Herschel PACS Observations of 4–10 Myr Old Classical T Tauri Stars in Orion OB1

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Received 2017 December 25; revised 2018 April 11; accepted 2018 April 16; published 2018 May 16

Abstract
We present Herschel PACS observations of eight classical T Tauri Stars in the ~7–10 Myr old OB1a and the ~4–5 Myr old OB1b Orion subassociations. Detailed modeling of the broadband spectral energy distributions, particularly the strong silicate emission at 10 μm, shows that these objects are (pre-)transitional disks with some amount of small optically thin dust inside their cavities, ranging from ~4 to ~90 au in size. We analyzed Spitzer IRS spectra for two objects in the sample: CVSO-107 and CVSO-109. The IRS spectrum of CVSO-107 indicates the presence of crystalline material inside its gap, while the silicate feature of CVSO-109 is characterized by a pristine profile produced by amorphous silicates; the mechanisms creating the optically thin dust seem to depend on disk local conditions. Using millimeter photometry, we estimated dust disk masses for CVSO-107 and CVSO-109 lower than the minimum mass of solids needed to form the planets in our solar system, which suggests that giant planet formation should be over in these disks. We speculate that the presence and maintenance of optically thick material in the inner regions of these pre-transitional disks might point to low-mass planet formation.

Key words: infrared: stars – open clusters and associations: individual (Orion OB1 association) – protoplanetary disks – stars: formation – stars: pre-main sequence

1. Introduction
Understanding how solid material in protoplanetary disks evolves from conditions similar to those in the interstellar medium (ISM) to planetary embryos and beyond requires both theoretical developments and observational constraints. As many complex processes are at play, observations are essential to inform theory and set constraints on the multiple effects occurring in these disks.

Many studies have now revealed stars with inner disks devoid of optically thick material—the so-called transitional disks (TDs)—and with spectral energy distributions (SEDs) characterized by small or negligible near-infrared excesses but significant emission in the mid-infrared and beyond (Strom et al. 1989; Skrutskie et al. 1990; Calvet et al. 2002; Espaillat et al. 2007, 2008a, 2014). This morphology has been interpreted as cavities in the inner regions and has been confirmed through (sub)millimeter interferometric imaging and, recently, by spatially resolved images (e.g., Andrews et al. 2009, 2011a, 2011b; Brown et al. 2009; Hughes et al. 2009; Isella et al. 2010; van Dishoeck et al. 2015; Carrasco-González et al. 2016), especially those taken with the Very Large Telescope (VLT)/SPHERE and the Atacama Large Millimeter/submillimeter Array (ALMA; ALMA Partnership et al. 2015; Andrews et al. 2016; Nomura et al. 2016; Schwarz et al. 2016; van Boekel et al. 2017). A subset of these disks, commonly called pre-transitional disks (PTDs), show similar features but with substantial near-infrared excesses over the stellar photosphere. This excess has been explained by an optically thick disk located close to the star, separated from the outer disk by a gap (Espaillat et al. 2008a, 2010, 2011).

TDs and PTDs are thought to be at an important phase of disk evolution. The distinct SEDs of these sources have puzzled researchers over the years. For instance, dust-clearing mechanisms in TDs/PTDs are still under debate. It is uncertain whether processes act simultaneously or a single process dominates the evolution. Observations made with the Spitzer Space Telescope (Werner et al. 2004) have been widely used to identify TDs/PTDs and to characterize their IR emission. Moreover, Spitzer IRS spectra have also provided unprecedented details regarding disk cavities and dust properties within them. Extensive modeling of several TDs/PTDs around T Tauri stars (TTs) has been made (Calvet et al. 2002, 2005; Uchida et al. 2004; D’Alessio et al. 2005; Espaillat et al. 2007, 2008b, 2010; McClure et al. 2010, 2012, 2013). Some mechanisms have been proposed to explain the substantial dust clearing observed on these disks, e.g., grain growth, photoevaporation, and interaction with embedded planets or stellar companions (Espaillat et al. 2014). Many researchers have proposed planet formation as the most likely mechanism, since models of planet-disk interaction have resulted in cleared disk regions (e.g., Paardekooper & Mellema 2004; Dodson-Robinson...
Studies of disk frequencies as a function of age have set timescales for disk evolution of ~5–7 Myr for late-type (K to M) stars (e.g., Hernández et al. 2007a). However, most disk studies have concentrated on populations ~2 Myr old (i.e., Taurus, the Orion Nebula Cluster), and much less information exists for older populations, especially around 10 Myr. The main reason is that already at ages of ~4 Myr the parent molecular clouds have largely dissipated, such that these somewhat older stars are harder to identify among the general field population. It is not surprising that many of the ~4–10 Myr old groups have been discovered in the past ~20 yr. The TW Hya association (Webb et al. 1999) and the η Cha cluster (Mamajek et al. 1999) are among the nearest 10 Myr old groups but contain only around 20 stars. The Scorpius-Centaurus OB association, with ages ~5–20 Myr (e.g., Preibisch & Mamajek 2008; Pecaut & Mamajek 2016), is the closest OB association (~130 pc) and has been studied extensively as a source of older pre-main-sequence (PMS) disk-bearing stars. The Upper-Scorpius (US) region has ~800 members reported by Luhman & Mamajek (2012), though spectroscopic confirmation of many low-mass members is still ongoing (Pecaut & Mamajek 2016); the age is still debated, proposed to be in the range of 4–10 Myr (Preibisch & Mamajek 2008; Pecaut & Mamajek 2016). ALMA submillimeter studies in US have reported disk properties and disk sizes in samples of ~100 disk systems (Carpenter et al. 2006, 2009; Barenfeld et al. 2016, 2017).

As the closest region with active low- and high-mass star formation (d ~ 400 pc), the Orion OB1 association contains large samples of young stars, spanning ages from the protostellar stage up to “older” PMS stars, and sharing a common origin (Bally 2008; Briceno 2008). Sco-Cen only hosts slightly more evolved stars (>4 Myr) and no recognizable star clusters, Orion has populous stellar aggregates at all ages up to ~10 Myr. These young, dense stellar groups provide an opportunity for exploring the evolution of protoplanetary disks in clustered environments. At the young end of optically visible PMS stars, the ~1 Myr old Trapezium cluster contains >2000 stars (Muench et al. 2008), and the ~3 Myr σ Ori cluster has over 300 confirmed members (Hernández et al. 2014). At the “old” end of the PMS age spectrum, the ~10 Myr old 25 Ori cluster (Briceno et al. 2007) has ~250 members, which have been characterized spectroscopically and photometrically by us in a consistent and uniform way. Here we present Herschel Space Telescope 70 and 160 μm observations of four fields in the Orion OB1 association, targeting a limited subset of the stellar population in the 4–10 Myr age range, including the 25 Ori cluster.

