GASPS observations of Herbig Ae/Be stars with PACS/Herschel*

The atomic and molecular content of their protoplanetary discs

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ABSTRACT

We observed a sample of 20 representative Herbig Ae/Be stars and five A-type debris discs with PACS onboard of Herschel. The observations were done in spectroscopic mode, and cover far-IR lines of [O \textsc{i}], [C \textsc{ii}], CO, CH, H$_2$O and OH. We have a [O \textsc{i}] 63 µm detection rate of 100% for the Herbig Ae/Be and 0% for the debris discs. [O \textsc{i}] 145 µm is only detected in 25 %, CO J=18-17 in 45 % (and less for higher J transitions) of the Herbig Ae/Be stars and for [C \textsc{ii}] 157 µm, we often found spatially variable background contamination. We show the first detection of water in a Herbig Ae disc, HD 163296, which has a settled disc. Hydroxyl is detected as well in this disc. CH$^+$, first seen in HD 100546, is now detected for the second time in a Herbig Ae star, HD 97048. We report fluxes for each line and use the observations as line diagnostics of the gas properties. Furthermore, we look for correlations between the strength of the emission lines and stellar or disc parameters, such as stellar luminosity, UV and X-ray flux, accretion rate, PAH band strength, and scattering. We find that the stellar UV flux is the dominant excitation mechanism of [O \textsc{i}] 63, with the highest line fluxes found in objects with a large amount of scattering and greatest PAH strength. Neither the amount of accretion nor the X-ray luminosity has an influence on the line strength. We find correlations between the line flux of [O \textsc{i}] 63 and [O \textsc{i}] 145, CO J = 18-17 and [O \textsc{i}] 6300 Å, and between the continuum flux at 63 µm and at 1.3 mm, while we find weak correlations between the line flux of [O \textsc{i}] 63 and the PAH luminosity, the line flux of CO J = 3-2, the continuum flux at 63 µm, the stellar effective temperature and the Br line luminosity. Finally, we use a combination of the [O \textsc{i}] 63 and $^{12}$CO J = 2-1 line fluxes to obtain order of magnitude estimates of the disc gas masses, in agreement of the values we found from detailed modelling of 2 HAEBEs, HD 163296 and HD 169142.

Key words. Stars – infrared, Astrochemistry, Line: identification, Protoplanetary discs

1. Introduction

Circumstellar discs around young stars are the sites of planet formation (e.g. Pollack et al. 1996, Alibert et al. 2005). During the first 10 Myr, the initially gas-rich disc will evolve into first a transitional and then a debris disc, while dispersing its gas content. The understanding of this dispersal process and what favours/hinders it is a crucial part of the planet formation puzzle, as the amount of gas present in a disc is crucial to determine whether gas giant planets can still be formed. Furthermore, the disc mass controls the migration of planetary bodies of all sizes, from gas giants to meter-sized planetesimals. Three components need to be characterised well: the disc geometry, the dust, and the gas content.

The disc geometry of young intermediate-mass stars, the Herbig Ae/Be stars (HAEBEs), is constrained through multi-wavelength imaging, interferometry, and radiative transfer modelling (e.g. Benisty et al. 2010). Meeus et al. (2001) empirically divided the HAEBE discs into group I (flared) and group II (flat). A general consensus exists that discs become flatter as dust grains grow and settle towards the midplane (Dullemond & Dominik 2004). Lately, several of the group I sources have been found to have an inner opacity hole in the disc (e.g. Grady et al. 2007, 2009), possibly due to a lack of small dust grains in the inner disc. In HD 100546, the gap may be caused by a planet (e.g. Bouwman et al. 2003, Tatulli et al. 2011).
In a study of 53 HAEBEs, 85% show a silicate emission feature at 10 μm with a variety in grain size and crystallinity, proving the presence of warm small grains in these discs (Juhász et al. 2010). Polycyclic Aromatic Hydrocarbons (PAH) features were clearly detected in 70% of the sample, with a clear preference towards flared discs (Acke et al. 2010). PAHs located in the disc atmosphere are transiently excited by UV photons and are an important heating source for the gas in the disc surface through the photo-electric effect.

The study of gas properties is difficult as, in general, emission lines are rather weak. Different gas species and transitions probe different regions in the disc: lines in the near- and mid-IR generally trace the inner disc (<10-20 AU), while lines in the far-IR and mm mainly trace the outer disc. We refer to Carmona et al. (2010) for a discussion of different gas tracers, their location in the disc and observational characteristics. To understand the disc radial and vertical structure, it is necessary to observe several transitions of different species, as they arise under different conditions (density, temperature, radiation field). H2 and CO lines are most often used, since they are the most abundant species present, with the canonical H2 lines having a number ratio in the ISM being 104. However, the detection of H2 in the disc has proven to be difficult because of its weak rotational and ro-vibrational transitions - it has only been detected in 3 HAEBEs. In a survey of 15 Herbig Ae/Be stars with CRITRES, Carmona et al. (2011) detected ro-vibrational transitions of H2 at 2.1218 μm in only two objects: HD 97048 and HD 100546. Earlier, Bittner et al. (2008), Carmona et al. (2008), Martin-Zaidi et al. (2009) searched for mid-IR pure rotational lines of H2 at 17.035 μm in a sample of in total 20 HAEBEs; only two detections were made, in AB Aur and HD 97048. In sharp contrast, the detection of CO, although much less abundant, is easier as its rotational/ro-vibrational lines are much stronger. CO is routinely detected in HAEBEs (e.g. Thi et al. 2001, Dent et al. 2005). Lorenzetti et al. (2002) showed ISO/LWS observations of atomic and molecular lines in the far-IR for a sample of HAEBEs. They detected the fine-structure lines of [O ii] 63 & 145.5 μm and [C ii] at 157.7 μm.

Despite the wealth of observations, it is still not clear how HAEBE discs dissipate with time. In the less massive T Tauri stars, disc dispersal is thought to be initiated by photo-evaporation, mainly due to ionising EUV (hv > 13.6 eV) photons that first create a gap in the inner disc, which is subsequently rapidly viscously accreted. In a next step, the outer disc is efficiently removed through a photo-evaporative disc wind (Alexander et al. 2006). However, Gorti et al. (2009) showed that UV can rapidly disperse the outer disc, where the bulk of the disc mass is located, thus setting the disc lifetime. Also X-rays are thought to play an important role in those discs (e.g. Ercolano et al. 2008, Owen et al., 2012). And finally, also the accretion of a planet with a mass of a few Jupiter can play an important role in the dissipation of the disc. Which mechanism is ultimately dominating the dispersion process is not yet determined.

We present ESA Herschel Space Observatory (Pilbratt et al. 2010) spectroscopy of 20 HAEBEs and 5 A-type debris discs, covering several transitions of abundant atoms and molecules that can be used as crucial tests of our understanding of disc physics and chemistry in the upper layers of the disc. The observations cover a significant part of the disc surface that was not accessible before. Our observations are part of the Herschel Open Time Key Programme (OTKP) "GAS in Protoplanetary Systems" (GASP; P.I. Dent; see Dent et al. 2012). With this paper, we want to obtain a better understanding of HAEBE discs by relating several gas tracers and excitation mechanisms with stellar and disc properties. What gas species are present in a HAEBE disc and at what temperatures? What is the physical and chemical structure of the disc chemistry? What is the dominant excitation mechanism of gas in HAEBE discs?

In Sect. 2, we describe the sample and our methods to derive the stellar and disc parameters. In Sect. 3, we present the spectroscopy and the line detections. We discuss gas lines as a diagnostic tool in Sect. 4 and look for correlations between the observed line fluxes. We relate our detections and upper limits to stellar and disc parameters in Sect. 5. Finally, we round off with conclusions in Sect. 6.

2. Targets

The sample consists of 20 Herbig Ae/Be stars with spectral types ranging between B9.5 and F4, to which we will refer as Herbig Ae (HAe) stars. We do not include the more massive Herbig Be stars which are, in general, younger and have smaller discs and often an additional remnant envelope (e.g. Natta et al. 2000, Verhoef et al. 2012). We also include HD 141569A, an object that completely lacks a near-IR excess for λ < 4.5 μm, attributed to inner disc clearing, but still has a substantial amount of primordial gas; in this paper, we will call this a transitional disc. We are aware that several of our sources are also called pre-transitional discs in the literature, such as HD 100546 (Grady et al. 2005) and HD 135344B (Andrews et al. 2011), which are observed to have a gap in their disc, but for the purpose of this paper, we include them in the HAe sample, since they still have a substantial near-IR excess and their total IR excess is much larger than that of HD 141569A. Besides the Herbig Ae sample, we include five debris discs around A-type stars with ages between ~10 and 1200 Myr for comparison, as the Herbig Ae stars are seen as their precursors. We list the main stellar parameters in Table 1. The sample is representative for the known Herbig Ae stars: there are nine objects in Meeus group I and ten in group II (to which we will refer as flaring and flat discs). Furthermore, we have a good coverage of T \textsubscript{eff}, age, stellar luminosity L, and accretion rate. 49 Cet is the only debris disc in our sample for which gas was detected through CO observations with the JCMT (Dent et al. 2005). Hughes et al. (2008) later resolved the CO gas emission using the SMA.

For 3 stars in our sample, members of the GASPS team have performed detailed modeling of their discs with the radiative transfer code MCFOST (Pinte et al. 2006, 2009) and the thermo-chemical code ProDiMo (Woitke et al. 2009a): HD 169142 (Meeus et al. 2010), HD 100546 (Thi et al. 2010) and HD 163296 (Tilling et al. 2012).

2.1. Stellar and disc properties

To characterize the sample in a consistent way, we first aimed at determining the stellar component of the spectral energy distribution (SED). In the next step, several parameters that can be important in the context of gas excitation in the disc were computed, namely, ultraviolet luminosities, infrared excesses, and accretion luminosities.

