an inner CO radius of 1.5 AU. If we adopt an inclination of 12°, The best fit CO inner radius becomes 0.35 AU, the distance of the central star where T_{dust} = 2000K. For HD 98922, there exists ambiguity about the derived lower limit on the distance (Blondel & Tjin A Djie (2006) propose a distance of 200 parsec). If we scale the stellar luminosity accordingly down, _R_{subl} become 0.44 and 0.78 AU, for a temperature of 2000 and 1500 K respectively.

#### 4.6.1 Keplerian fits to the line profiles

In this chapter, we interpret the CO emission in the context a Keplerian rotating disk. We test this assumption with a simple disk model, and find that the bulk of the emission can be understood in the context of Keplerian rotation.

To investigate the spatial distribution of the CO emission, and to what extent the narrow (0.2”) slit obscures the disk and influences the line profiles, we create a basic model of the CO emission. In this model, the gas is in
Keplerian orbit in a flat disk with known inclination and PA around a star with known stellar mass and distance. The intensity of the emission decreases as \( I(R) = I_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\alpha} \), with \( \alpha = 2 \), \( I_{\text{in}} \) the intensity at the inner radius \( R_{\text{in}} \), and \( R \) the radial distance from the star. The simulated disk is then convolved with the observed telluric PSF to simulate the atmosphere, and finally we project the slit over the simulated disk and calculate the resulting line profile. HD 104237 and HD 98922 have no known disk PA's, and we assume those to be 0 degrees. We show these fits together with a sketch of the best fit disk+slit system in Figure 4.14.

Our model yields good fits for the line wings of the disks, but predicts a double peaked emission line where a single peaked line profile is observed for HD 98922, HD 135344B, HD 141569 and HD 190073. The lack of low projected velocity CO gas in the models of HD 98922, HD 135344B, HD 141569 and HD 190073 can be remedied by extending the outer radius of the disks. However, because the spectrograph slit truncates large parts of the outer disk, an outer radius \( > 100 \) AU is needed to fill in the double peak. We expect to resolve such disks given the orientation of the disk+slit system and their angular size. This line core 'problem' is also noted in 8 out of a sample of \( \sim 50 \) T Tauri stars by Bast et al. (submitted), and hints at an alternative process that also contributes to the line emission.

To illustrate the spatial aspect of the model, we compare the continuum subtracted spatial resolved CO emission with the best fit Keplerian model for the two spatially resolved sources with the highest SN data available in Figures 4.15 and 4.16. We subtract the continuum emission by sampling the continuum on the red side of the line and subtracting this of the line emission after scaling the continuum to the intensity of the telluric spectrum at each wavelength bin.

The CO emission in R CrA is also spatially resolved, but unlike the other targets only in one spatial direction, and the CO emission is blue shifted by 10 km/s with respect to the surrounding cloud. Considering also the positioning of the slit over the disk (Figure 4.14, bottom left panel), the likely origin of the CO emission is an outflow.

### 4.6.2 A comparison to CO emission from T Tauri stars

CO emission around T Tauri stars, the less massive siblings of HAEBE stars, is often detected at much smaller radii than in HAEBE stars. Najita et al. (2003) find an average FWHM of 70 km/s for 12 surveyed T Tauri stars, corresponding to inner radii of 0.02 - 0.05 AU, and conclude that most emission comes from (close to) the co rotation radius. Salyk et al. (2009) study 14
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Figure 4.1: Normalized composite line profiles (black histogram) and the best model fit (gray line). Also plotted are the respective simulated disk+slit (North is up, East is left), and the best fit CO inner- and outer radius used in the model. The line profile for HD 101412 is a mix of the $^{13}$CO $v_u = 1$ R(23) and $^{12}$CO $v_u = 4$ R(35) lines.
Figure 4.15: Top panel: Continuum subtracted position velocity plot of the v = 2-1 R(5) line in HD 97048. Middle panel: Simulated disk with $R_{in} = 11$ AU, $R_{out} = 68$ AU, and $\alpha = 2$. Bottom panel: Residue after subtraction of the model.
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Figure 4.16: Top panel: Continuum subtracted position velocity plot of the $v = 2-1$ R(5) line in HD 100546. Middle panel: Simulated disk with $R_{\text{in}} = 8$ AU, $R_{\text{out}} = 51$ AU, and $\alpha = 2$. Bottom panel: Residue after subtraction of the model.
transitional (circumstellar disks with an optically thick outer zone but an
inner region significantly depleted of small dust grains, of which 13 T Tauri
stars and 1 HAEBE star) disks, and find that the disks with partially depleted
inner disks most often have CO that extends to rather small (≤1 AU) radii,
but compared to “classical” disks the CO emission radii are larger than that
expected for dust sublimation.

