SPITZER OBSERVATIONS OF THE ORION OB1 ASSOCIATION: DISK CENSUS IN THE LOW-MASS STARS

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ABSTRACT

We present new Spitzer observations of two fields in the Orion OB1 association. We report IRAC/MIPS observations for 115 confirmed members and 41 photometric candidates of the ~10 Myr 25 Orionis aggregate in the OB1a subassociation, and 106 confirmed members and 65 photometric candidates of the 5 Myr region located in the OB1b subassociation. The 25 Orionis aggregate shows a disk frequency of 6%, while the field in the OB1b subassociation shows a disk frequency of 13%. Combining IRAC, MIPS, and 2MASS photometry, we place stars bearing disks in several classes: those with optically thick disks (class II systems), with an inner transitional disks (transition disk candidates), and with “evolved disks”; the last exhibit smaller IRAC/MIPS excesses than class II systems. In all, we identify one transitional disk candidate in the 25 Orionis aggregate and three in the OB1b field; this represents ~10% of the disk-bearing stars, indicating that the transitional disk phase can be relatively fast. We find that the frequency of disks is a function of the stellar mass, suggesting a maximum around stars with spectral type M0. Comparing the infrared excess in the IRAC bands among several stellar groups, we find that inner disk emission decays with stellar age, showing a correlation with the respective disk frequencies. The disk emission at the IRAC and MIPS bands in several stellar groups indicates that disk dissipation takes place faster in the inner region of the disks. Comparison with models of irradiated accretion disks, computed with several degrees of settling, suggests that the decrease in the overall accretion rate observed in young stellar groups is not sufficient to explain the weak disk emission observed in the IRAC bands for disk-bearing stars with ages 5 Myr or older; larger degrees of dust settling are necessary to explain these objects.

Subject headings: infrared: stars — open clusters and associations: individual (Orion OB1 association) — planetary systems: protoplanetary disks — stars: pre-main-sequence

Online material: color figures

1. INTRODUCTION

Observational and theoretical studies indicate that important processes in the evolution of protoplanetary disks take place at ages between 1 and 10 Myr. About 90% of the low-mass stars (~K5 or later) have lost their primordial disks at 5–7 Myr (e.g., Haisch et al. 2001; Hartmann 2005; Hernández et al. 2007). Grains grow to sizes of ~1000 km stirring up the leftover small objects in the disks and originating the first generation of reprocessed dust by collisional cascades (Kenyon et al. 2005; Hernández et al. 2006). Giant planets are expected to form in this period (Pollack et al. 1996; Alibert et al. 2004). However, additional studies of disk population in this crucial age range are necessary to improve our knowledge and clarify many details about the evolution from primordial disks to planetary systems.

OB associations are excellent laboratories for comparative studies of protoplanetary disk evolution, because they harbor young stellar populations (1–10 Myr) originating from the same giant molecular clouds, spanning a wide range of stellar masses, and in a variety of evolutionary stages and environments (Brown et al. 1999; Sicilia-Aguilar et al. 2006; Briceño et al. 2007b; Preibisch & Zinnecker 2006). In particular, the Orion OB1 association (Ori OB1), as other OB associations, shows a well-defined age sequence, suggesting a large-scale triggered star formation scenario (Briceño et al. 2005, 2007b; Lee & Chen 2007). Ori OB1 contains very young subgroups (ages ≤1 Myr) still embedded in their natal gas (e.g., Orion A and B clouds; Megeath et al. 2005), subgroups in the process of dispersing their natal gas (e.g., the σ Orionis cluster, age ~3 Myr; Hernández et al. 2007) and more evolved populations, which have long since dissipated their progenitor molecular clouds (e.g., the 25 Orionis aggregate, age ~10 Myr; Briceño et al. 2007a).

We are carrying out an optical photometric and spectroscopic survey of ~128 deg² in Ori OB1 in order to identify the low- and intermediate-mass stellar populations, and study the properties linked to the first stages of star and disk evolution (Briceño et al. 2001, 2005, 2007a, 2008, in preparation; Calvet et al. 2005a; Hernández et al. 2005, 2006, 2007). In this work we expand the results from the optical survey with the capabilities of the Spitzer Space Telescope at near- and mid-infrared wavelengths to identify and characterize protoplanetary disks around young stellar objects (e.g., Allen et al. 2004; Megeath et al. 2004; Gutermuth et al. 2004; Muzerolle et al. 2004; Hartmann et al. 2005; Sicilia-Aguilar et al. 2006; Hernández et al. 2007). In particular we study the near- and mid-infrared properties of stars in two IRAC/MIPS Spitzer fields encompassing an area of ~2.5 deg². One field is located in the 7–10 Myr 25 Orionis stellar aggregate (Briceño et al. 2007a), the most populous ~10 Myr stellar group known within 500 pc; the other is located in the Ori OB1b subassociation, in which we have estimated an age of ~5 Myr.
SPITZER DISK CENSUS IN ORI OB1