We compiled a set of literature and catalogue stellar parameters (effective temperatures, gravities and metallicities), and critically selected what we considered the best. Multi-wavelength photometry from different sources and ultraviolet spectra obtained by the International Ultraviolet Explorer

\footnote{http://sdc.cab.inta-csic.es/ines/}
Table 1. Main stellar parameters of the stars.

| Star      | Alternative Name | Sp. Type | $T_{\text{eff}}$ (K) | log $g$ | [M/H] | Refs. | $d$ (pc) | $L_*/L_{\odot}$ | $\dot{M}$ | Age (Myr) |
|-----------|------------------|----------|----------------------|--------|-------|-------|---------|---------------|----------|-----------|
| AB Aur    | HD 31293         | A0 Ve    | 9280 4.00            | 0.00   | 0.00  | 1     | 139.3 ± 19.0 | 33.0 ± 9.2  | 0.25     | 5.0 ± 1.0   |
| HD 31648  | MWC 480          | A3-5 Ve  | 8250 4.00            | 0.00   | 0.00  | 2     | 137.0 ± 26.2 | 13.7 ± 5.5  | 0.16     | 8.5 ± 2.0   |
| HD 35187  | MWC 758          | A5 IVe  | 7700 3.50            | –0.08  | –0.14| 4     | 279.3 ± 75.0 | 33.7 ± 19.3 | 0.16     | 3.7 ± 2.0   |
| HD 97048  | MWC 36910        | F3 Ve    | 6900 4.35            | 0.00   | 0.00  | 3     | 114.2 ± 32.4 | 17.4 ± 10.6 | 0.78     | 9.0 ± 2.0   |
| HD 36141  | MWC 863          | A2 Ie    | 8915 4.00            | 0.00   | 0.00  | 4     | 3.5 ± 2.0    |             |           |           |
| HD 100453 | MWC 758          | A9 Ve    | 7700 4.20            | +0.30  | 0.00  | 6     | 121.5 ± 9.7  | 8.8 ± 1.4   | 0.00     | 10.0 ± 2.0  |
| HD 100546 | B9 Ve            | 10470 3.50| –0.08               | –1.30  | 4     | 96.9 ± 4.0  | 22.7 ± 1.9  | 0.09     | 9.0 ± 2.0   |
| HD 104237 | DX Cha           | A4-5 Ve  | 8550 3.90            | +0.16  | 8     | 114.7 ± 4.7 | 28.8 ± 2.4  | 0.16     | 5.5 ± 0.5   |
| HD 135344 B| SAO 206462      | F3-4 Ve  | 6810 4.40            | +0.14  | 10.4  | 142.0 ± 27.0| 8.1 ± 3.1   | 0.37     | 10.0 ± 2.0  |
| HD 139614 | A7 Ve            | 7400 4.00| –0.50               | –0.08  | 4     | 140 ± 42   | 7.6 ± 4.6   | 0.00     | 9.2 ± 2.0   |
| HD 141569 A| B9.5 Ve         | 10000 4.28| –0.50               | –1.30  | 4     | 116.1 ± 8.1 | 29.6 ± 4.2  | 0.37     | 4.7 ± 0.3   |
| HD 142527 | F6 IIIe          | 6250 3.62| 0.00                 | 12     | 233.1 ± 56.2| 33.2 ± 16.9 | 0.59     | 7.0 ± 0.5   |
| HD 142666 | A8 Ve            | 7500 4.30| +0.20               | 6      | 145 ± 43 | 13.5 ± 8.0 | 0.93     | 9.0 ± 2.0   |
| HD 144668 | HR 5999          | A7 IVe  | 7925 4.00            | 0.00   | 13     | 162.9 ± 15.3| 50.8 ± 9.5  | 0.47     | 2.8 ± 1.0   |
| HD 150193 | MWC 863          | A2 Ie    | 8970 3.99            | 0.00   | 2     | 216.5 ± 76.0| 48.7 ± 38.0 | 1.55     | 3.8 ± 2.0   |
| HD 163296 | MWC 275          | A1 Ve    | 9250 4.07            | +0.20  | 14     | 118.6 ± 11.1| 33.1 ± 6.2  | 0.47     | 5.5 ± 0.5   |
| HD 169142 | MWC 925          | A7-8 Ve  | 15000 4.50           | –0.50  | 15     | 145 ± 43 | 9.4 ± 5.6 | 0.00     | 7.7 ± 2.0   |
| 49 Cet    | HD 9672          | A4 V     | 9500 4.30            | +0.10  | 2      | 59.4 ± 10 | 21.0 ± 0.7 | 0.22     | 8.9 ± 2.46 |
| HD 32297  |                  | A0 V     | 9520 4.15            | 0.00   | 0.00  | 18    | 112.4 ± 10.8| 10.9 ± 2.1  | 0.62     | –           |
| HR 1998   | MWC 36878        | A2 IV-V | 8500 4.27            | –0.76  | 9, 19  | 21.6 ± 0.1| 14.0 ± 0.1 | 0.00     | 1250 ± 250 |
| HR 4796 A | HD 109573 A      | A0 Ve    | 9750 4.32            | 0.00   | 9     | 72.8 ± 1.8| 23.4 ± 1.1 | 0.00     | 10.0 ± 2.0  |
| HD 158352 | HR 6507          | A7 V     | 7350 3.85            | 0.00   | 9     | 59.6 ± 0.9| 17.7 ± 0.6 | 0.00     | 1000 ± 200  |

Notes: Quantities in italics are assigned. (a) These metallicities are weighted averages of all the elemental abundances listed in Tables 2, 3 and 4 of Acke & Waelkens (2004), see Appendix A of Montesinos et al. (2009) for details; (b) [c/d] Metallicities assumed to be in the same proportion as the species [Fe ii]/([Si ii]/[Fe ii], respectively (see Table 3 of Acke & Waelkens, 2004). Refs.: (1) Woitke et al. (GASPS) (in prep), (2) Montesinos et al. (2009), (3) Manoj et al. (2006), (4) Acke & Waelkens (2004), (5) Testi et al. (2003), (6) Guimarães et al. (2006), (7) Levenhagen et al. (2006), (8) Fumel & Böhm (2011), (9) Allende-Prieto et al. (1999), (10) Müller et al. (2004), (11) Merin et al. (2004), (12) Verbunt et al. (2011), (13) van Boekel et al. (2005), (14) Tilling et al. (GASPS) (2012), (15) Meeus et al. (GASPS) (2010), (16) Herbig (2005), (17) Carmona et al. (2007), (18) Torres et al. (2006), (19) Gray (2006). Distances are from the revised parallaxes by van Leeuwen (2007) except for HD 135344 B (Müller et al. 2011) and HD 139614, HD 142666 and HD 169142 (van Boekel et al. 2005).
Table 2. Derived properties of the sample. Disc group classification from Meeus et al. (2001) and Acke et al. (2010). For the derivation of $L_{IR}/L_\odot$, $L_{UV}/L_\odot$ and $log L_{acc}/L_\odot$, see the description in Sect. [2.1].

| Star  | Disc group | $L_{IR}/L_\odot$ | $L_{UV}/L_\odot$ | $log L_{acc}/L_\odot$ |
|-------|------------|------------------|------------------|-----------------------|
| AB Aur | II         | 0.76             | 4.63             | < 0.55                |
| HD 31648 | II          | 0.46             | 0.75             | < 0.19                |
| HD 35187 | II          | 0.12             | 2.23             | 1.13                  |
| HD 36112 | II          | 0.66             | 1.32             | < -0.81               |
| CQ Tau | II         | 1.01             | 0.19–0.3         | < -1.16               |
| HD 97048 | I          | 0.39             | 7.69             | < 0.95                |
| HD 100453 | I         | 0.62             | 0.29             | < -0.91               |
| HD 100546 | I          | 0.56             | 7.22             | 1.62                  |
| HD 104237 | II         | 0.32             | 1.54             | 0.87                  |
| HD 135344 B | I        | 0.56             | 0.11+           | -0.22                 |
| HD 139614 | I          | 0.39             | 0.39             | < -1.12               |
| HD 141569 A | II/TO      | 0.09             | 6.83             | < 0.70                |
| HD 142527 | I          | 0.98             | 0.15+           | < -1.04               |
| HD 142666 | I          | 0.33             | 0.37–0.68       | 0.85                  |
| HD 144668 | I          | 0.51             | 1.55–2.94       | < 0.23                |
| HD 150193 | II          | 0.48             | 8.53             | 1.32                  |
| KK Oph A+B | II         | 2.01             | 2.35             | 1.70                  |
| 51 Oph | II          | 0.03             | 71.32            | < 0.37                |
| HD 163296 | I          | 0.29             | 3.21–5.58       | <0.04                 |
| HD 169142 | I          | 0.42             | 0.45             | < -0.05               |
| 49 Cet | Debris     | 6.0×10^{-4}     | 2.96             | < -0.11               |
| HD 32297 | Debris     | 0.003            | 1.91+           | –                     |
| HR 1998 | Debris     | 6.6×10^{-5}     | 1.25             | –                     |
| HD 4796 A | Debris     | 0.003            | 5.59             | –                     |
| HD 158352 | Debris    | 1.6×10^{-4}     | 0.64             | –                     |

Notes: Disc groups I and II refer to Meeus et al. (2001) classification, "TO" stands for "Transition Object". (a) UV fluxes measured on the model photosphere (no UV observations available).

The age estimations were done by placing the values of $log T_{eff}$ - $log L_\odot$ for each star on an HR diagram containing tracks and isochrones computed for its particular metallicity. For some stars this parameter is unknown, therefore a solar abundance was assumed, which introduces an uncertainty which is difficult to estimate. Metallicity is an important parameter to take into account when determining ages using this procedure since the position of a set of tracks and isochrones in the HR diagram changes substantially with metallicity. The evolutionary tracks and isochrones for a scaled solar mixture from the Yonsei-Yale group (Yi et al. 2001) – Y2 in their notation – have been used in this work. From the $Y^2$ set, the isochrones with $Z = 0.02$ (solar) have been used for those stars with measured metallicities [M/H] between $-0.10$ and $+0.10$ and for the stars for which no abundance determinations are available. The remaining metallicities are treated with the isochrones in the grid whose value of $Z$ is closer to 0.02 × 10^{[M/H]}.

There is one star (HD 32297) for which a determination of the age was impossible; its position falls below the main sequence in a $Z = 0.02$ HR diagram, therefore, it is quite likely that this star has subsolar abundance. The evolutionary stage of 49 Cet is interesting and was studied in detail in Montesinos et al. (2009). Two ages, corresponding to PMS and MS isochrones, are listed in Table 2.

