Molecular Gas in Debris Disks around Young A-type Stars

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Abstract

According to the current paradigm of circumstellar disk evolution, gas-rich primordial disks evolve into gas-poor debris disks that are composed of second-generation dust. To explore the transition between these phases, we searched for 12CO, 13CO, and C18O emission in seven dust-rich debris disks around young A-type stars, using the Atacama Large Millimeter/submillimeter Array (ALMA) in Band 6. We discovered molecular gas in three debris disks. In all of these disks, the 12CO line was optically thick, highlighting the importance of less abundant molecules in reliable mass estimates. By supplementing our target list with literature data, we compiled a volume-limited sample of dust-rich debris disks around young A-type stars within 150 pc. We obtained a CO detection rate of 11/16 above a 12CO J = 2–1 line luminosity threshold of ⋅1.4 × 10^4 Jy km s^{-1} pc^{-2} in the sample. This high incidence implies that the presence of CO gas in the bright debris disks around young A-type stars is more likely than the exception. Interestingly, dust-rich debris disks around young FG-type stars exhibit, with the same detectability threshold as A-type stars, a significantly lower gas incidence. While the transition from the protoplanetary phase to the debris phase is associated with a drop in the dust content, our results exhibit a large spread in the CO mass in our debris sample, with peak values that are comparable to those in the protoplanetary Herbig Ae disks. In the particularly CO-rich debris systems, the gas may have a primordial origin, which is a characteristic of a hybrid disk.

Key words: circumstellar matter – infrared: stars – stars: individual (HD 121191, HD 121617, HD 131488)

1. Introduction

During their early evolution, newborn stars are surrounded by massive gas-rich circumstellar disks. Most these primordial disks dissipate by the age of 10 Myr (e.g., Alexander et al. 2014), which is partly because their material is incorporated into planetesimals and planets. Later, the collisional erosion of the planetesimals may produce fresh dust (Wyatt 2008). The tenuous debris disk, which is formed by these second-generation dust particles, may accompany the star almost throughout all of its life. The transformation from the primordial disk to the debris disk is perhaps the most radical change during a disk’s lifetime, the details of which are still not well understood (Wyatt et al. 2015). The evolution of the dust component is relatively well known because the infrared and submillimeter continuum observations outline how the dust mass decreases with time (Wyatt 2008). Due to the rarity of gas detections in debris disks, we know significantly less about the gas component. Mature debris disks are expected to have low gas-to-dust ratios because processes like collisions, evaporation, and photodesorption from icy grains or planetesimals can only produce a small amount of secondary gas, and moreover, the most detectable species, like CO, photodissociate rapidly in the interstellar radiation field (Matthews et al. 2014).

Recent surveys with single dish radio telescopes and the Atacama Large Millimeter/submillimeter Array (ALMA) interferometer identified a growing population of debris disks that contains detectable amounts of molecular gas. Through the detection of rotational transitions of CO molecules, 12CO-bearing debris disks have now been discovered: 49 Cet (Zuckerman et al. 1995), HD 21997 (Moór et al. 2011), β Pic (Dent et al. 2014), HD 131835 (Moór et al. 2015b), HD 181327 (Marino et al. 2016), HD 110058, HD 138813, HD 146897, HD 156623 (Lieman-Sifry et al. 2016), HD 32297 (Greaves et al. 2016), η Crv (Marino et al. 2017), and Fomalhaut (Matrà et al. 2017b). These disks share several distinctive physical characteristics; most of them are young (<50 Myr), are surround A-type stars, exhibit high fractional luminosity, and have a dust component that is relatively cold (<140 K), resembling the Kuiper Belt rather than the asteroid belt in solar system terminology. The gas component may have a secondary origin, such as possibly being produced from icy material within the planetesimal belt. However, considering the youth of the systems, it may also be the remnant of the protoplanetary disk (primordial origin). There is now proof of secondary gas in four systems: β Pic, (Matrà et al. 2017a), Fomalhaut (Matrà et al. 2017b), HD 181327 (Marino et al. 2016), and η Crv (Marino et al. 2017). The large amount of gas in HD 21997 and HD 131835 is difficult to explain within the framework of the current secondary gas production models (Köppl et al. 2013; Kral et al. 2017), raising the possibility that the gas is primordial, while the dust is secondary, forming a hybrid disk (Kóspál et al. 2013; A. Moór et al. 2017, in preparation).