Disk fluxes are strongly dependent on the stage of dust evolution at the wavelength range probed by Herschel. Wide-field Infrared Survey Explorer (WISE) covered wavelengths from 3.6 to 22 μm, and Spitzer was most sensitive from 3.6 to 24 μm, with limited sensitivity at 70 μm. Therefore, studies of dust depletion have mostly been limited to the inner disk regions. With Herschel we now have a window into longer wavelengths important for disk studies. Additionally, the smaller beam size and higher spatial resolution of PACS compared with Spitzer/MIPS result in a lower rate of confusion, with background sources making it easier for Herschel to detect faint sources. Combining the Herschel data with optical V, R, I, near-infrared J, H, K photometry and mid-IR data from Spitzer/WISE, we assemble SEDs for eight disk-bearing sources, which we then fit with detailed irradiated accretion disk models to infer the structure, characteristics, and evolutionary state of these disks. In Section 2 we discuss observations, sample selection, and data reduction; our analysis and results are shown in Section 3, where we present the observed SEDs of our objects (Section 3.1), the stellar parameters and mass accretion rate estimates (Section 3.2), a description of our disk models (Section 3.3), and the method we used to model the SEDs (Section 3.4); the main results are discussed in Section 4; and finally, our conclusions are listed in Section 5.

2. Observations

In this section we summarize the observational data sets obtained for our sample. Optical photometry was used to characterize the stellar properties, which are inputs in our models, and as an indicator of how variable these stars are, which was included as an additional uncertainty in the χ² estimate. Mid-IR data were used in the modeling of the silicate bands, particularly at 10 μm. PACS photometry allowed the characterization of the outer disk edge, while submillimeter data were used to estimate disk mass and to constrain the properties of the outer disk.
2.1. Sample

We targeted a set of 165 TTSs distributed in four fields (Figure 1), two in the ~4–5 Myr old Orion OB1b subassociation and two in the ~7–10 Myr old Orion OB1a region (Briceño et al. 2005). These stars have been confirmed as members of the OB association based on their K and M spectral types, Hα emission, and the presence of Li I (λ6707) in absorption (Briceño et al. 2005). For this sample, we also have multiband, multiepoch optical photometry from the CVSSO (Briceño et al. 2005, 2018, in preparation) and from the Sloan Digital Sky Survey (SDSS);12 near-infrared J, H, and Ks magnitudes from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006); Z, J, H, and Ks photometry from the Visible and Infrared Survey Telescope for Astronomy Science Verification Survey of Orion OB1 (VISTA; Petr-Gotzens et al. 2011); and infrared photometry from the Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) at 3.6, 4.5, 5.8, 8.0, and 24.0 μm from our GO-13437 and GO-50360 programs (Hernández et al. 2007b; C. Briceño et al. 2018, in preparation) and at 3.6, 4.5, 6, 12, and 22 μm from WISE (Wright et al. 2010). The two fields in the OB1a region are roughly centered on the 25 Ori cluster (Briceño et al. 2007) and the HR 1833 stellar aggregate (C. Briceño et al. 2018, in preparation), and combined they encompass 118 confirmed TTSs. The two Ori OB1b fields contain 47 confirmed TTSs. The spectral types for the young stars in both regions are similar and span the range K4–M5, which at the ages of our stars corresponds to masses 0.12 ≲ M/M☉ ≲ 1.2 (Baraffe et al. 1998).

2.2. Herschel PACS Photometry

Our Herschel/PACS imaging survey of the Orion OB1 fields was carried out with eight unique Herschel observations at 70 and 160 μm, obtained on 2012 March 16, 18, 28, and 29. We used the “scan map” observational template with medium scan speed (20′/s) to map a square field 30′ per side. Each scan line was 30′ long, and 134 overlapping scan lines with a step size of 15 arcsec were sufficient to reach the target size and sensitivity. Each field was observed twice at orthogonal scan directions. This technique is commonly used to mitigate the low-frequency drift of the bolometer time lines. With this configuration, we aimed at reaching a 1σ point source sensitivity of 2.6 and 6 mJy in the blue and red channels, respectively. Our Herschel program identifier is OT1_cncalvet_1.

We rely on the Herschel data processing pipelines (Ott 2010) for the initial data processing and begin further processing at the so-called Level 1 stage. All data discussed here are based on the “FM6” version of the PACS calibration (Nielbock et al. 2013) and processed with version 9 of the Herschel Interactive Processing Environment (HIPE Ott 2010) software.

We processed the Level 1 data with the Scanamorphos technique, a mapmaking software developed and described by Roussel (2012). Scanamorphos removes the 1/f noise13 by making use of the redundancy built in the observations. Readers are referred to Roussel (2012) for details about the processing steps. Scanamorphos preserves atmospheric emission on all spatial scales, ranging from point sources to extended structures with scales just below the map size; therefore, the maps produced are suitable for both spatially extended and point sources.

We performed source detection on the 70 μm images processed with Scanamorphos, using the daofind task in IRAF.14 We then proceeded to obtain aperture photometry on both 70 and 160 μm channels, using the IRAF apphot task. Following Fischer et al. (2013), for the 70 μm images we used an aperture radius of 9″6, inner sky annulus radius of 9″6, and sky annulus width of 9″6; for the 160 μm images we used an aperture radius of 12″8, inner sky annulus radius of 12″8, and a 12″8 sky annulus width. Because the pixel scale is 1″/pixel for the 70 μm images and 2″/pixel for the 160 μm images, these apertures correspond to 9.6 and 6.4 pixels, respectively. Though the relatively small apertures require large aperture corrections, 0.7331 for the blue channel (70 μm) and 0.6602 for the red channel (160 μm), they minimize uncertainties due to large variations in the sky background in regions with significant nebulosity, especially with the 160 μm images. Photometric errors were determined as the sum in quadrature of the measurement error and the calibration error.

Of the 165 TTSs located within the PACS fields, only 16 are classified as disk sources based on their Kσ − [4.5] excess, using the criterion in Figure 1 of Luhman & Mamajek (2012). The number of disk sources goes up to 25 if we use the excess emission at Kσ − [8.0] or Kσ − [24]. We detected eight of these disk sources with PACS (33%–50% depending on the disk indicator), all classified as accreting classical TTSs (CCTTs)15 based on our optical spectra. These objects are also tagged as Class II stars based on the IRAC SED slopes in Hernández et al. (2007b). They are distributed as follows: two are located in the OB1a region, specifically in the 25 Ori cluster and the HR 1833 group (C. Briceño et al. 2018, in preparation), and six in the two OB1b PACS fields. We present Herschel PACS photometry at 70 and 160 μm for these objects, PACS photometry is shown in Table 1 in the following order: target CVSO ID, 2MASS ID, right ascension, declination, 70 μm photometry at 70 and 160 μm for these objects, PACS photometry is shown in Table 1 in the following order: target CVSO ID, 2MASS ID, right ascension, declination, 70 μm flux, 160 μm flux, and the location of each source.