2.1.1. KK Oph

Special attention had to be paid to KK Oph. This object is a close binary separated by 1.61 arcsec (300 AU at our adopted distance, see discussion below; Leinert et al. [1997], the hot component (A) is a Herbig Ae star and the cool component (B) is a T Tauri star, both of them actively accreting (Herbig, 2005, and references therein). The SED shows an infrared excess from 1 to 100 µm, for each star on an HR diagram containing the 10-23 and $188.77–190.30 \mu$m. The observation identifiers (obsids) can be found in Table A.1 of Appendix A. In a later stage, we obtained PACS (Poglitsch et al. 2010) spectroscopy.

Table 3. Ranges and lines targeted with the PACS spectrometer.

| Set | Observed Range | Species | Transition | Wavelength (µm) |
|-----|----------------|---------|------------|-----------------|
| A   | 62.68 – 63.68   | [O I]   | $^2P_1 \rightarrow ^2P_3$ | 63.184       |
|     | 188.77 – 190.30 | H$_2$O  | $^2P_1 \rightarrow ^2P_3$ | 63.324       |
| B   | 71.90 – 73.05   | CH      | $^2P_1 \rightarrow ^2P_3$ | 63.946       |
|     | 144.0 – 146.1   | H$_2$O  | $^2P_1 \rightarrow ^2P_3$ | 144.518      |
| C   | 78.55 – 79.45   | OH      | $^2P_1 \rightarrow ^2P_3$ | 78.741       |
|     | 157.1 – 158.9   | CH      | $^2P_1 \rightarrow ^2P_3$ | 157.741      |
| D   | 89.45 – 90.50   | H$_2$O  | $^2P_1 \rightarrow ^2P_3$ | 158.309      |
|     | 178.91 – 181.0  | CH      | $^2P_1 \rightarrow ^2P_3$ | 179.527      |
|     | 180.488         | OH      | $^2P_1 \rightarrow ^2P_3$ | 180.488      |

3. Herschel PACS spectroscopy

We obtained PACS (Poglitsch et al. 2010) spectroscopy in both line and range modes (PacsLineSpec, 1669s and PacsRangeSpec, 5150s). The observation identifiers (obsids) can be found in Table A.1 of Appendix A. In a later stage, we obtained deeper range scans to confirm tentative detections by doubling the integration time for 7 sources. All the observations

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were carried out in ChopNod mode, in order to remove the emission of the telescope and background. PACS is an IFU with 25 spaxels, 9.4 arcsec on each side. Due to the characteristics of the PSF at 60\,\mu\text{m}, only \sim 70\% of a point source flux falls in the central spaxel, with a decrease towards longer wavelengths, down to 45\% at 180\,\mu\text{m}.

The spectroscopic data were reduced with the official release version 8.0.1 of the Herschel Interactive Processing Environment (HIPE; Ott 2010), using standard tasks provided in HIPE. These include bad pixel flagging; chop on/off subtraction; spectral response function division; rebinning with oversample = 2 and upsample = 1, corresponding to the native resolution of the instrument; spectral flattening and finally averaging of the two nod positions. In order to conserve the best signal and not to introduce additional noise, we only extracted the central spaxel, and corrected for the flux loss with an aperture correction provided by the PACS instrument team (\texttt{pointSourceLossCorrection.py}). This is only possible when the source is well-centered. If that was not the case (e.g. for HD 142666), several spaxels needed to be taken into consideration to obtain the full target’s emission.

The main lines targeted are the fine structure lines of \([\text{O}\,\text{i}]\), \([\text{C}\,\text{ii}]\) and the molecular lines of CO, OH, CH\(^+\) and H\(_2\)O. In total we observed eight spectral regions; the details of the transitions can be found in Table 1. The spectral resolution varies between 3400 (shortest wavelengths) and 1100 (longest wavelengths), which are equivalent to \sim 88\,\text{km s}^{-1} at 60\,\mu\text{m}, and 177\,\text{km s}^{-1} at 190\,\mu\text{m}. In our sample, we do not resolve the emission lines as our objects do not have such high-velocity components. The line flux sensitivity is of the order a few \(10^{-2}\) W/\text{m}\(^2\). The line fluxes were extracted using a gaussian fit to the emission lines with a first-order polynomial to the continuum. We used the RMS on the continuum (excluding the line) to derive a 1\sigma error on the line by integrating a gaussian with height equal to the continuum RMS and width of the instrumental FWHM. This approach is necessary as HIPE currently does not deliver errors for the spectra. In case of a non-detection, we give a 3\sigma upper limit, also calculated from the continuum RMS. The absolute flux calibration error given by the PACS instrument team is currently <15\%. The measured line fluxes - in case of detection - or their upper limits are listed in Tables 4 and 5. Several atomic and molecular lines were observed, as described in the following paragraphs.

3.1. Oxygen fine structure lines

The third most abundant element in the interstellar medium is oxygen. Its fine structure line at 63.2\,\mu\text{m} is by far the strongest line observed in our spectra (see Table 1). It is detected in all Herbig Ae/Be stars, and absent in the debris discs. For five of our objects, the line flux is larger than \(200 \times 10^{-18}\) W/m\(^2\), while our faintest detection is \(20 \times 10^{-18}\) W/m\(^2\). The other fine structure line \([\text{O}\,\text{i}]\) 145\,\mu\text{m} is also one of the strongest lines in our spectra, however it is only detected in five objects (25\% of the HAEBES).

In Figs. 1 and 2 we show the spectra centered on \([\text{O}\,\text{i}]\) 63 and \([\text{O}\,\text{i}]\) 145\,\mu\text{m} for the whole sample.

| Star     | \([\text{O}\,\text{i}]\) 63.18 | \([\text{O}\,\text{i}]\) 145.53 | \([\text{C}\,\text{ii}]\) 157.75 |
|----------|-----------------|-----------------|-----------------|
| AB Aur   | 851.2 (21.5)    | 44.6 (14.7)     | 51.0 (8.3)      |
| HD 31648 | 94.9 (3.5)      | < 7.8           | < 9.7           |
| HD 35187 | 32.8 (4.8)      | < 4.6           | < 5.9           |
| HD 36112 | 37.3 (2.4)      | < 6.3           | < 9.6           |
| CQ Tau   | 47.9 (4.0)      | < 3.8           | < 11.3          |
| HD 97048 | 1592.5 (4.3)    | 65.6 (2.6)      | 106.8 (6.3)     |
| HD 100453| 61.6 (7.5)      | < 6.1           | < 15.4          |
| HD 100546| 6043.4 (13.4)   | 194.7 (9.9)     | 203.8 (8.6)     |
| HD 104237| 79.1 (3.5)      | < 5.9           | < 7.6           |
| HD 135344B| 47.9 (5.6)    | < 4.6           | < 6.4           |
| HD 139614| 44.5 (6.1)      | < 4.7           | < 8.3           |
| HD 141569A| 245.3 (4.8)    | 24.9 (1.4)      | 11.4 (2.1)      |
| HD 142527| 52.3 (3.8)      | < 11.6          | < 28.7          |
| HD 142666| 18.9 (3.1)      | < 4.7           | < 9.0           |
| HD 144668| 140.2 (4.3)     | < 5.8           | < 5.4           |
| HD 150193| 24.6 (2.8)      | < 6.6           | < 5.3           |
| KK Oph   | 172.8 (5.0)     | 6.2 (1.3)       | 9.2 (1.2)       |
| 51 Oph   | 53.3 (2.5)      | < 5.1           | < 6.8           |
| HD 163296| 208.4 (4.2)     | < 4.0           | ABS            |
| HD 169142| 91.5 (4.4)      | < 3.6           | < 8.0           |

49 Cet   < 0.10          < 0.3           < 9.1
HD 32297 < 7.4           < 4.2           < 7.1
HR 1998  < 7.0           < 5.1           < 6.6
HR 4796A < 6.3           < 3.8           < 5.4
HD 158352< 8.2           n.a.           < 3.8

3.2. Carbon fine structure line

When detected, the \([\text{C}\,\text{ii}]\) 157.7\,\mu\text{m} line can be strong - more than \(100 \times 10^{-18}\) W/m\(^2\). However, it is only seen in six objects (30\% of the HAEBEs; see Fig. 3) - these are the same objects for which \([\text{O}\,\text{i}]\) 145\,\mu\text{m} was also detected (see Table 1), apart from HD 3612. The low detection rate for \([\text{C}\,\text{ii}]\) is surprising, given the high detection rate (83\%) in ISO/LWS spectra reported by Lorenzetti et al. (2002). This can be attributed to a difference in aperture: 80 arcsec for LWS versus 9 arcsec for PACS. Moreover, we noticed that the line can also be present in the off-source chop positions (in a spatially variable amount), contaminating our spectra. In two cases, the dominating emission is present in all on and off-source spaxels, so that our chop-off subtracted spectra even show the feature in absorption as the chop-off position shows stronger emission (HD 142527 and HD 163296, see Fig. 3). The interpretation of the \([\text{C}\,\text{ii}]\) emission line is complex. Besides originating in the disc, it could also form in the remaining envelope, or simply in cloud material in the line of sight. A detailed analysis of background \([\text{C}\,\text{ii}]\) emission is beyond the scope of this paper, but a dedicated study is underway (Pantin et al., in preparation).

3.3. Carbon monoxide

In our PACS ranges, we cover four transitions of the CO molecule: \(J=3-36\) (72.85\,\mu\text{m}), \(J=33-32\) (79.36\,\mu\text{m}), \(J=29-28\) (90.16\,\mu\text{m}) and \(J=18-17\) (144.78\,\mu\text{m}). These are all mid to higher \(J\) transitions, with \(E_{\text{up}}\) between \sim 950 and 3700 K. The
highest $J$ transitions in our settings ($J=36-35$ and $J=33-32$) are not detected in any star of our sample. In Fig. 4, we show the region around 90 $\mu$m, covering the CO $J=29-28$ transition. This CO line is only clearly seen in AB Aur and HD 100546, with a tentative detection for HD 97048. For the lowest $J$ observable (18-17, at 144.78 $\mu$m) we see many more detections in our spectra (see Fig. 2): it is detected in nine objects, and there is one tentative detection, for HD 169142. The strongest CO lines are observed in AB Aur, HD 97048 and HD 100546. HD 141569A is the only star for which we have a clear (more than 5$\sigma$) detection of [O\textsc{i}] 145 $\mu$m, but no detection of CO at 144.78 $\mu$m, showing that both species trace different excitation conditions and chemistry (atomic versus molecular). We will discuss this further in Sect. 4.3.