2. OBSERVATIONS

2.1. Infrared Photometry

We have obtained near-infrared (NIR) and mid-infrared photometry of two regions in the Orion OB1 association using the four channels (3.6, 4.5, 5.8, and 8.0 $\mu$m) of the InfraRed Array Camera (IRAC; Fazio et al. 2004), and the 24 $\mu$m band of the Multiband Imaging Spectrometer (MIPS; Rieke et al. 2004), on board the Spitzer Space Telescope. The field located in the 25 Orionis aggregate (hereafter “25 Orionis”) covers an area of $\sim1.1$ deg$^2$ centered at R.A. $\sim5.42^h$ and decl. $\sim1.64^\circ$; the other field (hereafter “OB1b”) covers an area of $\sim1.4$ deg$^2$ on the Orion OB1b subassociation centered at R.A. $\sim5.52^h$ and decl. $\sim-1.71^\circ$. Dust infrared emission maps (Schlegel et al. 1998) reveal that at least 90% of the regions covered by IRAC images in 25 Orionis and OB1b have visual extinctions smaller than $A_V \sim 0.12$ and 0.6, respectively (see Hernández et al. 2006). These values are mostly in agreement with the mean visual extinction calculated from individual stars in Briceno et al. (2005).

The IRC observations were done using a standard raster map with 290" offsets, to provide maximum areal coverage with just a slight overlap between frames, to aid in mosaicking the data. Each position is composed of three dithers, with a single-frame integration of 12 s. The IRC observations were processed using the IRAcproc (Schuster et al. 2006) package to create the final mosaics with a scale of 0.86 " pixel$^{-1}$ (see Hernández et al. 2006). Point-source detections were carried out individually on each IRC channel using PhotVis tool (an IDL GUI-based photometry visualization tool developed by R. Gutermuth). More than 20,000 sources in each field were detected in at least one Spitzer band. We extracted the photometry of these objects using the apphot package in IRAF, with an aperture radius of 3.7" and a background annulus from 3.7" to 8.6". We adopted zero-point magnitudes for the standard aperture radius (12") and background annulus (12"--22.4") of 19.665, 18.928, 16.847, and 17.391 in the [3.6], [4.5], [5.8], and [8.0] channels, respectively. Aperture corrections were made using the values described in IRAC Data Handbook (Reach et al. 2006).

MIPS observations were obtained using the medium scan mode with full-array cross-scan overlap, resulting in a total effective exposure time per pointing of 40 s. The images were processed using the MIPS instrument team Data Analysis Tool (DAT), which calibrates the data and applies a distortion correction to each individual exposure before combining it into a final mosaic (Gordon et al. 2005). We obtained point-source photometry at 24 $\mu$m with IRAF/DAOPHOT point-spread function fitting, using an aperture size of about 5.7" and an aperture correction factor of 1.73 derived from the STinyTim PSF model. The absolute flux calibration uncertainty is less than 5%. Our final flux measurements are complete down to about 1 mJy in both maps (the limit flux is about 0.5 mJy).

Figures 1 and 2 show color images combining three channels of IRAC ([3.6], [4.5] and [8.0]) for 25 Orionis and for OB1b, respectively. We display the low-mass spectroscopic members from Briceno et al. (2005, 2007a, 2008, in preparation) and the low-mass photometric candidates selected in § 2.3; the stars bearing disks studied in § 3.1; and the intermediate-mass members including the debris disk candidates and the Herbig Ae stars studied in Hernández et al. (2006).

2.2. Optical Photometry

Optical (V and $I_C$) magnitudes were obtained from the CIDA Variability Survey which is being carried out using the QUEST I camera (Baltay et al. 2002) installed on the Jurgen Stock Telescope (a celar aperture 1 m Schmidt Telescope) at the Venezuela National Astronomical Observatory. The camera, an array of 4 x 4 CCDs, is designed to work in drift-scan mode, which is a very efficient way to survey large areas of the sky. Each scan was reduced and calibrated with the standard QUEST software and the method described in Vivas et al. (2004) in which variable stars can be identified (see Briceño et al. 2005).
2.3. Low-Mass Members and Photometric Candidates

We follow the procedures described in Hernández et al. (2007) to reject nonstellar objects and contaminating sources using IRAC color–color and IRAC color–magnitude diagrams. In brief, we select stars with $[3.6] < 14.5$, below this limit, the contamination from extragalactic sources is expected to be more than 50% (Fazio et al. 2004). The $[4.5] - [5.8]$ versus $[5.8] - [8.0]$ and $[3.6] - [5.8]$ versus $[4.5] - [8.0]$ color–color diagrams were used to eliminate most of the galaxies with polycyclic aromatic hydrocarbon (PAH) emission and objects with strong 8 μm contamination (Gutermuth et al. 2008, in preparation).

Optical and 2MASS counterparts for the IRAC sources were found using a 2σ matching radius. A preliminary list of 623 objects in 25 Orionis and 918 objects in OB1b were created using optical-2MASS color–magnitude diagrams ($V$ vs. $V - I_C$, $V$ vs. $V - J$, and $J$ vs. $J - K$) to select those objects above the zero-age main sequence (ZAMS; Siess et al. 2000) at the distance of each stellar group (330 and 440 pc for 25 Orionis and OB1b, respectively; Briceno et al. 2005, 2007a; Hernández et al. 2005). We rejected by visual inspection nonmembers sources, like diffuse objects, and objects with an apparent problem in the photometry, like close binaries, faint-companion binaries, and stars on the image border.

Low-mass members were confirmed by Briceno et al. (2005, 2007a, 2008, in preparation) for more details about spectroscopic membership confirmation of stars belonging to the Ori OB1 association. Tables 1 and 2 show the IRAC and MIPS analysis (Hernández et al. 2005) to select those objects above the zero-age main sequence (ZAMS; Siess et al. 2000) at the distance of each stellar group (330 and 440 pc for 25 Orionis and OB1b, respectively; Briceno et al. 2005, 2007a; Hernández et al. 2005).