We have only a few constraints on how circumstellar disks reach the gas-poor phase, how closely the gas evolution is coupled to the disappearance of the primordial dust, when the...
secondary gas production starts, and how long the disk can retain the primordial gas. Motivated by these open questions and a desire to explore the conditions under which a disk could keep its primordial gas component longer, we initiated a systematic investigation of the molecular gas in debris disks. We focus on young A-type stars and determine the incidence system. 

2. Sample Selection

In order to obtain a complete census of all debris systems within 150 pc that are similar to the known CO-bearing debris disks, we adopted the following criteria: (1) A-type host star; (2) $5 \times 10^{-4} < L_{\text{disk}}/L_{\text{bol}} < 10^{-2}$, thus the fractional luminosity is higher than the lowest value (in HD 21997) found in any CO-bearing debris disk younger than 50 Myr, but is lower than the typical values in protoplanetary disks; (3) a dust temperature $< 140$ K to ensure that—similar to all of the previous detections—the disks have a cold dust component; (4) a $> 70 \mu$m detection with Spitzer/MIPS or Herschel/PACS; and (5) an age between 10 and 50 Myr. We searched the literature (Moór et al. 2011; Ballering et al. 2013; Melis et al. 2013; Chen et al. 2014) and found 17 systems within 150 pc that satisfied these criteria. The age estimates for all of the systems are well established because they were based on the stars’ membership in young moving groups or associations, except one target, HD 32297. We excluded those 10 systems where sensitive ALMA observations were already available from this sample. The remaining seven disks formed the target list of our dedicated ALMA survey. Remarkably, all these objects belong to the Sco-Cen association. Table 1 gives the main parameters for all 17 sources, including our present targets.

3. Observations

Our targets were observed with ALMA in Band 6 (project 2015.1.01243.S, PI: M. Curé). Table 2 shows the log of observations. We used an identical correlator setup in each case. Two spectral windows centered at 217 and 233.5 GHz were dedicated to continuum measurements, providing a 1875 MHz bandwidth individually. The other two spectral windows were tuned to cover the $^{12}$CO, $^{13}$CO, and C$^{18}$O $J = 2$–1 lines. The observations of the $^{12}$CO($2$–1) transition were performed using a window centered at 230.743 GHz with a bandwidth of 468.75 MHz, while the isotopologue lines were measured together in a window centered at 219.492 GHz with a bandwidth of 1875 MHz. The spectral resolutions in the two windows were 244 kHz ($0.32$ km s$^{-1}$) and 976 kHz ($1.33$ km s$^{-1}$), respectively. The calibration and imaging were done using the standard ALMA reduction tool Common Astronomy Software Applications (CASA v4.5; McMullin et al. 2007). To extract the continuum image and the spectral cubes of different lines from the calibrated visibilities, we used the CASA task clean with Briggs weighting, using a robustness parameter of 0.5. For the line data, we first fitted a continuum to the line-free channels and subtracted it in the $uv$ space using the uvcontsub task. The continuum image was compiled by concatenating the dedicated continuum spectral windows and line-free channels of the other two spectral windows. The beam sizes, position angles, and rms noises are also summarized in Table 2.

4. Results

Continuum data. Figure 1 presents the 1.3 mm continuum images of our targets. For HD 121191, HD 121617, HD 131488, and HD 98363, we detected a significant ($\text{peak} > 3\sigma$) signal toward or close to the position of the central star. For HD 109832, the peak emission that is close to the stellar position is only $2.8\sigma$. The remaining two objects were undetected. The continuum flux densities of HD 98363 and HD 121191 were determined by fitting a point source to their visibility data using the CASA uvmulti task. To derive the integrated flux density of the bright extended disks around HD 121617 and HD 131488, we used the uvmulti task (Martí-Vidal et al. 2014) to fit a Gaussian ring model to the visibilities. These models also provide structural information about these disks (see Section 5). We determined upper limits for the nondetected sources by measuring the flux at random positions in the images in an aperture radius that corresponds to 100 au. The measured fluxes and the $3\sigma$ upper limits are listed in Table 2, along with uncertainties that contain a 10% absolute calibration error, which was added quadratically.