3.4. Hydroxyl

With our settings, we only cover the OH doublet at 79.11/79.18 $\mu$m. In Fig. 5 we can see evidence for the doublet in HD 100546 and HD 163296; however, the only 3 $\sigma$ detection (of one line of this doublet) is found in AB Aur and HD 163296 (see Table 6). Sturm et al. (2010) detected several OH lines at
Table 6. Molecular line strengths of H$_2$O, hydroxyl and CH$^+$ for the sources with at least one detection in these lines. Line flux in units of $10^{-18}$ W/m$^2$, 1$\sigma$ continuum RMS between brackets in case of a detection or, in case of a non-detection, 3$\sigma$ upper limits. With ‘:’ we indicate that the feature is between 2 and 3$\sigma$. At 90 and 179.5 µm, there is a possible blend of CH$^+$ and H$_2$O. For the water lines, we also give the upper energy level in K.

| Star   | o-H$_2$O | o-H$_2$O | CH$^+$ | o-H$_2$O | OH    | OH     | CH$^+/p$-H$_2$O | CH$^+/o$-H$_2$O | o-H$_2$O |
|--------|----------|----------|--------|----------|-------|--------|-----------------|-----------------|----------|
| $\lambda$ (µm) |          |          |        |          |       |        |                 |                 |          |
| AB Aur | 63.32    | 71.946   | 72.14  | 78.74    | 79.11 | 79.18  | 90.00          | 179.52          | 180.42   |
| $E_\text{up}$ (K) | 1071.0   | 843.5    | 432.2  |          |       |        |                 |                 |          |
| HD 31648 | <29.8    | <19.0    | <36.7  | <26.5    | 24.6  | (7.9)  | <24.8          | <18.4           | <13.5    |
| HD 97048 | <16.4    | <16.8    | <18.6  | <18.2    | <17.0 | <18.9  | 17.4 (4.9)     | 18.3            | 13.8     |
| HD 100546 | <25.9    | <50.9    | 127.5  | (7.0)    | <57.0 |        | <41.9          | <42.1           | 116.0    |
| HD 163296 | 14.2     | 16.5     | 50.3   | <19.9    | 10.2  | (4.1)  | 11.4 (3.4)     | <9.1            | 4.7      |

Fig. 2. The settings around 145 µm. The lines of CO J=18−17 at 144.8 µm and [O i] 145 µm are only clearly detected in a three objects.

Far-IR wavelengths (53-200 µm) in the SED-mode PACS spectra of HD 100546.

3.5. Water

The only star in our sample with convincing evidence for water is HD 163296. The measured line fluxes are listed in Table 6. While the feature at 63.32 µm is seen in HD 163296 with 3$\sigma$ confidence, we list it as a tentative detection given the spurious absorption feature next to it (in HD 31648, a potential feature of water at 63.32 µm is redshifted by 0.009 µm so we also consider it a tentative detection). Also in our deeper range scans at 71.946 and 78.74 µm we see evidence for water in HD 163296 (see Fig. 5). The features are close to 3$\sigma$, however, the fact that we do see emission lines at the positions where water lines are predicted to be present further strengthens the detection of water in HD 163296. The analysis of the water in HD 163296 will be presented in a separate paper (Meeus et al. 2012).

In two other objects, HD 97048 and HD 100546, we do see several emission lines at the position of water. In Fig. 3 we show the region around 90 micron, where the transition of para-H$_2$O can appear. However, when we zoom in on these stars in the regions where other water lines are expected to be present, we get a different picture; in Fig. 5 we show the spectra covering water lines. At 90.00 µm (see Fig. 5), we do see an emission peak for both stars, which could be the para-H$_2$O line at (89.988 µm), but it is a blend with CH$^+$ at 90.02 µm. At other positions of water, which are not blended with CH$^+$, we do not see any emission line: 71.948, 78.741 and 78.93, 180.488 µm).

To summarise, the only times we detect an emission feature at the position of a water line in these two objects, is in a blend...
with CH$^+$. We can conclude that there are no H$_2$O emission lines detected in these two objects at the sensitivity of our observations. Therefore, we do not confirm the detection of water in HD 100546 reported by Sturm et al. (2010) as also seen in a later improved reduction of the original data (Sturm, priv. comm.).

3.6. CH$^+$

Thi et al. (2011) reported the first detection of CH$^+$ in a Herbig Ae/Be disc, HD 100546. We detect the feature of CH$^+$ in both HD 97048 and HD100546 at 90.00 µm. For HD100546 we have detections of two more lines, at 72.14 and 179.61 µm. The features at 90.0 and 179.6 µm are also at the position of water features, but given the lack of other water features, they can be attributed to CH$^+$. 

4. Gas lines as tracers of the conditions in the disc

The far-IR lines observed with PACS form in different regions of the disc. The exact locations vary with geometry, i.e. flaring, inner holes, gaps, but we will discuss here for simplicity the general case of a continuous flaring disc around a Herbig Ae star.

The [C ii] line depends strongly on the irradiation of the star, especially UV photons shortward of 1200 Å (Pinte et al. 2010; Kamp et al. 2011). The emission originates foremost in the upper tenuous layers of the disc (low critical density) where UV photons can penetrate. The [O i] 63 and [O i] 145 µm form deeper in the disc where the atomic oxygen abundance is still high. Most of their emission comes from 10-100 AU as the temperatures beyond 100 AU are generally too low to excite those lines (Kamp et al. 2010). The high excitation water lines ($E_{\text{upper}} \geq 400$ K) form mostly in the surface layers of the hot water reservoir inside the snow line (15 AU for an effective temperature of 10500 K, moving inwards for cooler stars while keeping the disc structure constant). The low excitation lines ($E_{\text{upper}} \leq 200$ K) form in a thin layer beyond the snow line where water can be photodesorbed from the icy grains into the gas phase (Cernicharo et al. 2009; Woitke et al. 2009b). The exception is the 89.988 µm water line with an upper level energy of ~ 300 K which forms across the snow line (for TW Hya, a T Tauri disc - Kamp et al. in preparation). Bruderer et al. (2012) modelled the CO ladder in HD 100546. They found that the high J lines of CO can only be reproduced by a warm atmosphere in which $T_{\text{gas}}$ is much higher than $T_{\text{dust}}$. The low J lines of CO (observed in the mm) trace the outer disc (at several 100 AU radial distance), while the mid to high J lines observed in the far-IR originate at distance of several tens of AU. The highest J lines of CO form mostly in the very inner disk (typically inside a few AU, or at the rim of transition discs).

The fundamental ro-vibrational CO band ($\Delta v = 1$) at 4.7 µm band, tracing the terrestrial planet-forming region is routinely observed in HAEBEs (e.g. Brittain et al. 2007). The bands are rotationally excited up to high $J$ (> 30), with $T_{\text{gas}}$ between 900 and 2500 K (van der Plas et al. 2012). If the gas is not in LTE,
then the vibrational temperature, \( T_{\text{vib}} \), can depart from \( T_{\text{rot}} \) when UV fluorescence causes super-thermal level populations. This is observed in several UV bright HAEBEs where \( T_{\text{vib}} > 5000 \) K: HD 97048 and HD 100546 have \( T_{\text{vib}} > 6000 \) K, while \( T_{\text{rot}} \sim 1000 \) K (Brittain et al. 2007, van der Plas et al. 2012). Also, in group I discs \( T_{\text{rot}} < T_{\text{vib}} \), while in group II discs, \( T_{\text{vib}} \lesssim T_{\text{rot}} \) (van der Plas et al. 2012).

Furthermore, the line profile suggests CO depletion in the innermost regions of HAEBE discs (van der Plas et al. 2009), with group I clearing a larger radius (\( r_{\text{cm}} \sim 10 \) AU) than group II discs (\( r_{\text{cm}} \sim 1 \) AU; van der Plas et al. 2012). The transitional disc HD 141569A stands out for having a low \( T_{\text{rot}} \sim 250 \) K, while its \( T_{\text{vib}} \sim 5600 \) K is in a similar range of the hottest CO observed in HAEBE discs, attributed to UV fluorescence (Brittain et al. 2007). Furthermore, Goto et al. (2006) showed that this disc has an inner clearing in CO up to a radius of 11 AU, comparable to the group I discs.

\(^{12}\)CO lines observed in the millimeter come from low \( J \) transitions of optically thick CO located in the outer disc surface. These pure rotational transitions of cold CO (\( \Delta v = 0 \)) are routinely detected in HAEBE discs (e.g. Piétu et al. 2003; Dent et al. 2005). Earlier, the existence of Keplarian Rotation in discs was confirmed with mm interferometry of CO lines (Koerner et al. 1993). Furthermore, as the lines are optically thick, a simple model of the line profile allows for an estimate of the outer disc radius and even inclination (e.g. Dent et al. 2005; Panic et al. 2008).

Woitke et al. (2010) calculated a grid of disc models with the thermo-chemical radiation code ProDiMo. This model grid, called “Disc Evolution with Neat Theory” is a useful tool to derive statistically meaningful dependencies on stellar and disc properties. Kamp et al. (2011) used the model grid to derive line diagnostics that are relevant for the PACS observations. We will refer to these diagnostics in our discussion below. Our sample includes several objects that stood out in earlier papers, in terms of detections of \( \text{H}_2 \), CO and/or OH, which can be attributed to a high level of UV fluorescence; we will relate these results also to our new observations. We will now discuss the results presented in the previous sections in the context of our current understanding of these discs. The following sections present our interpretation of observational correlations and their meaning in the context of disc structure and evolution.

In order to remove the bias that can be introduced by the distance of the stars, we scaled our data to a distance of 140 pc (to ease comparison with objects in Taurus and predictions of the model grid). The scaled data are all the PACS line and continuum fluxes, the \(^{12}\)CO \( J = 3-2 \) and 2-1 line fluxes, and the mm continuum fluxes.