3. RESULTS

3.1. Disk Diagnostics

Figures 4 and 5 show three diagrams used to identify and roughly characterize the stars bearing disks in 25 Orionis and OB1b, respectively. The top panels show the SED slope, determined from the $[3.6] - [8.0]$ color (IRAC SED slope), versus the $[8.0]$ magnitude for members (open circles) and photometric candidates (open squares). The photospheric level is described by the upper solid line, which is calculated using the photometric errors propagated from the $[3.6] - [8.0]$ color (Hernández et al. 2007). Stars with excess emission at 8 μm can be identified in this diagram. For comparison, IRAC SED slope diagrams for Taurus (Hartmann et al. 2005) and for the σ Orionis cluster (Hernández et al. 2007) are displayed. In general, disk-bearing stars in Taurus (solid histogram) are located in a well-defined region (which we call the class II region) with an IRAC SED slope $> -1.8$ (see Lada et al. 2006); this limit (dashed lines) is used to identify objects with optically thick disks in which the inner disk emission has not been affected significantly by evolutionary processes. In contrast, 15% of the disk-bearing stars in the σ Orionis cluster exhibit smaller IRAC excesses (dashed histogram) suggesting a reduction in disk photosphere height, possibly due to dust growth and/or settling (Hernández et al. 2007). The bottom left panel shows the $K - [24]$ versus $V - J$ color–color diagram, in which we identify members (big open circles) and photometric candidates (big open squares) with 24 μm infrared emission above the photospheric level (solid lines) indicating that disks are present around these objects (e.g., Gorlova et al. 2006; Hernández et al. 2006, 2007). In this panel, we display the $K - [24]$ color distribution for stars bearing disks in the σ Orionis cluster with an IRAC SED slope $> -1.8$ (which represents a disk population similar to those found in Taurus) and we use this histogram to identify stars with $K - [24]$ color characteristic of stars with optically thick disks ($K - [24] > 3.5$, class II region). In the top panel and in the bottom left
| OB1a ID   | 2MASS ID          | R.A. (J2000.0)   | Decl. | [3.6]   | [4.5]   | [5.8]   | [8.0]   | [24.0]  | References | Disk Types |
|----------|-------------------|------------------|-------|---------|---------|---------|---------|---------|------------|------------|
|          |                   | (deg)            | (deg) | (mag)   | (mag)   | (mag)   | (mag)   | (mag)   |            |            |
| 9............. | 05224654+0134010  | 80.69393         | 1.56697 | 12.419 ± 0.030 | 12.629 ± 0.131 | 12.275 ± 0.036 | 12.458 ± 0.042 | ... ± ... | 3 | CIII |
| 25............. | 05224842+0140348  | 80.7076          | 1.67885 | 12.817 ± 0.030 | 12.777 ± 0.031 | 12.753 ± 0.041 | 12.824 ± 0.057 | ... ± ... | 3 | CIII |
| 47............. | 05225186+0145132  | 80.71609         | 1.75367 | 13.269 ± 0.031 | 13.262 ± 0.032 | 13.139 ± 0.050 | 13.450 ± 0.112 | ... ± ... | 3 | CIII |
| 53............. | 05225304+01512151 | 80.72102         | 1.87088 | 12.416 ± 0.030 | 12.348 ± 0.031 | 12.240 ± 0.036 | 12.258 ± 0.043 | ... ± ... | 3 | CIII |
| 905............. | 05245885+0125183  | 81.24523         | 1.42177 | 12.904 ± 0.031 | 12.724 ± 0.031 | 12.456 ± 0.037 | 11.889 ± 0.040 | 9.20 ± 0.04 | 3 | EV |
| 930............. | 05250192+0134563  | 81.25801         | 1.58232 | 11.720 ± 0.030 | 11.865 ± 0.030 | 11.562 ± 0.032 | 11.825 ± 0.036 | ... ± ... | 2 | CIII |
| 931............. | 05250205+0137210  | 81.25855         | 1.62252 | 11.435 ± 0.030 | 11.228 ± 0.030 | 11.326 ± 0.032 | 11.137 ± 0.033 | ... ± ... | 1 | Disk[8]? |
| 948............. | 05250362+0144121  | 81.26511         | 1.73670 | 11.949 ± 0.030 | 12.061 ± 0.030 | 11.831 ± 0.034 | 11.876 ± 0.036 | ... ± ... | 2 | CIII |