Assuming an optically thin emission, the measured flux densities were converted to dust masses using

$$M_d = \frac{F_d d^2}{B_\nu(T_{\text{dust}}) \kappa_\nu},$$

where $d$ is the distance, $B_\nu(T_{\text{dust}})$ is the Planck function at 1.3 mm for a characteristic dust temperature, $T_{\text{dust}}$, which was taken from Table 1, while $\kappa_\nu$ is the opacity at 1.3 mm for which a value of $2.3$ cm$^2$ g$^{-1}$ was adopted (Andrews et al. 2013).

For consistency, the dust masses of the other 10 disks from Table 1 were also computed using submillimeter/millimeter data collected from the literature and by adopting an opacity value of $\kappa_\nu = 2.3\left(\frac{\nu}{230 \text{ GHz}}\right)^{0.7}$ cm$^2$ g$^{-1}$. Taking into account uncertainties in the measured flux densities, distances, and dust temperature values, the formal uncertainty of our dust mass estimates is between 11% and 30%. However, there are other factors that can influence the estimates. The emitting dust grains were characterized by a single temperature, which was derived from the analysis of the spectral energy distribution (SED) and therefore reflects the temperature of the smallest grains and not of those large ones that we observe at millimeter wavelengths. The latter grains are probably colder; thus, using the SED-based $T_{\text{dust}}$, we may underestimate the dust mass. An even more serious uncertainty is related to the adopted $\kappa_\nu$ value. Depending on the chemical composition, shape, and size distribution of the dust grains, the millimeter opacity can vary significantly (Miyake & Nakagawa 1993; Ossenkopf & Henning 1994), thereby introducing an uncertainty of a factor of $\sim 2$ in the calculation. The obtained dust masses are listed in Table 1.

Line data. We detected a significant CO emission in HD 121191, HD 121617, and HD 131488. We detected all three CO isotopologues in all three targets, except for the C$^{18}$O in HD 121191. Integrating for the velocity ranges where the significant line emission can be seen, we calculated zeroth moment maps (Figure 2 shows these for $^{12}$CO and $^{13}$CO),

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Table 1
Stellar and Disk Parameters

| Name          | Spt. | Dist. (pc) | Lum. ($L_\odot$) | Group | Age (Myr) | $T_{\text{bol}}$ (K) | $L_{\text{disk}}/L_{\text{bol}}$ | $M_{\text{bol}}$ ($M_\odot$) | CO | $S_{12CO}$ (Jy km s$^{-1}$) | $M_{\text{CO}}$ ($M_\odot$) |
|---------------|------|------------|------------------|-------|-----------|---------------------|-----------------------------|---------------------------|----|------------------------|--------------------------|
| HD 98363      | A2V  | 123.6      | 10.5             | LCC (7)| 15 (4)    | 295/112             | $9.2 \times 10^{-4}$ (2)  | $6.8 \times 10^{-3}$ (8) | N  | <0.036 (8)            | ...                      |
| HD 109832     | A9V  | 111.9      | 9.3              | LCC (7)| 15 (4)    | 186/92              | $7.6 \times 10^{-4}$ (1)  | <0.038 (8)                |    | ...                    | ...                      |
| HD 121191     | A5IV/V | 135.9      | 8.2              | LCC/UCL (4)| 15−16 (4) | 555/118             | $4.7 \times 10^{-3}$ (9)  | $9.5 \times 10^{-3}$ (8) | Y  | $0.23 \pm 0.04$ (8)   | $2.7 \times 10^{-3}$     |
| HD 121617     | A1V  | 128.2      | 17.0             | UCL (2)| 16 (4)    | 105                 | $4.8 \times 10^{-3}$ (4)  | $1.4 \times 10^{-1}$ (8) | Y  | $1.27 \pm 0.13$ (8)   | $1.8 \times 10^{-3}$     |
| HD 131488     | A1V  | 147.7      | 13.1             | UCL (4)| 16 (4)    | 570/94              | $5.5 \times 10^{-3}$ (9)  | $3.2 \times 10^{-1}$ (8) | Y  | $0.78 \pm 0.08$ (8)   | $8.9 \times 10^{-3}$     |
| HD 143765     | A5IV/V | 113.4      | 7.1              | UCL (7)| 16 (4)    | 374/127             | $5.9 \times 10^{-4}$ (2)  | <0.078 (8)                |    | ...                    | ...                      |
| HD 145880     | B9.5V | 127.9      | 32.8             | ARG (8)| 16 (4)    | 196/70              | $1.1 \times 10^{-3}$ (1)  | <0.071 (8)                |    | ...                    | ...                      |