The relations between parameters are analysed with their corresponding ‘\( p \)-values’ (see Table 7), which gives the probability that the two variables considered are not correlated. Two parameters will be classified as ‘correlated’ if one or more of the three (Spearman, Kendall and Cox-Hazard) differently obtained \( p \)-values are not larger than 1%, and as ‘tentatively correlated’ when 1% < \( p \) < 5% (e.g. Bross 1971). When \( p > 5 \) %, the parameters are classified as ‘not correlated’, as their \( p \)-values are similar to \( p \)-values derived for randomly generated samples. The
Table 7. Probability $p$ (in percentage) that the two parameters (x,y) under consideration are not correlated, calculated with several statistical methods: Spearman’s, Kendall’s and Cox-Hazard’s. Under ‘Result’ we indicate what we can derive from these statistical tests.

| $x$               | Parameters $y$       | $p$ Spearman | $p$ Kendall | $p$ Cox-Hazard | Result | Linear fit: $y = a \times x + b$ |
|-------------------|---------------------|--------------|-------------|----------------|--------|-------------------------------|
| $\log [O\text{I}] 63\mu m$ | $\log [O\text{I}] 145\mu m$ | 0.07         | 0.06        | <0.1           | Correlated | $1.2 \pm 0.21 \quad 1.8 \pm 3.3$ |
| $\log [O\text{I}] 63\mu m$ | $\log [O\text{II}] 121.6\mu m$ | 0.06         | 0.03        | <0.1           | Correlated | $0.64 \pm 0.07 \quad -7.1 \pm 1.1$ |
| $L_{UV}$          | $\log [O\text{I}] 63\mu m$ | 0.33         | 0.32        |                | –       | $0.72 \pm 0.20 \quad -16.1 \pm 0.1$ |
| $E_{\text{eff}}$ | $L_{UV}$            | 0.05         | <0.1        | <0.1          | Correlated | $9.3 \pm 0.2 \quad -36.5 \pm 4.4$ |
| $L_{\text{CO}(60, 300\mu m)}$ | $\log [O\text{I}] 63\mu m$ | 0.88         | 0.45        | –              | Correlated | $0.83 \pm 0.21 \quad -12.4 \pm 1=0.9$ |
| $F_{6.7\mu m}$   | $F_{1.3mm}$         | 0.19         | 0.09        | 0.01           | Correlated | $0.72 \pm 0.1 \quad -0.20 \pm 0.2$ |
| $L_{\text{CO} J=2-1}$ | $\log [O\text{I}] 63\mu m$ | 4.6          | 4.4         | 2.7            | Correlated | –                             |
| $L_{\text{CO} J=3-2}$ | $\log [O\text{I}] 63\mu m$ | 3.7          | 2.4         | –              | Correlated | –                             |
| $E_{\text{eff}}$ | $L_{\text{CO} J=3-2}$ | 4.7          | 3.5         | 1.6            | Correlated | –                             |
| $L_{\text{CO} J=2-1}$ | $L_{\text{CO} J=3-2}$ | 6.6          | 4.4         | –              | Correlated | –                             |
| $F_{\text{1.3mm}}$ | $L_{\text{CO} J=2-1}$ | 4.6          | 4.4         | –              | Correlated | –                             |
| $L_{\text{CO} J=2-1}$ | $\log [O\text{I}] 63\mu m$ | 34           | 27          | 44             | Correlated | –                             |
| $L_{\text{CO} J=3-2}$ | $\log [O\text{I}] 63\mu m$ | 84           | 83          | –              | Correlated | –                             |
| $F_{\text{1.3mm}}$ | $\log [O\text{I}] 63\mu m$ | 21           | 27          | 47             | Correlated | –                             |
| $L_{\text{CO} J=2-1}$ | $\log [O\text{I}] 63\mu m$ | 43           | 38          | 72             | Not correlated | –                             |

$p$-values and linear fits provided in Table 7 take into account that several of our datasets include upper/lower limits instead of detections, as they were derived with the ASURV package (Feigelson & Nelson 1985, Isobe et al. 1986 and Lavalley et al. 1992), that was specifically designed to deal with censored data. We used the Spearman’s partial correlation technique to quantify the influence of the common distance parameter on the probability of false correlation and found that this is negligible for our sample – the $p$-values considering the distances, or random values instead, are practically equal. The absence of influence of the distances on the correlations most probably comes from the relatively narrow range covered by this parameter in our sample. We excluded 51 Ophi in the correlation test with $L_{UV}$ and [O I] 63, as it is an outlier when comparing its extremely high $L_{UV}$ to the rest of the sample (see Table 2 and Fig. 9), and an enigmatic object (e.g. van den Ancker et al. 2001).

4.1. Oxygen fine structure lines

In Fig. 6, we plot the strength of the [O I] 63 $\mu m$ line as a function of the continuum flux at 63 $\mu m$. The variables are weakly correlated (see Table 7). The three sources with the highest line fluxes also have the highest continuum fluxes: AB Aur, HD 97048 and HD 100546, to which we will refer to as ‘the bright three’. These are also the only HAEBEs in which H$_2$ emission has been detected in the IR (see Sect. 3).

The ratios of the fine structure line fluxes of [O I] 63, [O I] 145 and [C II] 157 $\mu m$ are diagnostics of the excitation mechanism (e.g. Kaufman et al. 1999). Unfortunately, for most of the sources we only obtained upper limits for one or more of these lines. We show the line flux of [O I] 63 as a function of [O I] 145 in Fig. 6 and find a clear correlation (see Table 7). We find line ratios of [O I] 63/[O I] 145 between 10 and 30. These ratios are not compatible with predictions of the PDR model in Tielens & Hollenbach (1985) for optically thick lines with $T_{\text{gas}} < 200$ K. Our line ratios (median of 24) are in agreement with predictions from the model grid, which gives a median line ratio of 25 (Kamp et al. 2011). These authors conclude, based on those disc models, that the line ratio is not sensitive to the average oxygen gas temperature (for $50 < T_{\text{gas}} < 500$ K), but instead correlates with the gas to dust ratio.

4.2. Ionised carbon fine structure line

The [C II] line flux is very sensitive to the UV radiation field, and the line is mostly optically thin. Unfortunately, most of our sources are background contaminated, as [C II] is also detected in off-source positions, in a variable amount, depending on the location. For the few sources with solid, non-[C II] background contaminated detections, we find line ratios of [O I] 63/[C II] 157 between 10 and 30.

4.3. Carbon monoxide

Freeze-out of CO on grains is not expected in the disc of an A-type star (e.g. Panic et al. 2009), so that the strength of the low-$J$ 12CO lines can be used to obtain a lower limit on the cold gas mass. The disc size can be derived from the 12CO flux and profile. In Fig. 7, we plot the [O I] 63 line flux as a function of the 12CO J=2–1 and J=3–2 line strengths (data from Dent et al. 2005, Panic et al. 2009, Isella et al. 2010, Oberg et al. 2010, 2011 and our own data, see Appendix B). We do not find a clear correlation with the $J=2$–transition, while we do find a weak correlation with the $J=3$–2 transition (see Table 7).

Kamp et al. (2011) showed that the ratio of [O I] 63/12CO J=2–1 can be used to derive the gas mass in the disc to an order of magnitude. The idea is that this ratio is determined by the average gas temperature in the disc. If the [O I] 63 line is optically thin, the line flux will mainly depend on the gas mass and average [O I] temperature (Woitke et al. 2010). Once the temperature is known, the line flux of [O I] 63 can thus be related to the disc gas mass. In our sample, we have nine sources for which the 12CO J=2–1 line flux is known. We calculated the ratio for those sources, and found that log ([O I] 63/12CO J=2–1) falls between 2.5 and 3.5. This means that we have a similar average gas temperature in all cases. We apply the relation for this ratio range between log [O I] 63 and the gas mass, derived by Kamp et
al. (2011) to obtain an estimate of the disc mass. The results are shown in Table 8. We derive $M_{\text{gas}}$ between 0.24 and $25 \times 10^{-3} M_\odot$. These values are of course only indicative; for a more accurate estimate, a full model of all the available observations needs to be done for each disc. The masses are consistent with the estimates derived from a detailed modelling of HD 163296 ($M_{\text{gas}} \sim 15 \sim 120 \times 10^{-3} M_\odot$; Tilling et al. 2012) and HD 169142 ($M_{\text{gas}} \sim 3 \sim 7 \times 10^{-3} M_\odot$; Meeus et al. 2010).

Table 8. Line fluxes of $^{12}$CO $J=2-1$, log of the line ratios and derived gas masses.

| Object     | $^{12}$CO $J=2-1$ (10$^{-18}$ W/m$^2$) | log ([O I] 63/CO $J=2-1$) | $M_{\text{gas}}$ (M$_\odot$) |
|------------|-------------------------------------|---------------------------|-------------------------------|
| HD 31648   | 0.169                               | 2.75                      | $6.5 \times 10^{-3}$          |
| HD 35187   | 0.026                               | 3.10                      | $2.5 \times 10^{-3}$          |
| HD 36112   | 0.099                               | 2.58                      | $0.24 \times 10^{-3}$         |
| CQ Tau     | 0.024                               | 3.30                      | $4.4 \times 10^{-3}$          |
| HD 135344 B| 0.080                               | 2.78                      | $2.2 \times 10^{-3}$          |
| HD 139614  | 0.054                               | 2.92                      | $2.2 \times 10^{-3}$          |
| HD 142527  | 0.160                               | 2.52                      | $0.66 \times 10^{-3}$         |
| HD 142666  | 0.052                               | 2.57                      | $0.62 \times 10^{-3}$         |
| HD 163296  | 0.053                               | 3.59                      | $25.4 \times 10^{-3}$         |
| HD 169142  | 0.164                               | 2.75                      | $5.3 \times 10^{-3}$          |
| 49 Cet     | 0.015                               | 2.84                      | $< 3.3 \times 10^{-3}$        |

4.4. Hydroxyl

Although less abundant than H$_2$ and CO, hydroxyl (OH) is also an important molecule, as it plays a central role in the formation/destruction of H$_2$O, H$_2$ and [O I]. Mandell et al. (2008) were the first to detect ro-vibrational transitions of warm OH (at 3.0-3.7 µm) in two HAEBEs, AB Aur and HD 36112. They derived a rotational temperature of 650-800 K, and argue that fluores-
cent excitation is responsible for the emission of OH located in the disc surface layer. Fedele et al. (2011) also searched for OH in 11 HAEBEs with CRIRES, and detected it in 4 sources with spectral types between B5 and A1; none of those objects are in our sample. They find that objects with an OH detection tend to be Meeus group I sources. Recently, several transitions of OH around 3 µm were detected in HD 100546 (Liskowsky et al. 2012). In our PACS spectra, we only detect OH in HD 163296 (and a tentative detection in AB Aur) - but we only cover one doublet, which is not the strongest in the far-IR, so it might be we are not sensitive enough. Indeed, Sturm et al. (2010) detected several OH lines in their full SED range mode PACS spectra of HD 100546, from which the 84 µm doublet is the strongest. In our spectrum at 79 µm, we do see a indications for the OH doublet, but it is not a 3σ detection (see Fig. 5).