2.3. CanariCam Photometry

We observed five sources in the OB1 fields (two in OB1a: CVSSO-35 and CVSSO-1265; three in OB1b: CVSSO-104, CVSSO-114NE, and CVSSO-121) in the Si2 (8.7 μm), Si4 (10.3 μm), Si5 (11.6 μm), and Si6 (12.5 μm) narrowband silicate filters on 2014 September 22 and 23 and October 3 and 5 with the CanariCam16 instrument (Telesco et al. 2003) on the Gran Telescopio de Canarias (GTC). The selection criterion was targets with Spitzer/IRAC and Herschel/PACS (70 and 160 μm) detections. CanariCam has a 26′′ × 19′′ field of view with a detector plate scale of 0.08″ per pixel. The reduction of the data was done using the CanariCam data reduction pipeline (RedCan). RedCan produces flux-calibrated images using the associated standard star images along with their theoretical spectra reported by Cohen et al. (1999). An extensive description of the RedCan pipeline can be found in González-Martín et al. (2013). Table 2 summarizes the CanariCam photometry. Column

12 http://www.sds3.org/dr9/
13 The term 1/f noise is used here to generically describe bolometer signal drifts that are inversely correlated with their Fourier frequency.
14 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
15 CCTTs are T Tauri stars still actively accreting from a circumstellar disk; they are usually classified as such from low-resolution spectra showing a strong Hα emission line, with an equivalent width above the value expected for chromospheric emission at the spectral type of the star (White & Buri 2003).
16 http://www.gtc.iac.es/instruments/canaricam/canaricam.php
(1) shows the CVSO ID following Briceño et al. (2005), while Columns (2)–(5) indicate the fluxes in the four narrowband silicate filters for each source. Errors are about 15% of the photometric value in each band (Alonso-Herrero et al. 2016).

2.4. Optical Photometry

We obtained new optical photometry of a subset of our stars for which there was no existing SDSS photometry, or stars with UV excesses, or those with strong photometric variability between the CVSO and the SDSS photometric bands. These observations were obtained at the 4.3 m Discovery Channel Telescope (DCT) at Lowell Observatory, Arizona, USA, and the 0.84 m telescope at the San Pedro Mártir National Astronomical Observatory in Baja California, México.

2.4.1. The Discovery Channel Telescope

We observed CVSO-107 and CVSO-109 in the $U$, $B$, $V$, $R$, and $I$ Johnson–Cousins filters on 2013 November 29 with the Large Monolithic Imager (LMI) on the DCT. The LMI has a 12/5 × 12/5 field of view, with an unbinned pixel size of 0.412; we utilized the 2 × 2 pixel binning mode, resulting in a pixel scale of 0.′′24 per pixel. We used IRAF to carry out bias and flat-field corrections, using twilight flats, and then to derive aperture photometry interactively. The optical photometry is listed in Table 3, where we show the CVSO ID following Briceño et al. (2005) in Column (1) and present the photometry of the $U$, $B$, $V$, $R_c$, and $I_c$ filters of our sample in Columns (2)–(6).

2.4.2. San Pedro Mártir

CVSO-35, CVSO-104, CVSO-114NE, and CVSO-121 were observed in the $UBV(R_i)$ system, during an open cluster campaign, in 2016 December 4 and 5 at the San Pedro Martir (SMP) Observatory with the 0.84 m telescope and the Marconi 3 CCD detector (a deep depletion e2v CCD42-40 chip with gain of 1.83 e−/ADU and readout noise of 4.7 e−).

The field of view was 7′′4 × 7′′4, and binning 2 × 2 was used during the observations. In order to properly measure both bright and dim stars, different exposure times were employed. We used 2, 20, and 200 s in both $R$ and $I$ filters; 4, 40, and 400 s for the $V$ filter; 6, 60, and 600 s for the $B$ filter; and 10, 100, and 1000 s for the $U$ filter. Standard stars in Landolt fields were observed during the night in order to calibrate the photometry. The data reduction was done with IRAF, following the standard procedure for correcting bias and flat-field frames. Instrumental magnitudes were derived using standard point-spread function photometry. Transformation equations, based on the observed standard stars, were then applied to convert the instrumental magnitudes to calibrated magnitudes. The resulting photometry is shown in Table 3.

2.5. Submillimeter Photometry

We observed CVSO-107 and CVSO-109 on 2010 January 1 with the Submillimeter Array (SMA) on top of Maunakea, Hawaii, using the compact array configuration (projected baselines of 9.8–81.2 m). The weather was excellent, with the 225 GHz opacity around 0.05 and a stable atmospheric phase. The double-sideband system temperatures were 72–156 K. Calibration of the visibility phases and amplitudes was achieved with observations of the quasar J0532+075, at intervals of about 30 minutes. The bandpass response was calibrated using 3C 454.3. Observations of Uranus provided the absolute scale for the flux density calibration, and the derived flux of J0532+075 was 0.71 Jy. The data were calibrated using the MIR software package. Continuum images were generated and CLEANed using standard techniques in the MIRIAD software package. Fluxes are listed in Column (2) of Table 4.

2.6. Spitzer IRS Spectra

CVSO-107 and CVSO-109 were observed by the Spitzer IRS instrument on 2006 March 18 (AORKEY: 14646016) with the short-wavelength, low-resolution (SL) module and the long-wavelength, low-resolution (LL) module of IRS. The observation was carried out in IRS Staring mode, covering

### Table 1

PACS Photometry for CTTSs in the OB1a and OB1b Subassociations

| CVSO ID | 2MASS ID | R.A. (J2000.0) (hh:mm:ss) | Decl. (J2000.0) (hh:mm:ss) | $F_{50}$ (mJy) | $F_{160}$ (mJy) | Location |
|---------|----------|---------------------------|---------------------------|---------------|---------------|----------|
| CVSO-35 | 05254589+0145500 | 05:25:45.90 | +01:45:50.3 | 18.83 ± 1.19 | 12.77 ± 2.48 | 25 Ori |
| CVSO-104 | 05320638−0111000 | 05:32:06.45 | −01:11:00.3 | 77.41 ± 2.35 | 56.28 ± 3.78 | OB1b |
| CVSO-107 | 05322578−0036533 | 05:32:25.77 | −00:36:53.2 | 105.34 ± 3.32 | 106.51 ± 8.34 | OB1b |
| CVSO-109 | 05323565−0113461 | 05:32:35.66 | −01:13:46.0 | 69.38 ± 2.69 | 38.97 ± 5.36 | OB1b |
| CVSO-114NE | 05330196−0020593 | 05:33:01.97 | −00:20:59.3 | 30.67 ± 2.56 | 94.33 ± 12.12 | OB1b |
| CVSO-120 | 05334027−0038541 | 05:33:39.82 | −00:38:53.9 | 71.59 ± 2.26 | 47.29 ± 3.11 | OB1b |
| CVSO-238 | 05320040−0140110 | 05:32:00.40 | −01:40:11.0 | 8.126 ± 1.12 | 5.13 ± 2.92 | OB1b |
| CVSO-1265 | 05303164+0203051 | 05:30:31.66 | +02:03:05.2 | 35.32 ± 1.45 | 48.56 ± 2.95 | HR 1833 |

### Table 2

CanariCam Photometry of Five PACS Sources in the OB1a and OB1b Subassociations

| CVSO ID | $F_{52}$ (Jy) | $F_{54}$ (Jy) | $F_{55}$ (Jy) | $F_{56}$ (Jy) |
|---------|---------------|---------------|---------------|---------------|
| CVSO-35 | 68.86 | 106.96 | 120.58 | 121.09 |
| CVSO-104 | 25.08 | 50.75 | 48.28 | 16.92 |
| CVSO-114NE | 29.01 | 23.97 | 24.39 | 25.48 |
| CVSO-121 | 35.58 | 50.22 | 35.11 | 17.05 |
| CVSO-1265 | 27.51 | 56.73 | 34.98 | 20.70 |

Note. Column (1): CVSO ID following Briceño et al. (2005). Column (2): Si2 flux. Column (3): Si4 flux. Column (4): Si5 flux. Column (5): Si6 flux. Errors are about 15% of the photometric value in each band.