Current Sample

| Name          | Spt. | Dist. (pc) | Lum. ($L_\odot$) | Group | Age (Myr) | $T_{\text{bol}}$ (K) | $L_{\text{disk}}/L_{\text{bol}}$ | $M_{\text{bol}}$ ($M_\odot$) | CO | $S_{12CO}$ (Jy km s$^{-1}$) | $M_{\text{CO}}$ ($M_\odot$) |
|---------------|------|------------|------------------|-------|-----------|---------------------|-----------------------------|---------------------------|----|------------------------|--------------------------|
| HD 49 Cet     | A1V  | 59.4       | 16.4             | ARG (8)| 40 (5)    | 155/56              | $1.1 \times 10^{-3}$ (5)  | $1.7 \times 10^{-1}$ (2)  | Y  | $2.00 \pm 0.30$ (3)   | $1.9 \times 10^{-4}$     |
| HD 21997      | A3IV/V | 71.9       | 11.2             | COL (5)| 42 (1)    | 61                  | $5.7 \times 10^{-4}$ (5)  | $1.1 \times 10^{-1}$ (7) | Y  | $2.17 \pm 0.23$ (4)   | 6.0 $\times 10^{-2}$    |
| HD 32297      | A6V  | 112.4      | 6.2              | ...   | <30 (2)   | 292/88              | $4.4 \times 10^{-3}$ (2)  | $2.0 \times 10^{-1}$ (4) | Y  | $5.11 \pm 0.49$ (1)   | $1.5 \times 10^{-3}$     |
| HR 9749       | A0V  | 72.8       | 23.4             | TWA (6)| 10 (5)    | 108                 | $4.6 \times 10^{-3}$ (8)  | $1.4 \times 10^{-1}$ (5) | N  | <0.65 (2)               | ...                      |
| HD 110058     | A0V  | 107.4      | 5.9              | LCC (7)| 15 (4)    | 499/112             | $1.4 \times 10^{-3}$ (2)  | $2.9 \times 10^{-2}$ (3) | Y  | $0.09 \pm 0.02$ (5)   | $2.5 \times 10^{-5}$     |
| HD 131835     | A2IV | 122.7      | 9.2              | UCL (7)| 16 (4)    | 176/71              | $3.0 \times 10^{-3}$ (6)  | $2.5 \times 10^{-1}$ (3) | Y  | $0.80 \pm 0.04$ (5)   | $3.2 \times 10^{-2}$     |
| HD 138813     | A0V  | 150.8      | 24.5             | US (7)| 10 (4)    | 194/94              | $9.0 \times 10^{-4}$ (2)  | $1.2 \times 10^{-1}$ (3) | Y  | $1.41 \pm 0.08$ (5)   | $7.5 \times 10^{-4}$     |
| HD 156623     | A0V  | 118.3      | 14.8             | UCL (3)| 16 (4)    | 605/123             | $5.0 \times 10^{-3}$      | $3.2 \times 10^{-2}$ (3) | Y  | $1.18 \pm 0.04$ (5)   | $3.9 \times 10^{-4}$     |