4.5. Water

Water was not yet reported to be detected in a Herbig Ae/Be disc despite several searches in the near- and mid-IR (e.g. Pontoppidan et al. 2010; Fedele et al. 2011). However, in the study by Pontoppidan et al. (2010), HD163296 shows a H2O emission line at 29.85 µm, but in that paper, water was only confirmed to be present when detected both at 15.17 and 17.22 µm, with at least 3.5σ confidence.

Thi & Bik (2005) showed that the ratio H2O/OH declines when the ratio of the intensity of the UV field over the density increases. Thus in lower density regions with a lot of UV radiation, the amount of water expected is low, compared to OH. Indeed, Fedele et al. (2011) conclude that, if water vapour is present, it must be located in deeper, colder layers of the disc than where OH is found; the disc atmosphere is depleted in water molecules.

We detect at least one water line and have evidence for several others in HD 163296, a group II source. Tilling et al. (2012) modelled the disc of HD 163296 based on our earlier, shallower, range scans, and showed that the disc is mostly settled, which results in slightly warmer dust and increased line flux. This fact, together with the rather high UV luminosity, can probably explain the water detections in this disc.

Kamp et al. (2011) found that strong dust settling will increase the water abundance in the disc surface. The reason is complex (we refer the reader to Sect. 5.3 of Kamp et al.), but the main idea is that there is an efficient cold water formation route in these discs. It is interesting to note that HD 100546, the source that has the highest UV flux and is richest in other, strong lines ([Oi] 63, CO and CH+) does not show evidence of warm water. HD 100546 is a group I source, thought to have its inner disc cleared (e.g. Bouwman et al. 2003; Benisty et al. 2010). Woitke et al. (2009b) showed that water lines originate in 3 distinct regions: 1) a deep midplane behind the inner disc wall, up to 10 AU, hosting most of the water vapour; 2) a midplane region between 20 and 150 AU where water freezes out and there is a small amount of cold water vapour; and 3) a warm water layer between 1 and 50 AU higher up in the disc. In HD 100546, region 1 and part of region 3 are missing, so that the amount of gas phase water is much smaller.

Furthermore, while in the inner disc of HD 163296 the density is too low for water to form (from OH + H2) to balance the fast photodissociation (see e.g. Thi & Bik 2005), water can survive in the inner 10 AU of the warm atmosphere. In contrast, in the UV strong star HD 100546, even at 30 AU the UV field is too strong for water to survive. This, in combination with the greater amount of settling in the HD 163296 disc, might explain the absence of detectable H2O emission in the disc of HD 100546 while it is detected in HD 163296.

4.6. CH*

The formation of CH* is controlled by the gas-phase reaction C* + H2 → CH* + H, which has an activation energy of 4500 K. Therefore, CH* not only traces the presence of H2 but also the presence of hot gas. In our sample, we have IR detections of molecular hydrogen in 3 targets: AB Aur, HD 97048 and HD 100546. In two of these objects, we also detect CH*, suggesting that their formation and excitation mechanisms are indeed related. For a more in-depth discussion of CH* in HD 100546 we refer to Thi et al. (2011).

5. Correlations with stellar and disc parameters

In the next paragraphs, we will look for correlations between the observed [Oi] 63 line fluxes and the properties of the objects. For this purpose, we did not include the debris discs, as their discs have a very different nature. Besides, in the debris discs, we did not detect any [Oi] 63 line, so that we would only be able to compare upper limits.

5.1. The influence of Teff, UV and X-ray luminosity

We searched for a correlation between stellar parameters and the [Oi] 63 line flux. We did not find a trend with age nor with stellar luminosity. In Fig. 8 we show the relation between the line flux of [Oi] 63 and the effective temperature of the stars. Both appear uncorrelated, until Teff reaches 10000 K, when the [Oi] 63 flux increases dramatically for a few sources. Our p-values (see Table 7) are inconclusive, therefore, the significance of a possible correlation cannot be established from our statistical analysis.

The UV and X-ray photons play an important role in the chemistry and temperature balance of protoplanetary discs. For HAEBEs, the UV photons are important in heating the disc, through their absorption by PAHs and the subsequent photoelectric effect. In Fig 8 we show the relation between the line flux of [Oi] 63 µm, the UV luminosity calculated from IUE spectra (see Sect. 2), and the X-ray luminosity (data mainly found in Hubrig et al. 2009; see Table C.1 for a full list). There is a clear correlation between the [Oi] 63 flux and the UV luminosity (see Table 7), as reported earlier for a limited sample in Pinte et al. (2010). This could be related to an increase in OH photo-dissociation in the disc surface and/or to a more efficient photoelectric heating of the gas by PAHs in those sources with a higher UV luminosity.

X-ray photons can ionise atoms and molecules. The X-ray fluxes observed in HAEBEs (log LX = 28-30) are on average lower when compared to those of the lower-mass T Tauri stars (TTS; log LX = 29-32). Aresu et al. (2011) found from theoretical modeling of discs a correlation between the X-ray luminosity and the [Oi] 63 line flux for X-ray luminosities above 1030 erg/s. Below that value, the gas temperature in the region where the [Oi] 63 line forms is dominated by UV heating while above that value, X-rays provide an additional heating source, thereby increasing the total line flux. Since all objects in our sample are below this LX threshold, it is not surprising that we do not see a correlation with the X-ray luminosity. Furthermore, X-rays in HAEBEs are softer than in TTS, so that they cannot penetrate as deep in the discs as in T Tauri discs. A dedicated study will use
spectral X-ray properties to interpret the observed PACS spectra (Güdel et al., private communication).

5.2. Relation with accretion rate

In Fig. 9 we plot the line flux of [O\textsc{i}] 63 $\mu$m as a function of $L_{\text{acc}}$ derived from the excess in the Balmer discontinuity. There is no trend visible, just more scattering at higher $L_{\text{acc}}$. However, we should point to the difficulties that lie in an accurate determination of the accretion rate, that will introduce additional scatter in the values. We also plot the [O\textsc{i}] 63 line flux against the Br\gamma luminosity (data from García-Lopez et al. 2006 and Donehew et al. 2011). Here we see a tentative correlation with $L_{\text{Br\gamma}}$. Given that we do not see a clear correlation between the accretion rate and the [O\textsc{i}] 63 line flux, we can conclude that the accretion is not an important contributor to the excitation of [O\textsc{i}] 63 in HAEBEs. This confirms the findings of an earlier study of a few HAEBEs by Pinte et al. (2010), that the emission from HAEBE discs can be explained by photospheric heating alone. Indeed, in

Fig. 8. [O\textsc{i}] 63 $\mu$m versus effective temperature, UV luminosity and X-ray luminosity. Diamonds: group I sources, asterix: group II sources.

Fig. 9. Top: [O\textsc{i}] 63 $\mu$m versus the accretion rate derived from the excess in the Balmer discontinuity. Middle: [O\textsc{i}] 63 versus the luminosity of the Br\gamma line. Bottom: $L_{\text{UV}}$ vs. $T_{\text{eff}}$. Diamonds: group I sources, asterix: group II sources.
5.4. Relation with disc properties

The continuum flux at 1.3 mm is often used to derive a minimum dust mass of the disc, under the assumption that the dust emission is optically thin (Beckwith et al. 1990). In Fig. 11 we plot the \([\text{O} \text{I}] 63 \text{ Å} \) flux as a function of the continuum flux at 1.3 mm (our mm data collected in the literature are listed in Appendix C). We also use our own unpublished SMA data, see Appendix B. We did not find that these variables are correlated (see Table 7). On the other hand, the continuum flux at 63 \(\mu m\) and at 1.3 mm are strongly correlated (see Fig. 11).

In Fig. 12 we plot the line flux of \([\text{O} \text{I}] 63 \text{ Å} \) as a function of the total IR excess, a proxy for the amount of dust continuum observed. We do not find a correlation. This is likely because the IR continuum is rather a tracer of the dust disc, and the scale height of the gas disc can be higher than that of the dust, as is already observed in a few HAEBEs (e.g. van der Plas et al. 2009). HD 141569A has a transitional disc, with a much lower \(F_{\text{IR}}/F_{\text{dust}}\) than the rest of the sample (see Table 2), indicating that the disc is barely flaring and perhaps has already dissipated much of its dust material. All these diagnostics lead to confirm that the disc of HD 141569A is much different (inner disc mostly cleared out from dust) from that of HD 97048 and HD 100546, which still have flaring gas-rich discs.

Modelling of the HD 141569A disc with ProDiMo will help us to better understand these differences in terms of excitation mechanisms, abundance of gas and disc structure (Thi, in preparation). Our data suggest that, in HD 141569A, the CO is located deeper in the disc (closer to the dust) from that of HD 97048 and HD 100546, which can be thermalised and/or shielded from photodissociation by direct UV photons.

The slope \(b\) of the far-IR to mm SED, where \(F_{\lambda} \sim \lambda^b\), can be related to the size of the dust grains radiating at mm wavelengths. However, grain size is not the only factor influencing the slope, also the composition (e.g. amount of carbon) and grain shape can be important factors. Acke et al. (2004a) showed that the SED of HD 141569A is consistent with a mixture of large, low-density grains with a high carbon mass fraction, which is a common feature among HAEBEs.

5.3. Relation with PAH and [O I] 6300 Å

PAHs are important for the heating of the disc through the photoelectric effect. In HAEBEs, the PAH luminosity, \(L_{\text{PAH}}/L_{\odot}\), is observed to reach up to \(9 \times 10^{-3}\). In Fig. 10 we show the relation between the PAH luminosity and the \([\text{O} \text{I}] 63 \text{ Å} \) line fluxes (data from Acke et al. 2004b and Keller et al. 2008). The \([\text{O} \text{I}] 63 \text{ Å} \) flux and the PAH flux weakly correlate with each other (see Table 7).