Notes.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Disk types: CIII, diskless stars; CII, optically thick disks; EV, evolved disks; TD, transitional disk candidates; disk[8]?, excess at 8 μm, but no MIPS detections. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References.— (1) Briceño et al. 2005; (2) Briceño et al. 2007a; (3) Briceño et al. 2007b.
| OB1b ID     | 2MASS ID         | R.A. (J2000.0) (deg) | Decl. (J2000.0) (deg) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) | [24.0] (mag) | Reference | Disk Type |
|-------------|------------------|----------------------|-----------------------|-------------|-------------|-------------|-------------|-------------|-----------|-----------|
| 21...........| 05290540−0127500 | 82.27250             | −1.46390              | 11.830 ± 0.030 | 11.865 ± 0.030 | 11.787 ± 0.034 | 11.846 ± 0.038 | ... ± ... | 3         | CIII      |
| 31...........| 05290635−0152122 | 82.27648             | −1.87008              | 12.751 ± 0.030 | 12.707 ± 0.031 | 12.632 ± 0.040 | 12.595 ± 0.057 | ... ± ... | 3         | CIII      |
| 63...........| 05290882−0125393 | 82.28679             | −1.42760              | 11.268 ± 0.030 | 11.291 ± 0.030 | 11.221 ± 0.032 | 11.076 ± 0.033 | ... ± ... | 1         | CIII      |
| 70...........| 05290925−0121227 | 82.28856             | −1.35633              | 12.383 ± 0.030 | 12.291 ± 0.031 | 12.122 ± 0.035 | 11.813 ± 0.038 | ... ± ... | 3         | CIII      |
| 78...........| 05291078−0117281 | 82.29495             | −1.29115              | 12.004 ± 0.030 | 11.989 ± 0.030 | 11.906 ± 0.034 | 11.974 ± 0.040 | ... ± ... | 3         | CIII      |
| 89...........| 05291202−0112236 | 82.30010             | −1.20657              | 13.138 ± 0.031 | 13.085 ± 0.031 | 13.120 ± 0.052 | 13.067 ± 0.089 | ... ± ... | 3         | CIII      |
| 148..........| 05291821−0204066 | 82.32590             | −2.06852              | 11.267 ± 0.030 | 11.152 ± 0.030 | 11.058 ± 0.032 | 10.917 ± 0.034 | ... ± ... | 3         | CIII      |
| 209..........| 05292326−0125153 | 82.34693             | −1.42092              | 9.457 ± 0.030  | 9.238 ± 0.030  | 8.809 ± 0.030  | 8.392 ± 0.030  | 5.23 ± 0.03 | 1         | CII       |

Notes.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Disk types: CIII, diskless stars; CII, optically thick disks; EV, evolved disks; TD, transitional disk candidates; disk[8]?: excess at 8 μm but no MIPS detections. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
panel, we define the “evolved disk region” between the class II region and the photospheric region. The bottom right panel shows the IRAC color-color diagram, in which we identify stars with excess emission in the IRAC bands (e.g., Allen et al. 2004; Megeath et al. 2004; Hartmann et al. 2005; Sicilia-Aguilar et al. 2006; Hernández et al. 2007). The dashed box displays the colors predicted for CTTS of different accretion rates by the models of D’Alessio et al. (2005a). In general, the IRAC colors observed for disk-bearing stars in Taurus are located in this region (Hartmann et al. 2005; Sicilia-Aguilar et al. 2006).

In the top panel of Figure 4, we identify six members and two photometric candidates located in the IRAC class II region; most of them are located near the class II limit, possibly indicating that these objects have begun the process of clearing the inner primordial disk. Two members have very small IRAC excesses just above the photospheric region. These objects, also located between the photospheric and the CTTS regions in the IRAC color-color diagram, have no MIPS detections and therefore it is not clear if the small excess observed at 8 μm originates from PAH background contamination, by an unresolved companion.
### TABLE 3

PHOTOMETRIC CANDIDATES OF THE 25 ORIONIS AGGREGATE

| OB1a ID | 2MASS ID      | R.A. (J2000.0) | Decl. (J2000.0) | [3.6] | [4.5] | [5.8] | [8.0] | [24.0] | $V$   | $VI$  | Disk Type |
|---------|----------------|----------------|-----------------|-------|-------|-------|-------|--------|-------|-------|-----------|
|         | (1)            | (2)            | (3)             | (4)   | (5)   | (6)   | (7)   | (8)    | (9)   | (10)  |           |
| 146...... | 05230905+0125355 | 80.78774      | 1.42654         | 11.383 ± 0.030 | 11.355 ± 0.030 | 11.278 ± 0.032 | 11.284 ± 0.034 | ... ± ... | 15.75 ± 0.04 | 2.43 ± 0.05 | CIII      |
| 297...... | 05233109+0144079 | 80.87958      | 1.73555         | 11.005 ± 0.030 | 11.079 ± 0.030 | 11.028 ± 0.031 | 10.967 ± 0.032 | ... ± ... | 13.91 ± 0.03 | 1.06 ± 0.05 | CIII      |
| 359...... | 05234182+0152261 | 80.92428      | 1.87394         | 13.144 ± 0.031 | 13.088 ± 0.031 | 12.986 ± 0.041 | 13.039 ± 0.055 | ... ± ... | 19.11 ± 0.05 | 3.09 ± 0.09 | CIII      |
| 427...... | 05235215+0136314 | 80.96732      | 1.60873         | 11.103 ± 0.030 | 11.191 ± 0.030 | 11.155 ± 0.032 | 11.074 ± 0.032 | ... ± ... | 13.84 ± 0.03 | 0.98 ± 0.05 | CIII      |
| 458...... | 05235854+0151255 | 80.99394      | 1.85709         | 12.114 ± 0.030 | 12.047 ± 0.030 | 12.003 ± 0.034 | 12.043 ± 0.040 | ... ± ... | 17.29 ± 0.04 | 2.58 ± 0.07 | CIII      |
| 477...... | 05240118+0128236 | 81.00493      | 1.47324         | 12.316 ± 0.030 | 12.289 ± 0.031 | 12.123 ± 0.035 | 12.165 ± 0.041 | ... ± ... | 16.87 ± 0.04 | 2.49 ± 0.06 | CIII      |
| 543...... | 05241034+0155024 | 81.04312      | 1.91735         | 10.322 ± 0.030 | 10.428 ± 0.030 | 10.365 ± 0.031 | 10.309 ± 0.031 | ... ± ... | 13.16 ± 0.03 | 0.80 ± 0.05 | CIII      |
| 1626..... | 05265473+0144337 | 81.72806      | 1.74271         | 10.168 ± 0.030 | 10.273 ± 0.030 | 10.061 ± 0.031 | 10.069 ± 0.031 | 9.83 ± 0.06 | 13.43 ± 0.03 | 0.86 ± 0.05 | EV        |