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http://www2.lowell.edu/~cqi/mircook.html
2007b median from Maucó et al. line is the stellar photosphere (VISTA UBVR CVSO ID 2018, in preparation).

Notes.
CVSO-121a 15.886
CVSO-114NEa 16.592
CVSO-109b 14.897
CVSO-107b 15.287
CVSO-104a 15.973

∼ DCT photometry.

a SPM photometry.
b DCT photometry.

Figure 2. Dereddened SEDs of the two stars in our sample that have Spitzer IRS spectra. Optical data are from the CVSO (Briceño et al. 2005, 2007; C. Briceño et al. 2018, in preparation), the SDSS, and the DCT; the near-IR magnitudes at J, H, and Ks are from 2MASS (Skrutskie et al. 2006); and those at Z, Y, J, H, and Ks are from VISTA (Petr-Gotzens et al. 2011). The mid-IR measurements at 3.6, 4.5, 5.8, 8, and 24 μm are from our Spitzer GO-13437 and GO-50360 programs (Hernández et al. 2007b), and those at 3.4, 4.6, 12, and 22 μm are from the AllWISE Source Catalog (Wright et al. 2010). The IRS spectra are shown as solid red lines. The dashed-blue line is the stellar photosphere (normalized to the J band of each object) of the same spectral type (Kenyon & Hartmann 1995), and the light-blue solid line is the Taurus median from Maucó et al. (2016). Error bars are typically smaller than the symbols.

Table 3
Optical Photometry

| CVSO ID  | U               | B               | V               | Rc               | Lc               |
|----------|-----------------|-----------------|-----------------|------------------|------------------|
| CVSO-35  | 16.744 ± 0.007  | 15.578 ± 0.002  | 14.059 ± 0.002  | 13.226 ± 0.002   | 12.388 ± 0.002   |
| CVSO-104 | 15.973 ± 0.017  | 15.659 ± 0.015  | 15.026 ± 0.076  | 14.442 ± 0.034   | 13.319 ± 0.007   |
| CVSO-107 | 15.287 ± 0.005  | 15.548 ± 0.004  | 14.628 ± 0.002  | 13.788 ± 0.004   | 12.831 ± 0.003   |
| CVSO-109 | 14.897 ± 0.012  | 14.997 ± 0.005  | 14.044 ± 0.003  | 13.260 ± 0.006   | 12.219 ± 0.005   |
| CVSO-114NE | 16.592 ± 0.005 | 16.984 ± 0.004  | 15.986 ± 0.010  | 15.086 ± 0.006   | 13.752 ± 0.007   |
| CVSO-121 | 15.886 ± 0.004  | 15.598 ± 0.001  | 14.392 ± 0.006  | 13.528 ± 0.003   | 12.672 ± 0.002   |

Notes.
a SPM photometry.
b DCT photometry.

dust structure needed to explain the emission. For objects with submillimeter data, we also show our disk mass estimates.

3.1. Spectral Energy Distributions

In Figure 2 we show the dereddened SEDs of our PACS sample for sources with Spitzer IRS spectra. Figure 3 shows the SEDs for those sources for which we do not have IRS data. We adopted the Mathis reddening law (Mathis 1990, R = 3.1) with visual extinctions, Av, from Briceño et al. (2005) and C. Briceño et al. (2018, in preparation). The dashed line indicates the stellar photosphere (normalized to the J band of each object) of the same spectral type following Kenyon & Hartmann (1995). The light-blue solid line is the Taurus median (estimated from photometric data only) for K and M, class II stars taken from Maucó et al. (2016). All our objects exhibit excesses over the photosphere from the near-IR to millimeter wavelengths consistent with the presence of a disk. Additionally, CVSO-35, CVSO-104, CVSO-121, and CVSO-1265 with CanariCam photometry and especially

Table 4
Submillimeter Fluxes

| CVSO ID | F_{1000} (mJy) |
|---------|----------------|
| CVSO-107| 7.1 ± 1.2      |
| CVSO-109| 3.2 ± 1.3      |

~5–40 μm at a resolving power of λ/δλ = 60–100. We extracted and calibrated the spectrum using the Spectral Modeling, Analysis, and Reduction Tool (SMART) software package (IRS instrument team; Higdon et al. 2004). More details on the data reduction can be found in Furlan et al. (2006).

3. Analysis and Results

In this section we examine the emission of the disks detected by PACS in the Orion OB1a and OB1b associations by comparing the predictions of irradiated accretion disk models to their SEDs. We estimate the stellar properties of our sample and describe the
CVSO-107 and CVSO-109 with IRS spectra show strong 10 μm silicate emission. CVSO-35, CVSO-104, CVSO-107, and CVSO-121 show significant variability in optical and near-IR as seen from the scatter in the $V$, $R_c$, $I_c$ magnitudes, as well as in the $J$, $H$, and $K_s$ bands taken at different epochs. Although most of our objects have typical full-disk excess emission beyond 20 μm, with SED comparable to the median of Taurus, objects like CVSO-107 and CVSO-238, and possibly CVSO-104 and CVSO-121, seem to have a flux deficit around 10–12 μm relative to the median, possibly the result of the first stages in the development of an inner disk gap; if so, these objects could be in the process of evolving to a TD, like CVSO-224 (see Espaillat et al. 2008b), which shows a deep emission deficit at wavelengths between ∼8 and 22 μm, the telltale sign of an inner disk hole cleared of dust. In the case of CVSO-114-NE PACS fluxes at wavelengths longer than 10 μm look flatter than in the rest of the sample. This star forms an apparent pair with the star CVSO-114SW, separated by 4.9′ (Thanathibodee et al. 2018) Both components have been observed and resolved using far-UV, optical, and near-IR spectroscopy, as well as high angular resolution imaging; analysis of the accretion properties indicates that the northeast (NE) component, studied here, is a CTTS, while the southwest (SW) component is a weak TTS (Thanathibodee et al. 2018). The SW component is only brighter than the NE component in the optical, so it is unlikely to have a contribution in the PACS range.