HD 141569A is the only star for which we saw a detection of \([\text{O} \text{I}] 145 \mu m\), but no detection of CO at 144.8 \(\mu m\). The \([\text{O} \text{I}] 63 \text{ Å} \) over \([\text{O} \text{I}] 145 \mu m\) ratio is smaller than 10, while it is around 20 in AB Aur, HD 97048 and HD 100546. Moreover, Brittain et al. (2007) showed from CO 4.7 \(\mu m\) modelling that \(T_{\text{rot}}\) is of the order of 250 K, while \(T_{\text{rot}}\) in HD 97048 and HD 100546 is much higher, \(\geq 1000 \text{ K}\). This difference cannot be attributed to a lower UV luminosity as it is rather similar (6.83 in HD 141569A vs. 7.69 in HD 97048 and 7.22 \(L_{\odot}\) in HD 100546). However, a lower PAH luminosity is observed in HD 141569A (a factor 10 less; Acke et al. 2010), so there is less heat contribution to the disc - there might also be an intrinsic difference in PAH abundance.
far-IR to mm wavelength is related to the SED group: self-shadowed discs (group II) have on average shallower slopes than their flaring counterparts (group I). In our sample, we do not see a correlation between the \( [\text{O} \text{i}] 63 \) line strength and the SED slope (see Fig. 11).

5.5. Non-detections in debris discs

In our sample we have five debris discs, for which the \( [\text{O} \text{i}] 63 \) line was not detected. We obtain 3\( \sigma \) upper limits for the \( [\text{O} \text{i}] 63 \) line flux (at their respective distances) \( \sim 6-10 \times 10^{-18} \) W/m\(^2\). This contrasts with the young debris disc \( \beta \) Pic, where \( [\text{O} \text{i}] 63 \) µm and \( [\text{C} \text{ii}] 158 \) µm emission lines were detected with Herschel/PACS (Brandeker et al. 2012). These authors give an \( [\text{O} \text{i}] 63 \) µm line flux \( = 13.2 \times 10^{-18} \) W/m\(^2\) for \( \beta \) Pic (at a distance of 19 pc), what would not have been detected at the distance of our debris discs. The only exception is HR 1998, at a distance of 22 pc, for which we have an upper limit \( \sim 5 \times 10^{-18} \) W/m\(^2\) when scaled to 19 pc, almost a factor 3 lower than the \( \beta \) Pic detection. \( \beta \) Pic appears to be a special debris disc that is relatively rich in gas, originating from the ongoing vapourisation of dust through grain-grain collisions, comet evaporation, and/or photodesorption of grain surfaces (Lagrange et al. 1998; Czechowski & Mann 2007; Chen et al. 2007).

6. Conclusions

In this paper, we studied the gas content with Herschel PACS spectroscopy for a sample of 20 Herbig Ae stars and five A-type debris discs, that can be summarised as follows:

1. We detect the \( [\text{O} \text{i}] 63 \) µm line in all the Herbig Ae stars of our sample, while it is absent in the debris discs, confirming the lack of a large amount of gas in these discs. The \( [\text{O} \text{i}] 63 \) line is by far the strongest line observed in our spectra, next in strength (if detected) are \( [\text{O} \text{i}] 145 \) and \( [\text{C} \text{ii}] \); they are only detected in 5 (25%) and 6 (30%) sources, respectively.

2. The CO mid to high \( J \) transitions (18-17 and 29-28) are only detected in 9 (45%) and 2 (10%) objects, respectively. The highest \( J \) (33-32 and 36-35) CO lines covered in our spectra are not seen at all in our sample. The three detections of CO \( J=29-28 \) are in the three strongest UV emitting objects, AB Aur, HD 97048 and HD 100546, revealing the need for
a large amount of UV photons for this line to become visible. Interesting in this respect is the transitional disc of HD 141569A, where we did not detect CO J=18-17, but did detect a strong line of [O i] 145. This cannot be attributed to a difference in UV luminosity but rather to significant inner disc clearing, and to a more tenuous disc.

3. We detect two lines of CH+ in HD100546, and also detect CH+ for the first time in HD 97048, only the second Herbig Ae star in which it is detected.

4. Hydroxyl and H2O are important ingredients of the disc chemistry. However, we found water and OH in only one object, HD 163296, which has a settled disc. The previous detection of H2O, announced by Sturm et al. (2010) in HD 100546 cannot be confirmed. The misidentification was caused by a blend with the CH+ line, often present at the same wavelength as H2O. The non-detection of H2O in most sources is in agreement with findings of Pontoppidan et al. (2010) and Fedele et al. (2011), who also did not detect water at IR wavelengths, despite dedicated surveys.

We correlated the strength of the [O i] 63 µm line with stellar parameters, as well as disc properties. We can summarise our findings as follows:

1. The [O i] 63 line flux correlates weakly with the continuum flux at 63 µm. The line flux ratios of [O i] 63/[O i] 145 and [O i] 63/[C i] are between 10 and 30.

2. We found that three of our sources, AB Aur, HD 97048 and HD 100546, have very strong [O i] 63 line fluxes, when compared to the rest of the sample. These three sources have group I discs and have the highest T eff values in the sample, and thus have more stellar UV flux. Indeed, we see a correlation between the total (stellar + accretion) UV luminosity and the strength of the [O i] 63 line. We do not see a correlation with the X-ray luminosity, which is rather low in our sample of HAEBE stars.

3. We did not find a correlation between the accretion rate estimated from the Balmer discontinuity, and a tentative one with the Bry line. This shows that accretion is not the main driver of the [O i] 63 excitation in HAEBEs. The bulk of the UV luminosity is photospheric rather than from accretion.

4. Sources with high [O i] 63 fluxes also have high PAH luminosity, which can both be related to their high UV fluxes. We also see a correlation with the luminosity of the [O i] 6300 Å line.

5. The disc geometry (flat versus flared) does not uniquely determine the strength of the [O i] 63 line flux. The three strongest lines are observed in flared discs, but once these sources are excluded, there is no significant difference in line strength observed between the group I and II discs.

6. We found a strong correlation between the continuum at 63 µm and at 1.3 mm. There is no correlation between the [O i] 63 line strength and the strength of the dust continuum at 1.3 mm. We did not find a correlation with the slope of the far-IR to mm SED, nor with the IR excess.

7. We see a weak correlation with the strength of 12CO J = 3-2 line. Based on the line ratio [O i] 63/12CO J=2-1, we can derive an estimate of the gas mass present in the disc. We found M gas between 0.25 and 25 × 10^{-3} M⊙, consistent with the estimates derived from a detailed modelling of HD 163296 (M gas ~ 15 – 120 × 10^{-3} M⊙; Tilling et al. 2012) and HD 169142 (M gas ~ 3 – 6.5 × 10^{-3} M⊙; Meeus et al. 2010).

A picture emerges for the protoplanetary discs around Herbig Ae/Be stars where the stellar UV flux is the main parameter controlling the strength of the [O i] 63 line, which is formed just below the disc surface. An increased amount of settling can enhance the line flux for those species (such as water or OH) that are formed deeper in the disc, where the density is higher. We plan to follow-up on this study with detailed modelling of a few key objects: AB Aur & HD 97048 and HD 135344 B & HD 142527 (group I, high and low UV, respectively), HD163296 (group II), HD141569 A (transitional disc), and finally the enigmatic compact disc of 51 Oph. Our modelling results will further aid in the understanding of the chemistry and physical processes present in Herbig Ae/Be discs.

Acknowledgements. We would like to thank the PACS instrument team for their dedicated support and A. Carmona for discussions about gas line diagnostics. G. Meeus, C. Eiroa, I. Mendigutia and B. Montesinos are partly supported by AYA-2008-01727 and AYA-2011-26202. G. Meeus is supported by RYC-2011-07920. CAG and SDB acknowledge NASA/JPL for funding support. WFT thanks CNES for financial support. FM thanks the Millennium Science Initiative (ICM) of the Chilean Ministry of Economy (Nucleo P10-022-F). FM, IK and WFT acknowledge support from the EU FP7-2011 under Grant Agreement No. 286405. CP acknowledges funding from the EU FP7 under contract PEP09- GA-2009-256513 and from ANR of France under contract ANR-2010-JCJC-0504-01. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL, CSL, IMEC (Belgium); CEA, OAMP (France); MPIA (Germany); IFSI, OAT/OAT, OAA/CAISMI, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI (Italy), and CICT/MCT (Spain). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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Interferometric observations of HD 32297, HD 35187, HD 142666, HD 144668, HD 158352, HR 1998, and KK Oph were carried out in five trucks with the Sub-Millimeter Array (SMA; Ho et al. 2004) in the compact configuration from November 2010 to October 2011. The observations were carried out at a central frequency of 223.9 GHz, with upper and lower band-passes of 4 GHz bandwidth and the center of each bandpass offset from the central frequency by 2.5 GHz. The continuum was sampled at 3.25 MHz, and a 104 MHz regions was set aside for 0.203 MHz resolution observations of the CO J=2–1 line (230.5379700 GHz) line. The compact array observations included seven or eight antennas, with baselines from 10–70 m.

Each object was observed for ~2.5 hours total integration time in good conditions (zenith $\tau_{\text{225GHz}}$ 0.06 - 0.25) with system temperatures of $\sim$100-230 K.