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| OB1b ID     | 2MASS ID      | R.A. (J2000.0) | Decl. (J2000.0) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) | [24.0] (mag) | V (mag) | V/ | Disk Type |
|------------|---------------|----------------|-----------------|-------------|-------------|-------------|-------------|-------------|--------|-----|-----------|
| 74......... | 05290984–0208250 | 82.29101       | −2.14030        | 12.269 ± 0.030 | 12.217 ± 0.031 | 12.141 ± 0.036 | 12.113 ± 0.042 | ... ± ... | 18.26 ± 0.05 | 2.89 ± 0.09 | CIII |
| 187........ | 05292160–0201546 | 82.34002       | −2.03184        | 11.142 ± 0.030 | 11.121 ± 0.030 | 11.073 ± 0.031 | 11.025 ± 0.034 | ... ± ... | 15.91 ± 0.06 | 2.04 ± 0.09 | CIII |
| 203......... | 05292300–0126559 | 82.34584       | −1.44888        | 13.500 ± 0.131 | 13.262 ± 0.032 | 13.186 ± 0.042 | 13.184 ± 0.085 | ... ± ... | 18.89 ± 0.05 | 2.83 ± 0.08 | CIII |
| 207......... | 05292313–0149203 | 82.34638       | −1.82231        | 13.109 ± 0.031 | 13.105 ± 0.031 | 13.059 ± 0.051 | 13.451 ± 0.153 | ... ± ... | 18.83 ± 0.05 | 2.63 ± 0.08 | CIII |
| 222......... | 05292426–0207354 | 82.35112       | −2.12651        | 12.953 ± 0.031 | 13.055 ± 0.031 | 12.730 ± 0.042 | 12.825 ± 0.063 | ... ± ... | 17.78 ± 0.05 | 2.27 ± 0.08 | CIII |
| 236......... | 05292591–0144580 | 82.35797       | −1.74945        | 10.810 ± 0.030 | 10.832 ± 0.030 | 10.757 ± 0.031 | 10.707 ± 0.032 | ... ± ... | 14.64 ± 0.04 | 1.41 ± 0.06 | CIII |
| 276......... | 05293010–0114446 | 82.37544       | −1.24573        | 11.116 ± 0.030 | 11.217 ± 0.030 | 11.175 ± 0.032 | 11.107 ± 0.034 | ... ± ... | 14.37 ± 0.00 | 1.25 ± 0.00 | CIII |
| 283......... | 05293049–0121500 | 82.37707       | −1.36389        | 11.303 ± 0.030 | 11.376 ± 0.030 | 11.314 ± 0.032 | 11.309 ± 0.036 | ... ± ... | 14.56 ± 0.04 | 1.30 ± 0.06 | CIII |
| 342......... | 05293578–0148046 | 82.39909       | −1.80129        | 11.138 ± 0.030 | 11.185 ± 0.030 | 11.129 ± 0.031 | 11.144 ± 0.034 | ... ± ... | 11.56 ± 0.04 | 1.30 ± 0.06 | CIII |

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or by disks present around these stars (flagged as “disk[8]?” in Table 1). Of particular interest are the member 1a_1121 and the photometric candidate 1a_1626, which are located between the photospheric and the class II region in the $V - J$ versus $K - [24]$ diagram, indicating that the outer disks around these objects are in a more evolved stage. Moreover, these stars are also located on the photospheric region in the IRAC color-color diagram and in the IRAC SED slope diagram, indicating that the inner disk has already dissipated and no disk emission can be detected at wavelength $\leq 8$ $\mu$m. The star 1a_1626 also has a very small excess at 24 $\mu$m ($\sim 2 \sigma$ above the photospheric level) indicating that the presence of a disk around this object is not yet conclusive. Overall, in 25 Orionis we identify seven stars with disks in the member sample [disk frequency (6.1 $\pm$ 2.3)%], and three in the photometric candidate sample [disk frequency (7.3 $\pm$ 4.2)%].

Similarly, in the top panel of Figure 5 we identify 13 members and four photometric candidates in Ori OB1b that show IRAC and MIPS excesses; five of these objects are located between the
class II region and the photospheric region. Eight members and one photometric candidate with no MIPS detection are located in the evolved disk region (flagged as “disk[8]?” in Tables 2 and 4). The existence of disks around these objects needs additional confirmation since they could be below the MIPS detection limit, or could be contaminated by PAH background emission (in Fig. 2 it can be clearly seen that the sky background emission at 8 μm is very patchy, and significant at some locations). In general, the range of infrared excesses at 24 μm in OB1b is similar to that of the optically thick disks in the σ Orionis cluster. Only one disk-bearing star (6%), the star 1b_337, has 24 μm excess below the class II limit, while six stars (39%) have 8 μm excess below this limit. This suggests a more rapid decrease in dust emission in the inner disk, in agreement with results from Sicilia-Aguilar et al. (2006) in the Cepheus OB2 association. The member 1b_337, located in the evolved disk region in the $V - J$ versus $K - [24]$ diagram, does not have excess in the IRAC bands. Overall, in Ori OB1b we identify 14 stars with disks in the member sample [disk frequency (13.1 ± 3.5)%] and the four disk systems in the photometric candidate sample (disk frequency 6.2% ± 3.1%).