### 3.2. Stellar and Accretion Properties

We estimated stellar and accretion properties of all the CTTSs detected by PACS in Orion OB1a and OB1b reported as members in Briceño et al. (2005, 2007), for which we have the necessary spectra and photometry. Table 5 lists the results as follows: target CVSO ID from Briceño et al. (2005), spectral type, effective temperature ($T_{\text{eff}}$), visual extinction ($A_v$), stellar mass ($M_*$), stellar radius ($R_*$), stellar luminosity ($L_*$), accretion rate ($\dot{M}$), stellar age, and distance. To characterize the stellar properties of the sources, we located them in the H-R diagram. For this, we estimated the luminosity of our sample using 2MASS $J$ photometry, visual extinctions, and spectral types from Briceño et al. (2005; C. Briceño et al. 2018, in preparation). We used bolometric corrections and effective temperatures from the standard table for 5–30 Myr old PMS stars from Pecaut & Mamajek (2013). Using these luminosities and effective temperatures, we estimated stellar radii. We used the PMS evolutionary tracks of Siess et al. (2000) to obtain stellar masses. We assumed a distance for the OB1b association of 440 pc and distances of 354 and 368 pc for the 25 Ori and HR 1833 stellar aggregates, respectively (Briceño et al. 2005; C. Briceño et al. 2018, in preparation). Since Pecaut & Mamajek (2013) only include three optical magnitudes ($B$, $V$, and $R_c$), we used the intrinsic colors from Kenyon & Hartmann (1995), which includes more optical magnitudes ($U$, $B$, $V$, $R_c$, and $I_c$), to represent the stellar photosphere.

Mass accretion rates ($\dot{M}$) were estimated from the Hα line luminosity. The Hα luminosity was estimated by approximating the flux of the line ($F_{\text{Hα}}$) as $\text{EW}(\text{Hα}) \times F_{\text{cont}}$, where $F_{\text{cont}}$ and $\text{EW}(\text{Hα})$ are the continuum flux around the line and the equivalent width, respectively. In turn, we calculated $F_{\text{cont}}$ from the $R_c$ magnitude of each source (Briceño et al. 2005) corrected by extinction and its equivalent width $\text{EW}(\text{Hα})$ from low-resolution spectra (C. Briceño et al. 2018, in preparation). Finally, we used the relation between the Hα luminosity and mass accretion rate from Ingleby et al. (2013). All the accretion parameters of PACS CTTSs are shown in Table 5.

Two of our sources, CVSO-107 and CVSO-109, have reported accretion rates in Ingleby et al. (2014). They estimated $\dot{M}$ by fitting the excess in spectra taken with the Magellan
Echellette Spectrograph (MagE)\(^\text{19}\) using accretion shock models from Calvet & Gullbring (1998). Our estimate agrees with their results for CVSO-107 and is consistent within a factor of 2 for CVSO-109. Differences are mainly due to uncertainties in stellar mass, radius, and extinction.

### 3.3. Disk Models

We used the “D’Alessio Irradiated Accretion Disk” (DIAD) models from D’Alessio et al. (2006) in order to fit the SEDs of our sources. These models assume that the disk is heated by stellar irradiation and viscous dissipation. The viscosity is parameterized through \(\alpha\) (Shakura & Sunyaev 1973) assuming steady accretion with constant \(M\). To simulate the settling of dust, D’Alessio et al. (2006) considered two populations of dust grains that follow a size distribution \(a^{-\frac{75}{2}}\), where \(a\) is the radius of the grain, between \(a_{\text{min}}\) and \(a_{\text{max}}\) (Mathis et al. 1977). We assumed that the grains are segregated spheres (Pollack et al. 1994). One population consists of small \((a_{\text{max}} = 0.25 \mu m)\) grains dominant in the upper layers of the disk, while the other is described by larger grains in the disk midplane. The settling of dust is parameterized with the parameter \(\epsilon\), defined as \(\epsilon = \frac{\zeta_{\text{small}}}{\zeta_{\text{dust}}}\), where \(\zeta_{\text{small}}\) is the dust-to-gas mass ratio of small grains and \(\zeta_{\text{dust}}\) is the sum of the assumed mass abundances of the different dust components relative to gas, i.e., \(\epsilon\) describes the depletion (in mass) of small grains relative to the standard value. Therefore, lower values of \(\epsilon\) represent more settled disks.

The main input parameters are the stellar properties \((M_*, R_*, L_*)\); the mass accretion rate \((\dot{M})\); the viscosity parameter \((\alpha)\); the disk outer radius \((R_o)\); the cosine of the inclination angle \((\mu)\); the maximum grain size at the disk midplane \((a_{\text{max}})\), at the disk inner edge or wall \((a_{\text{max}_w})\), and at the disk upper layers \((a_{\text{max}})\); and the dust settling parameter \(\epsilon\).

TDS are modeled with an optically thick outer disk with a sharp inner edge (“inner wall”). In PTDs, the inner disk has a sharp inner edge (“inner wall”) located at the dust destruction radius for silicate grains. The emission from the inner wall is calculated from the stellar properties, the maximum grain size \((a_{\text{max}})\), and the temperature \((T_e)\), assumed to be the sublimation temperature of silicate grains (Muzerolle et al. 2003; D’Alessio et al. 2006; 1400 K), with a dust composition of pyroxenes and \(\zeta_{\text{sil}} = 0.004\). The height of the inner wall \((\zeta_{\text{w}})\) was fixed to 4 times the gas scale height. The stellar radiation impinges directly onto the wall, which we assume is vertical. We calculate the structure and emission of the wall atmosphere following the prescriptions of D’Alessio et al. (2004, 2005). We calculated the location and height of the inner edge of the outer disk (“outer wall”) by varying its radius \(R_{in}^w\), or equivalently its temperature \(T_{in}^w\) (see D’Alessio et al. 2005; Espaillat et al. 2010) to achieve the best fit to the SEDs.

In both PTDs and TDS, the gap or hole sometimes contains a small amount of optically thin dust, which contributes to the 10 \(\mu m\) silicate emission feature. We calculated the emission from this optically thin dust region following Calvet et al. (2002). The optically thin dust inside the gaps/holes is composed of amorphous silicates (olivines), amorphous carbon, and organics. Troilites and crystalline silicates in the form of enstatite and forsterite were only included in modeling objects with Spitzer/IRS spectra. Opacities and optical constants for organics and troilite were adopted from Pollack et al. (1994) and Begemann et al. (1994), respectively. We added organics and troilite to the dust mixture following Espaillat et al. (2010) with \(\zeta_{\text{org}} = 0.0041\) and \(\zeta_{\text{troi}} = 0.000768\) and sublimation temperatures of \(T_{\text{org}} = 425 K\) and \(T_{\text{troi}} = 680 K\). For the amorphous carbon we use \(\zeta_{\text{amc}} = 0.001\), and for silicates we use \(\zeta_{\text{sil}} = 0.004\). The opacity for crystalline silicates is taken from Sargent et al. (2009). We did not include ice in the optically thin region since the temperatures here are high enough for it to be sublimated. Opacities were calculated using Mie theory, assuming spherical grains (Pollack et al. 1994). We note, however, that we do not aim to model the detailed composition of dust in this region, but rather to

\(^*\) \(M\) estimated using \(R_e\) magnitude from DCT.