For gain calibration, we interleaved 5 minute observations of close quasars between 20 minute observations of the targets. We combined observations of two or three targets per track. We used 60–90 minute observations of bright quasars for bandpass calibration, and 20 minute observations of available planets for flux amplitude calibration. Observations of flux and bandpass calibrators were carried out before or after our targets were available. We flagged and calibrated the data using standard routines in the facility IDL package MIR. We carried out baseline based phase calibration, finding rms phase errors of 10–20°. Based
Table A.1. Overview of the obsids that were observed. (D) means that it was a deeper observation than our regular settings; (D1) for settings at 79/158 µm, (D2) for settings at 72/145 µm and 79/158 µm and (D3) for all 3 range settings.

| Star   | Line Spec | Range Spec |
|--------|-----------|------------|
| HD 9672 | 1342188424 | 1342188423 |
| AB Aur  | 1342191355 | 1342191354 |
| HD 31648 | 1342226002 | 1342226003 |
| HD 32297 | 1342217849 | 1342217850 |
| HD 35187 | 1342226900 | 1342226901 |
| HD 36112 | 1342227635 | 1342227636 |
| HD 36910 | 1342227638 | 1342227637 |
| HR 1998  | 1342226192 | 1342226193 |
| HD 97048 | 1342188436 | 1342188435 |
| HD 100453 | 1342203059 | 1342203058 |
| HD 100546 | 1342188438 | 1342188437 |
| HR 4796A | 1342199242 | 1342199243 |
| HD 135344B | 1342190370 | 1342190369 |
| HD 139614 | 1342191300 | 1342191299 |
| HD 141569 | 1342190376 | 1342190375 |
| HD 142527 | 1342216173 | 1342216172 |
| HD 142666 | 1342214224 | 1342214225 |
| HD 144668 | 1342192146 | 1342216200 |
| HD 150193 | 1342216625 | 1342216626 |
| KK Oph   | 1342192148 | 1342192149 |
| HD 158352 | 1342190377 | 1342227800 (D1) |
| HD 158643 | 1342178221 | 1342178222 |
| HD 163296 | 1342192161 | 1342192160 |
| HD 169142 | 1342186310 | 1342186309 |
| HD 100453 | 1342190376 | 1342190375 |

Table B.1. $^{12}$CO 2-1 and $^{12}$CO 3-2 line fluxes observed with SMA.

| Star   | $^{12}$CO 2-1 Error (Jy km/s) | $^{12}$CO 3-2 Error (Jy km/s) |
|--------|-------------------------------|-------------------------------|
| HD 35187 | \(<0.55\) – – – – – | \(<0.55\) – – – – – |
| HD 142666 | \(<0.62\) – – – – – | \(<0.62\) – – – – – |
| HD 144668 | confused – – – – – | confused – – – – – |
| KK Oph | \(<1.08\) – – – – – | \(<1.08\) – – – – – |
| HR 1998 | \(<1.17\) – – – – – | \(<1.17\) – – – – – |
| HD 158352 | \(<0.48\) – – – – – | \(<0.48\) – – – – – |

Fig. A.1. The region around 72 micron.

Fig. A.2. The region around 79 micron.


In addition, HD 32927, HD 35187, HD 142666, KK Oph, HD 141569, HD 150193, and HD 158643 were observed for continuum emission at 1.2 mm using the MAMBO2 bolometer array (Kreysa et al. 1998) on the IRAM 30m telescope at Pico Veleta, Spain. Observations were conducted during the Nov. 2008 bolometer pool. Zenith opacity for our observations was typically \( \sim 0.2 - 0.3 \), and observations were carried out to a target 1\sigma sensitivity of 1 mJy, typically 20 minutes on source, in an ON-OFF pattern of 1 minute on target followed by 1 minute on sky, with a throw of 32\". Flux calibration was carried out using Mars, and local pointing and secondary flux calibration was carried out using nearby bright quasars. The data were reduced using the facility reduction software, MOPSIC\(^2\). We list the 1.2 mm continuum fluxes in Table B.2.

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### Table B.2. Continuum fluxes at 1.2 mm, observed with MAMBO and at 1.3 mm, observed with SMA.

| Star      | \( F_{1.2\text{mm}} \) (mJy) | Error  | \( F_{1.3\text{mm}} \) (mJy) | Error  |
|-----------|-------------------------------|--------|-------------------------------|--------|
| HD 32927  | 3.14                          | 0.822  | 3.10                          | 0.74   |
| HD 35187  | 33.96                        | 1.001  | 28.95                         | 0.85   |
| HD 141569 | 4.785                         | 0.507  | -                             | -      |
| HD 142666 | 102.5                        | 2.022  | 99.9                          | 4.3    |
| HD 144668 | 34                           | -      | 34.3                          | 0.9    |
| HD 151093 | 47.860                       | 2.091  | -                             | -      |
| KK Oph    | 36.160                       | 2.260  | 24.5                          | 4.3    |
| 51 Oph    | 5.007                        | 0.599  | -                             | -      |
| HR 4796 A | -                            | -      | < 9.3                         | -      |
| HD 158352 | -                            | -      | < 0.7                         | 5 -    |

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### Table C.1. X-ray luminosities collected from the literature, references listed: (1) Tellesschi et al. (2007), (2) Grady et al. (2010), (3) Stelzer et al. (2004), (4) Collins et al. (2009), (5) Stelzer et al. (2006), (6) Grady et al. (2009), (7) Stelzer et al. (2009), (8) Berghofer et al. (1996), (9) Grady et al. (2007) and (10) Stelzer & Neuhold (2000).

| Star         | \( \log L_{\text{x-ray}} \) (erg/s) | Instrument | ref. |
|--------------|-------------------------------------|------------|------|
| AB Aur       | 29.71                               | XMM        | (1)  |
| HD 31648     | 29.30                               | Chandra    | (2)  |
| HD 97048     | 29.58                               | XMM        | (3)  |
| HD 100453    | 28.82                               | Chandra    | (4)  |
| HD 100546    | 28.93                               | Chandra    | (5)  |
| HD 104237    | 30.11                               | Chandra    | (5)  |
| HD 135344 B  | < 28.1                              | ROSAT      | (6)  |
| HD 141569 A  | 29.66                               | ROSAT      | (8)  |
| HD 144668    | 28.3                                | Chandra    | (7)  |
| HD 150193    | 29.64                               | Chandra    | (5)  |
| 51 Oph       | < 28.98                             | ROSAT      | (8)  |
| HD 163296    | 29.6                                | Chandra    | (5)  |
| HD 169142    | 29.1                                | Chandra    | (9)  |
| HR 4796 A    | 29.38                               | ROSAT      | (10) |

### Table C.2. Continuum fluxes at 1.3 mm collected from the literature; references listed: (1) Henning et al. (1994), (2) Mannings et al. (1997), (3) Chapillon et al. (2008), (4) Meeus et al. (2002), (5) Sylvester et al. (1996), (6) Acke et al. (2004a), (7) Hughes et al. (2008).

| Star          | \( F_{1.3\text{mm}} \) (mJy) | Error | Instrument | ref. |
|---------------|-----------------------------|-------|------------|------|
| AB Aur        | 103                        | 20    | IRAM       | (1)  |
| HD 31648      | 360                        | 20    | OVRO       | (2)  |
| HD 36112      | 56                         | 1     | IRAM       | (3)  |
| CQ Tau        | 162                        | 2     | IRAM       | (3)  |
| HD 97048      | 450                        | 30    | IRAM       | (1)  |
| HD 100453     | 265                        | 21    | SIMBA/SEST | (4)  |
| HD 100546     | 470                        | 20    | IRAM       | (1)  |
| HD 104237     | 90                         | 20    | IRAM       | (1)  |
| HD 135344 B   | 142                        | 19    | UKT14/JCMT | (5)  |
| HD 139614     | 242                        | 15    | UKT14/JCMT | (5)  |
| HD 142527     | 1190                       | 30    | ATCA       | (6)  |
| HD 163296     | 780                        | 30    | OVRO       | (2)  |
| HD 169142     | 197                        | 15    | UKT14/JCMT | (5)  |
| 49 Cet        | 2.3                        | 0.6   | SMA        | (7)  |

### Appendix C: Data collected from the literature

In the Tables C.1, C.2, C.3 and C.4, we list the X-ray luminosities, millimeter continuum fluxes and CO line fluxes that we collected from the literature, as well as their references.
**Table C.3.** $^{12}$CO 2-1 line fluxes collected from the literature; references listed: (1) Oberg et al. (2010), (2) Isella et al. (2010), (3) Panic et al. (2009), (4) Hughes et al. (2008).

| Star      | $^{12}$CO 2-1 (Jy km/s) | Error (Jy km/s) | Instrument | ref. |
|-----------|-------------------------|-----------------|------------|-----|
| HD 31648  | 22.0                    | 0.2             | SMA        | (1) |
| HD 36112  | 12.9                    | 2.58            | SMA        | (2) |
| CQ Tau    | 3.10                    | 0.18            | SMA        | (1) |
| HD 135344B| 10.39                   | 0.21            | SMA        | (1) |
| HD 139614 | 7.00                    | 2.11            | RxA3/JCMT  | (3) |
| HD 142527 | 20.76                   | 0.23            | SMA        | (1) |
| HD 142666 | 3.12                    | 0.5             | SMA        | (22) |
| HD 163296 | 6.90                    | –               | RxA3/JCMT  | (3) |
| HD 169142 | 21.30                   | –               | RxA3/JCMT  | (3) |
| 49 Ceti   | 2.0                     | 0.3             | SMA        | (4) |

**Table C.4.** $^{12}$CO 3-2 line fluxes collected from the literature; references listed: (1) Dent et al. (2005) and (2) Panic et al. (2009). (a): JCMT flux dominated by emission from the dark cloud.

| Star      | $^{12}$CO 3-2 (Jy km/s) | Error (Jy km/s) | Instrument | ref. |
|-----------|-------------------------|-----------------|------------|-----|
| AB Aur    | 143.20                  | 3.29            | RxB3/JCMT  | (1) |
| HD 31648  | 53.00                   | 1.16            | RxB3/JCMT  | (1) |
| HD 35187  | < 5.00                  | –               | RxB3/JCMT  | (1) |
| HD 36112  | 15.70                   | 1.93            | RxB3/JCMT  | (1) |
| CQ Tau    | 6.00                    | 0.97            | RxB3/JCMT  | (1) |
| HD 100546 | 178.4                   | 19.20           | APEX       | (2) |
| HD 135344B| 18.80                   | 0.77            | RxB3/JCMT  | (1) |
| HD 139614 | 9.10                    | 2.12            | RxB3/JCMT  | (1) |
| HD 141569A| 14.70                   | 1.16            | RxB3/JCMT  | (1) |
| HD 142666 | 13.90                   | 2.70            | RxB3/JCMT  | (1) |
| HD 150193 | 1.40                    | –               | RxB3/JCMT  | (1) |
| HD 163296 | 8.30                    | 1.93            | RxB3/JCMT  | (1) |
| HD 169142 | 32.9                    | 2.51            | RxB3/JCMT  | (1) |
| 49 Ceti   | 6.58                    | 1.35            | RxB3/JCMT  | (1) |