Figure 6 displays the distribution of the disk-bearing stars in a SED slope space diagram for 25 Orionis (left panel) and OB1b (right panel). The vertical axis is the SED slope calculated from the $K - [5.8]$ color and the horizontal axis is the SED slope calculated from the $K - [24]$ color. The dashed areas define the photospheric level calculated with the STAR-PET Spitzer tool.
In order to characterize the stars bearing disks in 25 Orionis and OB1b, we identify several regions in Figure 6 defined by the dotted lines (‘‘class II region,” “evolved disk region,” and “transitional disk region”). The horizontal dotted line represents the lower quartile of the σ Orionis cluster. Above this line ~96% of the stars bearing optically thick disks in Taurus are also located, indicating a limit where the inner disk emission has not been affected significantly by evolutionary processes. We can identify the class II objects as stars located above this line.

In general, the class II objects identified using Figure 6 are located in the class II region in Figures 4 and 5. Disk-bearing stars below the dotted lines have decreased the disk infrared emission at 5.8 μm due to a decrease in the irradiation surface of the inner disks, and so they are in an stage where processes for inner disk dissipation have begun. The vertical dotted line represents the lower quartile of the stars bearing disks in the σ Orionis cluster (the lower quartile of Taurus is rightward from this line).

Using this limit, the stars located below the dotted lines could be sub-grouped on the basis of their disk emission at 24 μm: “evolved disk objects” (SED slope $K - [24] \leq -1.2$), in which we see an overall decrease in the disk emission in the IRAC and MIPS bands, indicating similar evolution in the inner and outer disk (Lada et al. 2006; Hernández et al. 2007); and “transitional disk candidates” (SED slope $K - [24] \geq -1.2$), which have an inner optically thin disk region, combined with an outer, optically thick disk (e.g., Calvet et al. 2005b). As reference, we plotted three transitional disk stars, CoKu Tau/4 (D’Alessio et al. 2005b), TW Hya (Calvet et al. 2002; Uchida et al. 2004), GM Aur (Calvet et al. 2005b), which occupy the region defined for the “transitional disk candidates.” In brief, we identify five stars with optically thick disks (class II objects), one transitional disk candidate and four evolved disk objects in 25 Orionis. We also identify 10 class II objects, three transitional disk candidates, and five evolved disk objects in OB1b. In spite of the evolved disks and transitional disks objects being a subsequent stage from class II objects, it is not clear if transitional disk objects are a prestage of evolved disks or each stage represents an independent stage from class II objects.

Figure 7 shows SEDs for selected stars in our samples illustrating the disk classification based on Figure 6. The first row of SEDs shows stars with optically thick disks (CII) located above the dotted line in Figure 6. The second row shows transitional disk candidates (TD) located right and below the dotted lines in Figure 6. Finally, last two rows of panels show stars with evolved disks located left and below the dotted lines in Figure 6.
3.2. Models

We have calculated SED slopes for models of irradiated accretion disks including dust settling from D’Alessio et al. (2006). In these models the disk is assumed to be steadily accreting at rates of $\dot{M} = 1 \times 10^{-9}, 1 \times 10^{-8},$ and $1 \times 10^{-7} M_\odot$ yr$^{-1},$ onto a star with mass of $0.6 M_\odot$ and luminosity of $1.2 L_\odot,$ which corresponds to a K7 star with age of 1 Myr (Siess et al. 2000). Dust settling was included using two populations of grains (big and small grains) having different spatial distributions, with the larger grains concentrated toward the midplane. The small grains located in the upper layers have different depletions given by the $\epsilon$ parameter (with values = 1, 0.1, 0.01, 0.001), which is the ratio of the dust to gas mass ratio of small grains relative to the standard dust to gas mass ratio ($\zeta_{\text{small}} / \zeta_{\text{std}}$; D’Alessio et al. 2006). The inner wall of the disk, located at the dust destruction radius, was settled self-consistently with the same degree of depletion used in the outer disk.

Figure 8 shows the theoretical SED slopes derived from the colors, $[3.6] - [8.0], K - [5.8],$ and $K - [24]$ versus the degree of settling represented by $\epsilon.$ SED slopes were calculated convoluting the theoretical SED with the transmission curves of the respective filters. We plot two inclination angles along the line of sight, 30° (left panels) and 60° (middle panels); this range in
angles represents 40% of probability of observation. Accretion rates are indicated for the different curves plotted in each panel. The slope has a strong dependency on $\dot{M}$, showing flatter slopes for the fastest accretors; the smallest variation in disk emission with $\dot{M}$ is observed for the slope $K_{24}/C_{138}$ of disks without settling ($\epsilon = 1$). In general, models with $\dot{M} = 10^{-9}M_\odot\text{yr}^{-1}$ show a stronger dependence with dust settling than models for large accretion rates.