\(^{19}\) http://www.lco.cl/telescopes-information/magellan/instruments/instruments/mage

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#### Table 5

Properties of PACS CTTS Sources in the OB1a and OB1b Subassociations

| CVSO ID      | SpT | \(T_e\) (K) | \(A_e\) (mag) | \(M_*\) (\(M_\odot\)) | \(R_\odot\) (\(R_\odot\)) | \(L_e\) (\(L_\odot\)) | \(\dot{M}_\ast\) (10^{-6} \(M_\odot\) yr^{-1}) | Age (Myr) | \(d\) (pc) |
|--------------|-----|-------------|--------------|------------------|-----------------|----------------|---------------------|-----------|----------|
| CVSO-35      | K6  | 4020        | 0.3          | 0.73             | 1.67            | 0.66           | 0.87                | 3.0       | 354      |
| CVSO-104     | K7  | 3970        | 0.1          | 0.67             | 1.77            | 0.67           | 5.62                | 2.6       | 440      |
| CVSO-107     | K7  | 3970        | 0.4          | 0.66             | 2.07            | 0.96           | 2.89\(^*\)          | 1.6       | 440      |
| CVSO-109     | K0  | 3770        | 0.0          | 0.65             | 2.66            | 1.28           | 6.71\(^a\)          | 0.6       | 440      |
| CVSO-114NE   | M1.5| 3560        | 0.0          | 0.65             | 1.87            | 0.47           | 0.52\(^a\)          | 1.5       | 440      |
| CVSO-121     | K7  | 4020        | 0.4          | 0.67             | 1.92            | 0.86           | 2.32                | 2.4       | 440      |
| CVSO-238     | M0.6| 3630        | 0.0          | 0.65             | 1.52            | 0.36           | 3.71                | 2.5       | 440      |
| CVSO-1265    | K7  | 3970        | 0.0          | 0.70             | 1.32            | 0.39           | 1.51                | 6.7       | 368      |

**Note.** Column (1): ID following Briceño et al. (2005). Column (2): spectral type. Column (3): effective temperature. Column (4): visual extinction. Column (5): stellar mass. Column (6): stellar radius. Column (7): stellar luminosity. Column (8): mass accretion rate. Column (9): age. Column (10): distance (Briceño et al. 2005; C. Briceño et al. 2018, in preparation).

\(^a\) \(M\) estimated using \(R_e\) magnitude from DCT.

\(^{19}\) http://www.lco.cl/telescopes-information/magellan/instruments/instruments/mage
illustrate what typical dust compositions can reasonably describe the observed SEDs.

### 3.4. SED Modeling of (Pre-)transitional Disks

We have calculated detailed disk structures for eight CTTSs detected in our PACS 70 and 160 μm survey in the Orion OB1a and OB1b subassociations. We used the DIAD models (D’Alessio et al. 2006), constrained by the mass accretion rates estimated independently from optical spectra (Section 3.2). As a result of our modeling, all our objects turned out to be PTDs/TDs, characterized by small deficits of mid-IR emission along with strong silicate features at 10 μm. We found that the emission of the silicate bands cannot be reproduced by the classical full-disk model; instead, we needed a dust distribution characteristic of PTDs/TDs with optically thin dust inside their gaps/holes. We inferred the properties of the edge or “wall” of the outer disk, the size of the cavity, the mass and composition of the optically thin dust inside the cavity, and, for those objects with millimeter photometry, we also estimated disk masses and radii.

We used as input for the models the stellar properties, accretion rates, and distances reported in Table 5. For each object we calculated a total of 2160 optically thick disk models and more than 1500 optically thin dust models. All the relevant parameters we varied are listed in Table 6. We selected as the best fit the model that yielded the minimum value of the \( \chi^2_{\text{red}} \) values between photometric bands taken at almost the same wavelength. The following pairs of photometric bands were averaged: SDSS(riz)–CVS0(VRI), 2MASS(JHK)–VISTA(JHK), and IRAC/MIPS(3.6,4.5,24)–WISE(W1,W2, W4). For objects without SDSS photometry or incomplete CVSO photometry, we used SPM and DCT data instead. When multiepoch photometry was available, we took the maximum difference between photometric values as the standard error used in the estimate of the \( \chi^2_{\text{red}} \). However, since our main purpose is to model the emission from the disk rather than stellar variability, we assigned a 90% weight to data with wavelength larger than 2 μm and the remaining 10% to the optical data in the final \( \chi^2_{\text{red}} \).

Figures 4 and 5 show the SEDs of our PACS disks (filled circles) with the resulting fit (solid lines). The contributions of the different model components are also shown. The CanariCam photometry around 10 μm and IRS spectra are highlighted (red). Tables 7 and 8 list the parameters of the best-fit model for each object; in Table 7 we show the outer disk properties, and in Table 8 we show the properties of the optically thin dust region.

As shown in Figures 4 and 5, PACS fluxes are almost completely dominated by the wall of the outer disk for most of our sources, so we cannot constrain the properties of the outer disks for objects without millimeter photometry. However, we did estimate confidence intervals for the location of the outer wall and its height. To set these intervals, we first estimated the likelihood function, \( L \), which is related to the \( \chi^2_{\text{red}} \) values through the expression \( L = \exp(-\chi^2_{\text{red}}/2) \). Since \( \chi^2_{\text{red}} \) is a multidimensional function, at every \( R_{\text{w}}^o \) or \( z_{\text{c}}^o \) we have several values of \( \chi^2_{\text{red}} \) for each one of the calculated models. Thus, the likelihood \( L \) is computed using the minimum \( \chi^2_{\text{red}} \) value in each case. Figures 6 and 7 show the likelihood function for \( R_{\text{w}}^o \) and \( z_{\text{c}}^o \), respectively. The confidence intervals are given as those extreme limits at which the area below the likelihood curve maximum is 68% (1σ) of its total area (Sivia & Skilling 2012). These intervals are indicated by light-blue shaded regions in each panel and are reported in Table 7. For those cases where the best parameter falls on one of the edges of the range of values used in the models, we have considered these values as upper or lower limits, and they are indicated by parentheses instead of square brackets in Table 7.

Even though we are including the errors in the photometry and a proxy of the star variability in the estimate of the \( \chi^2_{\text{red}} \), there are other sources of uncertainty, such as the inherent uncertainties in the distance, spectral types, and mass accretion rates. Therefore, the \( \chi^2_{\text{red}} \) should be taken only as a guide in order to obtain the model that provides the best fit to the photometry for each source and not as an actual estimate of the goodness of the fit.

#### 3.4.1. Inner Disk and Optically Thin Region

The inner parts of our PTDs consist of an optically thick dusty belt within the first ~0.2 au from the star and with grains that can reach 10 μm in size. The innermost edge of this ring of optically thick material is located at the dust destruction radius given by the sublimation temperature of silicate grains (1400 K).

All our objects needed the presence of a small amount of optically thin dust inside their cavities. Keeping the total mass fraction of silicates relative to gas constant, \( \zeta_{\text{silt}} = 0.004 \), we
varied the fractional abundance of the different silicate species (see Section 3.3) inside the gaps/holes, the extension of the optically thin region ($R_{i,\text{thin}}$, $R_{o,\text{thin}}$), the maximum size of the dust grains ($a_{\text{max,thin}}$), and the exponent of the power law describing the dust distribution ($p$) in order to fit the silicate feature. The total emission of the optically thin region was scaled to the vertical optical depth at 10 μm ($\tau_0$). Table 6 describes the parameter space we used in order to model the optically thin dust inside the cavities, while Table 8 lists its estimated properties.