Other Systems

Note. Column (1): target name. Column (2): spectral type (from SIMBAD, except for HD 32297; see Rodigas et al. 2014). Column (3): distance (from the Hipparcos parallax, when available, van Leeuwen 2007; except for HD 121617 and HD 121191, see Lindgren et al. (2016); and for HD 131488, whose kinematic distance was derived based on its membership in UCL). Column (4): luminosity. Column (5): moving group membership. ARG: Argus moving group; BPMG: β Pic moving group; COL: Columbia moving group; LCC: Lower Centaurus Crux association; UCL: Upper Centaurus Lupus association; US: Upper Scorpius association. References for membership assignments: (1) Barrado y Navascués et al. (1999), (2) Hoogerwerf (2000), (3) Lieman-Sifry et al. (2016), (4) Melis et al. (2013), (5) Möör et al. (2006), (6) Webb et al. (1999), (7) de Zeeuw et al. (1999), and (8) Zackernau & Song (2012). Column (6): stellar age. References for age estimates (the age of the corresponding group in case of group members): (1) Bell et al. (2015), (2) Kalas (2005), (3) Mamajek & Bell (2014), (4) Pecaut & Mamajek (2016), and (5) Torres et al. (2008). Column (7): dust temperature. For references, see Column (8). Column (8): fractional luminosity of the disk. References: (1) Ballering et al. (2013), (2) Chen et al. (2014), (3) Dent et al. (2014), (4) Möör et al. (2011), (5) Möör et al. (2015a), (6) Möör et al. (2015a), (7) Rhee et al. (2007), (8) Riviere-Marichalar et al. (2014), and (9) Vican et al. (2016). For HD 156623, the characteristic dust temperatures and the fractional luminosity were derived by fitting a two-component modified blackbody to the excess SED. Column (9): dust mass. References for the utilized (sub)millimeter observations: (1) Dent et al. (2014), (2) Hughes et al. (2017), (3) Lieman-Sifry et al. (2016), (4) Meeus et al. (2012), (5) Sheret et al. (2004), (6) Su et al. (2017), (7) Williams & Andrews (2006), and (8) this work. Column (10): CO detection status. Column (11): integrated line fluxes or 3σ upper limits for 12CO $J = 2−1$ ($L = 3−2$ for HR 4796).

References. (1) Greaves et al. (2016), (2) Hales et al. (2014), (3) Hughes et al. (2008), (4) Köpöl et al. (2013), (5) Lieman-Sifry et al. (2016), (6) Matrà et al. (2017a), (7) Su et al. (2017), and (8) this work. Column (12): mass of CO gas (for details, see Section 4).
Next, we determined an aperture that contains all CO fluxes, measured the integrated line fluxes, and calculated the spectra (Figure 2). The spectra with higher signal-to-noise ratio show the disk-like structure of the CO lines. The spectra indicate the presence of a disk with a mass of approximately 10 M☉, and a disk temperature of 10 K. The disk consists of a cold inner region and a warmer outer region.

For the three detected sources, we estimated the disk-averaged CO column densities by integrating the CO line fluxes over the disk area and normalizing to the stellar mass. The results are shown in Table 2.

| Parameters | HD 98363 | HD 109832 | HD 121191 | HD 121617 | HD 131488 | HD 143675 | HD 145880 |
|------------|---------|---------|---------|---------|---------|---------|---------|
| Obs. date  | 2016 Mar 22 | 2016 Mar 22 | 2016 May 23 | 2016 May 23 | 2016 May 08 | 2016 May 16 | 2016 May 16 |
| Number of antennas | 37 | 37 | 35 | 35 | 41 | 39 | 39 |
| Baseline lengths (m) | 15.3–460 | 15.3–460 | 16.7–640 | 16.7–640 | 15.1–640 | 16.5–640 | 16.5–640 |

| Beam size (') | 0.70 × 0.82 | 0.71 × 0.86 | 0.51 × 0.59 | 0.49 × 0.57 | 0.53 × 0.55 | 0.48 × 0.62 | 0.48 × 0.64 |
| Beam PA (°) | 32°5 | 6°7 | 50°3 | 64°1 | 34°6 | 51°9 | 51°3 |
| rms (mJy beam⁻¹) | 26 | 25 | 40 | 42 | 29 | 43 | 43 |

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\[ M_{\text{CO}} = 4\pi m d^2 \frac{S_{ud}}{x_u \hbar \nu_{ud} A_{ud}} f_{\text{C}^{13}\text{O}}/\text{CO}, \]
gas temperature, we determined $x_2$ from the Boltzmann equation. We used C$^{18}$O for HD 131488 and $^{13}$CO for HD 121191, yielding total CO masses of $(8.9 \pm 1.5) \times 10^{-2} M_\odot$ and $(2.7 \pm 0.9) \times 10^{-3} M_\odot$, respectively. In the case of HD 121617, both the $^{13}$CO and C$^{18}$O lines may be optically thin, providing the concordant CO gas mass estimates of $(1.8 \pm 0.3) \times 10^{-2} M_\odot$ and $(2.0 \pm 0.7) \times 10^{-2} M_\odot$, respectively.