CO emission in T Tauri stars thus probes distances as close as the co-
rotation radius, much closer to the central star than in HAEBE stars, and only
as the dust settles or gets depleted does the emission shift outwards. Possibly
because the paucity of small grains in the inner disks greatly enhances the gas
layer in full reach of the stellar UV photons, which in turn photo dissociates
the CO molecules. Compared to T Tauri stars, CO emission from HAEBE
stars originates from larger radii. To understand this behavior more detailed
modeling of combined circumstellar gas and dust is needed. This will be the
subject of chapter 6.

4.7 Conclusions

In this chapter we have presented detections of ro-vibrational fundamental
CO emission in 12 out of 13 surveyed HAEBE stars. We have investigated the
kinematics and temperature of this gas, and correlated these with disk dust
properties (the amount of flaring), and other disk-gas tracers: PAH and [OI]
emission. Keeping in mind the modest sample size, we report the following
trends between targets, and within the different isotopes and vibrational bands
for each target:

1. CO fundamental emission is common in disks around HAEBE stars;
2. CO first overtone emission is only detected in 1 out of 13 surveyed disks;
3. The $^{12}$CO temperature in flaring disks is lower than in self-shadowed
disks;
4. The CO emission in the flaring disks originates from larger distances
than the CO in self-shadowed disks;
5. The rotational temperature of the $^{13}$CO is lower than that of the $^{12}$CO,
but the $^{13}$CO line widths are not necessarily smaller than the $^{12}$CO widths.
This is probably a real physical effect and not due to the high opacity in the
$^{12}$CO lines;
6. There is a broadening of the emission lines as a function of excitation
temperature in the disks around stars (HD 98922 and HD 135344B), most
other targets are difficult to classify due to low S/N. The CO emission in
the higher vibrational bands of the flaring disks, however, does not show this
trend;
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[7] The 4.6 μm dust continuum emission in all three flaring disks, and the CO emission in two flaring disks, is spatially resolved;

[8] The dominant excitation mechanism for the CO vibrational band populations is thermal for self-shadowed disks, and fluorescence for flaring disks. In both cases, the rotational temperatures reflects the local gas temperature;

[9] fundamental CO emission from HAEBE disks, in contrast to T Tauri stars, does not necessarily trace the circumstellar disk up to, or inside the dust sublimation radius. Rather, the onset of the CO emission ranges between \( R_{\text{subl}} \) for self-shadowed disks, to tens of \( R_{\text{subl}} \) for flaring disks;

These findings are consistent with a picture where the CO emission is dominated by the disk surface, in flaring disks up to large distances, and in self-shadowed disks from much closer to the central star. There is a strong correlation between the dominant mode of CO excitation and the topology of the circumstellar dust disk. The disks that are flaring have line shapes that do not correlate with excitation energy; their higher vibrational bands are over populated compared to the expected values belonging to the rotational temperature of the gas; and their dust continuum and sometimes CO emission are spatially resolved up to tens of AU. The self-shadowed dust disks in contrast do not show these signs.

Why the CO emission in HAEBE disks originates from further out than for T Tauri stars, is a question we hope to answer in forthcoming work (van der Plas et al., in preparation, chapter 6).

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