By comparison, we plotted in the right panels of Figure 8 the quartiles observed for disk-bearing stars in Taurus, in the $\sigma$ Orionis cluster, in Ori OB1b and in 25 Orionis. The range of disk emission observed in Taurus (1–2 Myr) can be explained by the models, indicating optically thick disks systems with several degrees of settling (Furlan et al. 2006) and accretion rates (Hartmann et al. 1998; Calvet et al. 2005a). Most of the stars with disks in the $\sigma$ Orionis cluster (≈80%) can be explained by the theoretical SED slopes but with small accretion rates or/and higher degree of dust settling than in Taurus. Approximately half of the disks observed in 25 Orionis (Fig. 4) and OB1b (Fig. 5) require models with lower accretion rates ($\dot{M} < 10^{-9}M_\odot\text{yr}^{-1}$) or/and large...
degree of settling ($\epsilon < 0.001$) to explain the weak disk emissions observed at $[3.6] - [8.0]$ and $K - [5.8]$. However, $\sim75\%$ of disk-bearing stars in 25 Orionis and OB1b have disk emissions at $K - [24]$ in agreement with the SED slopes predicted by the models, supporting the scenario where the inner disk evolves faster than the outer disk.

### 3.3. Disk Frequencies

In Figures 4, 5, and 6 we identify seven members bearing disks in 25 Orionis and 14 in Ori OB1b, indicating disk frequencies in the member samples of $(6.1 \pm 2.3)\%$ and $(13.1 \pm 3.5)\%$, respectively. These frequencies include objects with $24 \mu$m excess as disk-bearing stars. In §3.1, we also identify two members of 25 Orionis and eight members of Ori OB1b that exhibit IRAC excesses but have no MIPS detections; if we add these stars as members with disks, the disk frequencies increase to $(7.8 \pm 2.6)\%$ in 25 Orionis and to $(20.6 \pm 4.4)\%$ in Ori OB1b. These later values are in better agreement with the disk frequencies calculated for the low-mass stars in the Ori OB1a ($7 \pm 3\%$) and Ori OB1b ($17 \pm 4\%$) subassociations, using the excess emission ($2 \sigma$ above the expected photospheric level) from the 2MASS color $H - K$ (Hernández et al. 2005). The lower disk frequencies derived using the $24 \mu$m excess could indicate a possible observational bias produced by the flux limit of MIPS observations ($\sim0.5$ mJy). Assuming the distances and ages (Siess et al. 2000) plotted in Figure 3, with a visual extinction of $A_F = 0.12$ mag for 25 Orionis and $A_F = 0.6$ mag for OB1b, we cannot expect to detect disks around a $0.6 \ M_\odot$ star in the 25 Orionis group if $E_{[24]} \leq 2.5$, and if $E_{[24]} \leq 4.5$ for objects in Ori OB1b; where the excess ratio, $E_{[24]}$, is the ratio of the observed flux to the expected photospheric flux at $24 \mu$m.

Using the stars identified as members with infrared excess in Figure 6, we plotted in Figure 9 the fraction of stars bearing disks versus spectral type for 25 Orionis (dotted line) and OB1b (dashed line). Error bars represent the statistical $\sqrt{N}$ errors in our derived frequencies. Previous studies have indicated that the frequency of disks is strongly dependent on the stellar mass, showing larger frequencies in the TTS mass range (spectral types K and M) than in stars with higher masses (Lada & Lada 1995; Sicilia-Aguilar et al. 2005; Hartmann 2005; Hernández et al. 2005; Carpenter et al. 2006; Bricénol et al. 2007b). Figure 9 also suggests that the disk frequency declines toward lower masses (spectral types later than M1) showing a maximum around K7–M1 stars, in agreement with results for the 2–3 Myr cluster IC 348 by Lada et al. (2006). However, given the degree of uncertainty in each individual point in Figure 9, caused by the small number of disk-bearing stars in each spectral type bin, plus the observational bias introduced by the limiting magnitude in the MIPS photometry, this result is not conclusive and additional data is necessary to confirm this trend.

Using Figure 6, the frequencies calculated for stars with evolved disks related to the total number of stars bearing disks in the $\sigma$ Orionis cluster $(15.6 \pm 4.0\%)$, in Ori OB1b $(27.8 \pm 12.4\%)$ and in 25 Orionis $(40 \pm 20\%)$, indicate a clear trend toward more evolved disks in older stellar groups. The transitional disks candidates in these stellar groups are less frequent than evolved disks $(8 \pm 3\%$ for the $\sigma$ Orionis cluster, $17 \pm 10\%$ for OB1b and $10 \pm 10\%$ for 25 Orionis), suggesting that the transitional disk phase is relatively fast or represents an independent and special stage in the disk clearing period of stars.

Disk frequencies of the sample members can be used to estimate the contamination level of nonmembers in the photometric candidates samples assuming that the photometric candidates bearing disks are actual members of young stellar groups. Since the overall disk frequencies of low-mass members $(6.1 \pm 2.1\%)$ and low-mass photometric candidates $(7.3 \pm 4.2\%)$ in 25 Orionis...
are similar, we can expect that photometric candidates sample have very low nonmember contamination. Since the disk frequency calculated in OB1b for the photometric candidates (6.2 ± 3.1%) is lower than the disk frequency of members (13.1 ± 3.5), we can expect that around 50% of the photometric candidates are not members of OB1b.