The quoted uncertainties account only for the errors in the measured line fluxes and in the distances. However, there could be other sources causing the uncertainties. Similar to the dust mass estimate, the gas temperature was characterized by a single value instead of a more realistic temperature distribution. By assuming an LTE, the fractional population of the upper $J = 2$ level has a maximum at around our adopted gas temperature of 20 K. By taking temperatures lower than $\sim 14$ K or higher than 20 K, we would get lower fractional populations, i.e., higher gas masses. Between gas temperatures of 8 and 48 K, the mass estimate is, at most, $1.5 \times$ higher than the one derived for 20 K.

The LTE requires a dense medium where the collisions of CO with other particles are sufficiently frequent. In lower density environments, however, the radiative excitation can dominate collisional processes. Such a non-LTE situation can lead to weakly populated levels, even at the $J = 2$ rotational level of the CO molecule, resulting in higher mass estimates. Isotopologue abundance ratios that are different from the local interstellar values also affect the results. The combination of all these effects may lead to somewhat higher values than our mass estimates in Table 1.

Eight out of the other 10 disks have been detected in CO lines. For HD 21997, $\beta$ Pic, and HD 131835, the mass estimates were taken from Kóspál et al. (2013), Matrà et al. (2017a), and A. Moór et al. (2017, in preparation), respectively. For the other detected targets (49 Cet, HD 32297, HD 110058, HD 138813, and HD 156623), we used their measured $^{12}$CO line fluxes (see Table 1), and by assuming an LTE, we adopted 32 K for 49 Cet (Hughes et al. 2017) and 20 K for the other sources as the gas excitation temperature in the CO mass calculation. Taking into account that the $^{12}$CO line could be optically thick in these targets, and considering the already mentioned caveats about CO mass estimates (see above), we considered our results to be lower limits (Table 1).

5. Discovery of Three New Gaseous Debris Disks

HD 131488. HD 131488 is an A1-type member of the $\sim 16$ Myr old UCL association. Based on its SED, the debris disk has a high fractional luminosity and may contain two belts, in which the inner one is exceptionally hot (Melis et al. 2013). This system has the highest dust and CO gas mass among the known gaseous debris disks. The dust emission is elongated in the east–west direction, with a central depression. We fitted the continuum visibilities with the uvmultiﬁt task using a Gaussian ring model (Martí-Vidal et al. 2014). The best-fit parameters are: a total flux of $2.9 \pm 0.1$ mJy, a ring diameter of 1″14 $\pm$ 0″04 (168 $\pm$ 6 au), an inclination of 82° $\pm$ 3°, a position angle of 96° $\pm$ 1°, and an FWHM of the ring thickness of 0″30 $\pm$ 0″08 (44 $\pm$ 11 au). The center of the model does not show a significant offset from the stellar position. The obtained ring may correspond to the cold, outer dust belt that is inferred from the SED, however, the measured ring radius is 2.7 $\pm$ 0.3 times larger than the one computed by assuming blackbody grains that are based on the stellar luminosity and the dust temperature quoted in Table 1. Using a sample of 34 spatially resolved debris disks, Pawellek et al. (2014) studied how the ratios of the measured disk radii to the blackbody radii ($\Gamma = R_{\text{meas}}/R_{\text{BB}}$) vary as a function of stellar luminosity. By placing our target in their Figure 4(b) (where they calculated $\Gamma$ similarly to our analysis), we found that the obtained $\Gamma$ value is higher than in any of the other systems with similarly bright host stars, suggesting an overabundance of small grains that are hotter than blackbodies.
HD 121617. HD 121617 is also an A1-type member of the \(\sim 16\) Myr old UCL association. Its SED shows a high fractional luminosity and is consistent with a single ring model, with \(T_{\text{dust}} = 105\) K (Moór et al. 2011). The continuum image shows an inclined ring-like morphology. The uvmultifit procedure yielded the following parameters: a total flux of \(1.9 \pm 0.2\) mJy, a ring diameter of \(129 \pm 12\) (165 \pm 16 au), an inclination of \(37 \pm 13\)°, a position angle of \(43 \pm 19\)°, and an FWHM of the ring thickness of \(0.44 \pm 0.15\) (57 \pm 19 au). In this case, the ratio of the inferred radius to the blackbody radius is \(\Gamma = 2.9 \pm 0.4\). This \(\Gamma\) value and the stellar luminosity are higher than that of our previous target, making HD 121617 an even more prominent outlier in Figure 4(b) of Pawellek et al. (2014), which also implies the presence of copious amount of small grains. Remarkably, by analyzing the characteristic grain sizes relative to the theoretical blow out size in 12 spatially resolved young debris disks, Lieman-Sifry et al. (2016) found that the CO-bearing systems in the sample had grain sizes on the small end of the distribution, and two of them had grain sizes smaller than the blow out size.