The silicate emission feature of all our objects with CanariCam photometry except CVSO-114NE can be explained with small submicron-sized grains. CVSO-114NE exhibits no 10 μm silicate feature, indicating a lack of small grains; in this case, we found that larger grains ($a_{\text{max,thin}} = 10 \mu m$) can describe the emission. Our modeling of the silicate features was more detailed for those objects with Spitzer/IRS spectra. The silicate feature of CVSO-109 resembles that of pristine spectra, e.g., with no signs of dust processing (Watson et al. 2009), and it is composed of dust made up entirely of amorphous silicates (~99%). CVSO-107, on the other hand, shows forsterite and enstatite features beyond 20 μm in its IRS spectra (e.g., the 33 μm forsterite feature). We found an optically thin dust composition consistent with ~79% amorphous silicates, ~13%
forsterite and enstatite crystals, and ~9% organics. Figure 8 shows the fit to the IRS spectrum range for both sources. The mass of optically thin dust populating the cavities (Table 8) ranges from $7.2 \times 10^{-11} M_\odot$ to $1.44 \times 10^{-8} M_\odot$. According to Table 8, the optically thin dust region extends to more than 50% the size of the disk gap for about half of the sample, and about 30% or less for the other half. These results should be taken as an approximation of how much dust is required within the gaps/holes to be able to explain the observed emission and not as a detailed prescription of the actual spatial distribution of dust. High-resolution IR interferometry is needed to probe the morphology of this component in detail.

### 3.4.2. Outer Disk

The disks in the sample have a wide range of gap/hole sizes, from ~4 au to almost 90 au in radius. Large confidence intervals obtained for some objects reflect the need for acquiring mid-IR spectra along with (sub)millimeter data to better constrain cavity sizes. We estimated outer disk properties for CVSO-107 and CVSO-109, the only two sources with SMA detections in the sample. The disks required low values of the viscosity parameter (Table 7), similarly to other PTDs/TPDs (Espaillat et al. 2007, 2008a, 2010), and a significant degree of dust settling, $\epsilon \lesssim 0.01$. CVSO-107 has a disk radius of $R_d = 300$ au, while CVSO-109 has a smaller disk with $R_d = 200$ au.

In CVSO-35, the only TD in the sample, the PACS emission is not entirely dominated by the outer wall, but seems to have a small contribution from a low-mass optically thick outer disk (see Figure 4). We found a disk with $\alpha = 0.01$, $\epsilon = 0.001$, and $R_d = 300$ au. However, these values should be taken as an approximation since we do not have (sub)millimeter data for this source.

### 3.4.3. Disk Masses

The dust masses of the best-fit models for objects in which we probe the outer disk are given in Table 7. The corresponding total disk mass, with a dust-to-gas mass ratio $\zeta = 0.0065$ (the sum of our assumed abundances), is also
given. We note, however, that the disk mass for CVSO-35 should be taken with caution since we need (sub)millimeter data to properly constrain this parameter.

We compared the masses obtained through detailed modeling of the SEDs with disk masses estimated using the SMA fluxes at 1.3 mm of CVSO-107 and CVSO-109 and assuming optically thin emission. Following Hildebrand (1983),

\[ M_{\text{dust}} = \frac{F_{\nu} d^2}{\kappa_{\nu} B_{\nu}(T_{\text{dust}})} \]

where \( F_{\nu} \) is the submillimeter flux at 1.3 mm, \( d \) is the source distance, \( T_{\text{dust}} \) is a characteristic dust temperature assumed to
be the median for Taurus disks (Andrews & Williams 2005; $T = 20$ K), $B_v$ is the Planck function at $T_{dust}$, and $\kappa_\nu$ is the dust grain opacity taken as $0.1 \text{ cm}^2 \text{ g}^{-1}$ at 1000 GHz using an opacity power-law index of $\beta = 1$ (Beckwith et al. 1990). Using the above equation and a dust-to-gas mass ratio of 0.01, we computed $M_{\text{disk}}$ of 0.0087 and 0.0039 $M_\odot$ for CVSO-107 and CVSO-109, respectively. These masses are a factor of $\sim 6$ and $\sim 3$ lower than the masses obtained from detailed modeling (Table 7). The difference is due in part to the difference in opacities (our opacity is a factor of 2 lower than the $\kappa_\nu$ used in Equation (1) and dust-to-gas mass ratios, due to the assumption of constant temperature, and also due to the contribution from hotter, optically thick disk regions to the $1.3 \text{ mm}$ flux, not included in Equation (1)). We stress that we used a consistent opacity law for each one of our objects, which depends on the mix of materials assumed in our disk models (silicates, graphite, water, etc.), their abundances, and their grain size distributions, rather than the simplified approach of a single grain opacity in an isothermal disk to estimate disk masses reported in Table 7.

4. Discussion

4.1. Why These Objects Fail to Be Described as Full Disks

In order to model our disk sample, we included both full and truncated disk models as priors, and the best fit was obtained with PTDs/TDs. We first note the small decrease of mid-IR emission in the SEDs of some of our objects compared to the median of CTTSs in Taurus (Figure 3, light-blue line). This points to a lack of optically thick material similar to those found in known PTDs (Espaillat et al. 2008a, 2010). More importantly, full-disk models do not appear to produce high enough IR emission at $10 \mu m$ to explain the observed silicate features, even in objects with IRS spectra as CVSO-107 and CVSO-109. Figures 9 and 10 show the best fit to the SEDs of CVSO-107 and CVSO-109, respectively, considering full-disk models. As shown, the model underestimates near- and mid-IR excesses, especially at the silicate bands at 10 and $20 \mu m$ (see figure insets). For CVSO-109 the model also overestimates the emission beyond $26 \mu m$. A viable way to generate high enough emission at the silicate bands and a small decrease in the mid-IR emission is by including optically thin dust inside gaps.

Even in the case of CVSO-238, which does not have photometry or spectra around $10 \mu m$, we were unable to model its PACS photometry along with its WISE $22 \mu m$ and IRAC/MIPS $24 \mu m$ photometry with a full disk.

Given the intermediate to advanced age of this region, it is not unreasonable to think that these objects may have experienced significant evolution over time. Based on our disk mass estimates for CVSO-107 and CVSO-109, we can assume that early on in their lives there was probably enough material to form multiple planets. If this is indeed the case, then these planets might be responsible for the radial structures—characteristic of disks with gaps and holes—observed here. However, there are other possible explanations. For instance, magnetized disks without planets (Flock et al. 2015), or fast pebble growth near condensation fronts (Zhang et al. 2015), may create structures in disks. In these cases, rings in disks can be the precursors of planets rather than the cause (e.g., Carrasco-González et al. 2016). The clear presence of near-IR excesses in the SEDs of all our stars, along with significant mass accretion rates, indicates that there is still gas and dust in the inner regions, and therefore these objects can be classified as PTDs/TDs based on the observational data currently available for these sources. We note, however, that high-resolution IR interferometric observations are still needed in order to confirm the morphology of these disks.

4.2. Implications for Dust Evolution

Investigating dust evolution in the outer disk requires far-IR observations of a significant sample of TTSs spanning the first several megayears in the lives of low-mass stars. Since by 5 Myr only about 20% of the stars still retain their inner disks (Hernández et al. 2007a), disk populations at intermediate ages are essential to link current disk properties with evolutionary processes.