3.4. Disk Evolution

The frequency of stars bearing disks in different stellar groups is a function of age, indicating a timescale for disk dissipation in low-mass stars of 5–7 Myr (e.g., Haisch et al. 2001; Briceño et al. 2007b; Hernández et al. 2005, 2007). The results presented in § 3.3 are in agreement with this trend. In addition to this decline in disk frequency, the amount of infrared disk emission also decreases with age. The top panel of Figure 10 shows the median SED slope derived from the color [3.6] − [8.0] for disk-bearing stars in stellar groups ranging in age from ~1 to ~10 Myr: 1–2 Myr (Taurus; Hartmann et al. 2005), 1–3 Myr (NGC 2264; Young et al. 2006), 2–3 Myr (IC 348; Lada et al. 2006), 3 Myr (σ Orionis; Hernández et al. 2007), 4 Myr (Tr 37; Sicilia-Aguilar et al. 2006), 5 Myr (OB1b; Briceño et al. 2007a; and this work), 7–10 Myr (25 Orionis; Briceño et al. 2007a; and this work), and 10–12 Myr (NGC 7160; Sicilia-Aguilar et al. 2006). We estimated the photospheric level using the STAR-PET Spitzer tool for the star templates with spectral types between K5 to M5. Error bars represent the quartiles given the median value for each stellar group. The median SED slope decreases with age, indicating a reduction of disk emission the inner regions of the disk. In the bottom panel we display two sets of models described in § 3.2 with different disk orientations, i = 30° (dashed lines) and i = 60° (dotted lines). The accretion rate is a function of age (Hartmann et al. 1998; Muzerolle et al. 2000; Calvet et al. 2005a), so we assumed $M = 10^{-8} M_\odot$ for 1 Myr old stellar groups, which is the mode value for accreting stars in Taurus (Hartmann et al. 1998) and $M = 10^{-9} M_\odot$ for 10 Myr old stellar groups, which is the mode value for accreting stars in the OB1a subassociation (Calvet et al. 2005a). This plot suggests that the expected decrease in accretion rate is not sufficient to explain the decrease of emission in the inner part of the disk, and it is necessary to increase the degree of settling ($\epsilon < 0.001$) in the inner disk to explain the observed slopes in stellar groups with ages 5 Myr or older.

Since the disk frequency and the infrared disk emission decrease with age, a correlation between these values can be expected. Figure 11 confirms this suggestion, showing that the disk frequency is correlated with the median SED slope in the IRAC bands (correlation coefficient $\rho = 0.76$). This plot clearly demonstrates that the disappearance of inner disks is related to the decrease of optical depth in the inner disk due to the increase of dust settling and the decrease of mass accretion rate (see D’Alessio et al. 2006).

4. CONCLUSIONS

We have used the IRAC and MIPS data from Spitzer to study the disk frequencies and properties of disks around confirmed members of the Orion OB1 association, 115 belonging to the ~10 Myr old 25 Orionis aggregate, and 106 in a region within the ~5 Myr old Ori OB1b sub association, near the Orion belt star $\epsilon$ Ori. Using optical-2MASS color magnitude diagrams, 41 stars were selected as additional photometric candidates of the 25 Orionis aggregate, and 65 as additional photometric candidates of the Ori OB1b field. We use IRAC-MIPS diagrams to detect disk-bearing stars, and to classify them as either having no detectable disk emission (class III), as systems with optically thick disks (class II), or as objects in an intermediate phase between class II and class III systems. These intermediate-type objects were further grouped in two categories: “transitional disks candidates,” which have an inner, optically thin disk region combined with an outer, optically thick disk (e.g., Calvet et al. 2002, 2005b); and “evolved disk objects,” in which there is an overall decrease of emission both the inner and outer regions of the disk (Lada et al. 2006; Hernández et al. 2007). It is not clear whether “evolved disks” are a subsequent event after transitional disks phase, or represent an independent evolutionary stage.

We found that the disk frequency in the 25 Orionis aggregate (6%) and in the Ori OB1b field (13%) is mass dependent, showing a maximum value for stars with spectral type M0, and suggesting a decrease in the disk frequency toward higher and lower masses. The trend toward higher masses has been observed in several stellar groups (e.g., Hernández et al. 2005; Sicilia-Aguilar et al. 2006; Carpenter et al. 2006). The decrease in disk frequency toward lower masses is not conclusive, but is consistent with the results for other regions like IC 348 (Lada et al. 2006). We find that objects with evolved disks are more frequent in older stellar groups, while the transitional disk candidates represent a relative small fraction of the disk-bearing stars in the various stellar groups, suggesting that the transitional disk phase is relatively fast.

Comparing the disk emission in the IRAC and MIPS bands for Taurus, the σ Orionis cluster, the Ori OB1b field, and the 25 Orionis aggregate, we find that disk emission decreases faster in the innermost regions of the disk; comparison with disk models from D’Alessio et al. (2006) support this scenario. Finally, comparing the disk emission in the IRAC spectral range of several stellar groups ranging in age from ~1 to ~12 Myr, we find that inner disk emission decreases systematically with age, showing a correlation between disk frequencies and inner disk emission. Comparison with models using a typical accretion rate for 1 and 10 Myr suggests that viscous evolution alone is not sufficient to explain the decrease in the inner disk emission, and that large
degrees of dust settling ($< 0.001$) are necessary to explain the observed SEDs at ages 5 Myr or older.

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