HD 121191. The position and space motion of this A5-type star can be consistent with either of the UCL (\(\sim 16\) Myr) or LCC (\(\sim 15\) Myr) subgroups of the Sco-Cen association (Melis et al. 2013). Based on its SED, it has a high fractional luminosity, and it may also have two belts, out of which the inner one is very hot and bright (Melis et al. 2013). The weak 1.3 mm continuum emission from this target is unresolved, and its peak is offset from the stellar position toward the southwest (\(\Delta\text{RA.} = -0\rlap{.}''16 \pm 0\rlap{.}''05; \Delta\text{Decl.} = -0\rlap{.}''17 \pm 0\rlap{.}''05\)). This may be an axisymmetric ring whose parts remain below the noise level, or it may be a ring with a highly asymmetric brightness distribution, although a possible contamination from a background source cannot be excluded either. Both \(^{12}\)CO and \(^{13}\)CO were firmly detected as compact sources centered on the stellar position. This disk has a lower dust mass than the previous two targets.

6. Molecular Gas in Bright Debris Disks

Until recently, only \(\beta\) Pic and 49 Cet were known as CO-bearing debris disks (Vidal-Madjar et al. 1994; Zuckerman et al. 1995; Roberge et al. 2000). Later, more such objects were
discovered, and the first statistical studies could be done (Greaves et al. 2016; Lieman-Sifry et al. 2016; Péricaud et al. 2017). Our present list partly incorporates these earlier samples and extends them to a full list of 17 dust-rich debris disks in the solar neighborhood (Section 2). In Figure 3(a), we display the $^{12}\text{CO} \ 2\rightarrow 1$ (or $^{13}\text{CO} \ 3\rightarrow 2$ for HR 4796) line luminosities (or upper limits), as a function of the fractional luminosity for our sample. Line luminosities of detected CO-bearing disks span almost two orders of magnitude, in which the brightest disks have luminosities that are comparable to those of fainter Herbig Ae and T Tauri disks (Ansdell et al. 2016; Péricaud et al. 2017). Since the sensitivity of the HR 4796 observation is nearly two orders of magnitude worse than that of the other measurements, we discard this object from the following analysis, reducing the size of our statistical sample to 16. For the other objects, by adopting the highest upper limit (source No. 7) in Figure 3(a), we derived a detectability threshold of $\sim 1.4 \times 10^4 \ \text{Jy km s}^{-1} \ \text{pc}^2$ for the $^{12}\text{CO} \ 2\rightarrow 1$ line luminosity. With our 3 new discoveries, we found 11 disks in this sample that harbor CO gas, resulting in a very high detection rate of 68.8$^{+13.1}_{-8.9}$. Because of the small sample, we computed the uncertainties (corresponding to 68% confidence interval) using the binomial distribution approach proposed by Burgasser et al.
(2003). Our result indicates that the presence of CO gas in dust-rich debris disks around young A-type stars is more likely the rule than the exception. The obtained incidence rate of 11/16 is valid above our detectability threshold for the $^{12}$CO $J = 2–1$ line luminosities. Nevertheless, we cannot rule out that all of our targets harbor CO gas at some level. Remarkably, as Figure 3(a) shows, apart from HR 4796, all of the disks with $L_{\text{disk}}/L_{\text{bol}} > 2 \times 10^{-3}$ contain detectable levels of CO gas.