As shown in Figure 4 and discussed in the previous section, the SED modeling of our sources indicates that these are PTDs/TDs. Moreover, while most PTD/TD studies have focused on young star-forming regions of less than 3 Myr, few have been done to address the physical mechanisms responsible for the existence of PTDs/TDs in older regions.

The intermediate to advanced age of our sources (4–10 Myr) poses two possible evolutionary scenarios: (1) that these stars had full disks until recently and have now become PTDs/TDs, or (2) that the PTD/TD appearance is
long-lasting, in which case we are actually looking at “mature” PTD/TD systems. The latter argument is reinforced by the fact that all our PACS detections turn out to be PTDs/TDs. This challenges the current understanding of disk evolution, where PTD morphology is thought to be a transient stage. Moreover, dust evolution models struggle to find viable ways to explain inner disk survival for long periods of time.

One possible mechanism that seems to explain PTD appearance is dust filtration induced by the presence of embedded planets (e.g., Paardekooper & Mellema 2006; Rice et al. 2006; Fouchet et al. 2007; Zhu et al. 2012; Espaillat et al. 2014; Pinilla et al. 2015). Since dust and gas in disks are not perfectly coupled, gas drag forces dust grains to drift toward a pressure maximum (Weidenschilling 1977; Johansen et al. 2014). This filtration process will lead to discontinuous grain populations in the radial direction, with small grains in the inner disk and larger grains outward. Recently, Pinilla et al. (2016) studied partial filtration of dust particles to explain the survival of the inner disks in PTDs by combining hydrodynamical simulations of planet–disk interactions with dust evolution models. According to them, in systems forming low-mass planets (<1 M\(_{\text{jup}}\)), the micron-sized particles (≤1 μm) are not perfectly trapped at the outer edge of the planet gap, but in constant movement through the gap via turbulent diffusion. This partial filtration of grains supports a constant replenishment of small dust from the outer to the inner disk. As a consequence, the near-IR excess can remain for up to 5 Myr of evolution, and the SED morphology remains almost identical. They concluded that the near-IR excess that characterizes PTDs is not necessarily an evolutionary effect, but depends on the type of planets sculpting the disks. Our sources are at the upper end of ages studied by Pinilla et al. (2016) (they only considered 1 and 5 Myr old disks); nonetheless, if this effect remains for older disks, which is possible since these disks are still accreting, then the results of Pinilla et al. (2016) suggest that the disks studied here could be forming low-mass planets.

Some of our targets exhibit strong silicate emission. The silicate feature at 10 μm carries vital information of the submicron grains left over inside the gaps and holes of PTDs/TDs. In particular, it carries information on dust processing in the inner disk through the presence of crystalline material. For the two sources with IRS spectra, we were able to estimate the general composition of dust grains producing the silicate characteristic emission. CVSO-109 has no signs of crystalline silicates, while CVSO-107 exhibits some degree of dust processing with small amounts of enstatite and forsterite crystals. This variety of dust properties for objects of the same region is hard to explain and might indicate some correlation between the processes that create the optically thin dust with disk local conditions, e.g., density and temperature, over time. The presence or absence of crystals inside disk cavities sets important constraints to the density and temperature profiles of the small dust (coupled to the gas) that will probably end up forming planets and thus setting their properties.

Total disk masses of the two targets with SMA fluxes are greater than 10 M\(_{\text{jup}}\), the minimum-mass solar nebula (Weidenschilling 1977). However, these masses are estimated assuming a dust-to-gas mass ratio of 0.0065. If one considers larger dust-to-gas mass ratios, which are expected in older star-forming regions, these values can easily drop below a few Jupiter masses. Moreover, dust disk masses for these objects are small and well below the minimum mass of solids needed to form the planets in our solar system (Weidenschilling 1977). This is consistent with previous studies in other star-forming regions indicating that disks older than 5 Myr lack sufficient dust to form giant planet cores and therefore that timescales for giant planet formation must be quite short (Carpenter et al. 2014; Barenfeld et al. 2016, 2017).

5. Summary and Conclusions

We present Herschel PACS fluxes at 70 and 160 μm and CanariCam 10 μm photometry of eight CTTSs in the Orion OB1a and OB1b subassociations. We combined the Herschel data with optical UBVR\(i\), near- and mid-IR, and submillimeter photometry and mid-IR spectra from Spitzer, when available, to construct the SEDs of these sources, which we modeled with irradiated accretion disk models (D’Alessio et al. 2006). Our main conclusions are as follows:
1. The best-fit models to the SEDs of the targets indicate that all are PTDs/TDs, with some amount of optically thin dust inside their cavities. PACS photometry was particularly useful to characterize the inner edge of the outer disks. Full-disk models cannot produce enough emission at 10 μm to explain the CanariCam photometry or the Spitzer IRS spectra.

2. The IRS spectra of CVSO-107 and CVSO-109 can be explained with small grains mostly composed of amorphous silicates. The silicate feature of CVSO-109 resembles that of a pristine spectrum with no signs of dust grain processing. In contrast, the IRS spectrum of CVSO-107 is better described with the presence of enstatite and forsterite crystals in its optically thin dust mixture.

3. The presence of near-IR excess in the SEDs of our 4−10 Myr PTD sample may point to low-mass (<1 M_jup) planet formation. According to Pinilla et al. (2016), the survival and maintenance of the inner disk could be explained by partial filtration of dust, in which the micron-sized grains pass through the gap, supporting a constant replenishment of dust from the outer to the inner disk.

4. Our inferred dust disk masses, M_dust, are less than the minimum mass of solids needed to form the planets in our solar system. This is consistent with previous studies on disk populations older than 5 Myr, giving support to the scenario of short timescales for giant planet formation.

We thank the referee for the helpful comments that improved the content and presentation of this work. We also thank the observers who were involved in acquiring one or more sets of observations.

K.M. acknowledges a scholarship from CONACYT.

C.C.E. was supported by the National Science Foundation under grant no. AST-1455042.

These results made use of the Discovery Channel Telescope at Lowell Observatory, supported by Discovery Communications, Inc., Boston University, the University of Maryland, the University of Toledo, and Northern Arizona University. The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration, including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

J.B.-P. acknowledges UNAM-PAPIIT grant no. IN110816 and UNAM’s DGAPA-PASPA Sabbatical program.

J.H. acknowledges UNAM-PAPIIT grant no. IA103017.

The grid of accretion disk models used in the present work has been calculated using the supercomputers Miztli, at DGTIC, provided by UNAM, and Mourioka, at IRIyA, provided by CONACyT grant number INFR-2015-01-252629.

Software: Astropy (Astropy Collaboration et al. 2013), Matplotlib (Barrett et al. 2005), HIPE (Ott 2010), RedCan (González-Martín et al. 2013), IRAF (Davis 1999), MIRIAD (http://www.cfa.harvard.edu/cqj/mircook.html), SMART (Higdon et al. 2004).

Facilities: Herschel(FACS), GTC(CanariCam), SMA, OANSP:0.8 m, DCT(LMI), Spitzer(IRS), WISE, Sloan, CTIO:2MASS.

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