By dividing our list into two subsamples that contain stars that have luminosities lower or higher than 10$^{-3}$, we get CO detection rates of 62.5$^{\pm}_{-7.5}$% (5/8) and 75.0$^{+1.9}_{-3.9}$% (6/8), respectively. This implies that there is no evidence to support a correlation of stellar luminosities within the A-type sample.

To compare with debris disks around later-type stars, we collected previous ALMA results for those young (10–50 Myr) debris disks that encircle F- and G-type stars, but still fulfill our original selection criteria (Section 2), and their ALMA measurements achieved the same detection threshold ($\sim 1.4 \times 10^4$ Jy km s$^{-1}$ pc$^2$) as that of our A-type sample. We found 16 such systems: 14 that belong to the Sco-Cen association (Lieman-Sifry et al. 2016) and two young moving group members, HD 61005 and HD 181327 (Marino et al. 2016; Olofsson et al. 2016). From the FG stars, two objects were found to harbor CO gas (HD 181327 and HD 146897). However, with its $^{12}$CO 2–1 line luminosity of $\sim 10^3$ Jy km s$^{-1}$ pc$^2$ (based on Marino et al. 2016), HD 181327 is at least an order of magnitude fainter than any of the other known gaseous disks from the studied samples. Its detection was only possible because of its proximity and the long exposure time. Such a faint CO disk would not be detectable at any objects in the A-type sample, therefore this source was discarded from the following analysis, yielding a detection rate of 6.7$^{+1.2}_{-2.2}$% for disks around young FG-type stars. By applying a Fisher’s exact test to compare the occurrence of CO-bearing disks in the two samples, we obtained a $p$ value of 6.4 $\times$ 10$^{-4}$, implying a statistically significant difference between dust-rich debris disks around young A-type and FG-type stars above our detectability threshold. This suggests that either the incidence of CO gas is truly lower around young FG-type stars than in A-type systems, or that the CO line luminosities are systematically lower. The reason for the latter may be related to the lower CO gas content and/or lower CO-bearing debris disks. To study the transition between primordial disks and debris disks, we also plotted some Herbig Ae/Be systems with CO isotopologue observations from the literature. There is a pronounced drop in dust masses from the primordial disks to the debris disks (see also, Roccatagliata et al. 2009; Panić et al. 2013). In the CO gas mass, however, debris disks show a significantly larger spread. Four gaseous debris disks—HD 121617 and HD 131488 from our current sample, as well as HD 21997 and HD 131835—harbor comparable amounts of CO to those of the two least massive Herbig disks in this figure. For these disks, our ALMA CO isotopologue observations revealed 30–250× more CO gas than was calculated from $^{13}$CO measurements (using an optically thin assumption), highlighting the importance of less abundant molecules in reliable mass estimates.

While the gas in the disk of $\beta$ Pic, and around the two F-type hosts, is secondary (Marino et al. 2016; Kral et al. 2017; Matrà et al. 2017a), the presence of significantly larger amounts of CO gas in HD 21997 and HD 131835 indicates that these systems may have hybrid disks, where the gas is leftover from the primordial phase (Kóspál et al. 2013; Kral et al. 2017; A. Moór et al. 2017, in preparation). The likely existence of hybrid disks would be a strong indication that in some systems the evolution of dust and gas, at least in the outer disk, are decoupled. By exhibiting CO masses similar to that of HD 21997 and HD 131835, the three newly discovered CO-bearing disks (particularly HD 121617 and HD 131488) could be prime hybrid disk candidates. The origin of the gas in these systems, along with their detailed morphological analysis, will be the topic of a future paper. Four gaseous systems, 49 Cet, HD 32297, HD 138813, and HD 156623, all have similar $^{12}$CO 2–1 line luminosities to the above subsample, therefore their current CO mass estimates should be considered as lower limits. The origin of the gas in these systems is not known. Further observations at CO isotopologue lines might reveal that some of them may exhibit a hybrid nature as well. If the disks with the highest $^{12}$CO line luminosities in Figure 3(a) indeed turn out to be hybrid disks, then it would indicate a strong link between the hybrid disk phenomenon and young A-type stars. If this link is exclusive, then it could help us to understand why we detect a lower number of gaseous debris disks around FG-type stars above our current detectability threshold.

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