MEDIUM-SEPARATION BINARIES DO NOT AFFECT THE FIRST STEPS OF PLANET FORMATION

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ABSTRACT

The first steps of planet formation are marked by the growth and crystallization of sub-micrometer-sized dust grains accompanied by dust settling toward the disk midplane. In this paper we explore whether the first steps of planet formation are affected by the presence of medium-separation stellar companions. We selected two large samples of disks around single and binary T Tauri stars in Taurus that are thought to have only a modest age spread of a few Myr. The companions of our binary sample are at projected separations between ~10 and 450 AU, with masses down to about 0.1 $M_\odot$. We used the strength and shape of the 10 $\mu$m silicate emission feature as a proxy for grain growth and for crystallization, respectively. The degree of dust settling was evaluated from the ratio of fluxes at two different mid-infrared wavelengths. We find no statistically significant difference between the distribution of 10 $\mu$m silicate emission features from single and binary systems. In addition, the distribution of disk flaring is indistinguishable between the single and binary system samples. These results show that the first steps of planet formation are not affected by the presence of a companion at tens of AU.

Subject headings: circumstellar matter — infrared: stars — planetary systems: protoplanetary disks

Online material: color figures

1. INTRODUCTION

Two-third of the G stars in the solar neighborhood are members of multiple-star systems (e.g., Duquennoy & Mayor 1991). These binaries and multiple systems are often found to harbor giant planets (e.g., Bonavita & Desidera 2007). Similarly, young low-mass pre-main-sequence stars are very frequently members of multiple systems, mostly binaries (Mathieu et al. 2000; Duchêne et al. 2007). This suggests that planet formation around single stars such as our Sun may be atypical, and urges us to understand the effects of stellar companions on planet formation. We tackle this question from an observational point of view. Because numerical simulations of grain agglomeration suggest short timescales for the formation of planetesimals (only a few $10^4$ yr; e.g., Beckwith et al. 2000), it is crucial to know how stellar companion(s) affect the dust processing in the first few million years.

Grain growth and the settling of dust grains toward the disk midplane are thought to represent the first steps in the planet formation process (e.g., Lissauer & Stewart 1993 for a review). The study of disks around intermediate-mass stars also indicates a link between grain growth and crystallinity. High crystallinity was found only when grains larger than the dominant sub-micron interstellar grains were present (van Boekel et al. 2005). In the context of these findings and dust evolution models (e.g., Dullemond & Dominik 2004), older disks are expected to have more processed dust (larger grains and crystals) than younger disks. In addition, their disk structure should be flatter because of the gradual settling of large dust grains toward the disk midplane. However, recent observations show that the degree of dust processing can be very different even for coeval disks around stars of similar spectral type in the same star-forming region (e.g., Przygodda et al. 2003; Apai et al. 2005). This demonstrates that dust evolution is not uniquely controlled by stellar age and luminosity; at least one additional parameter is present.

There are two studies suggesting that stellar multiplicity could play a major role in the initial dust processing. Meeus et al. (2003) found that among three coeval T Tauri disks in the Chamaeleon I star-forming region, the closest binary system (projected separation of ~120 AU) sports the strongest contribution from large (~2 $\mu$m) grains and has the highest crystalline mass fraction. Similarly, Sterzik et al. (2004) pointed out that the disk of a young brown dwarf with a companion at $\gtrsim 30$ AU shows more processed dust than the disk around a single brown dwarf. Although the small samples inhibit any firm conclusions, these results suggest that companions might trigger rapid dust evolution. Intuitively, this may happen in different ways. A companion could speed up dust evolution by dynamically stirring the circumstellar dust grains and leading to an enhanced collision and grain growth rate (e.g., Dubrulle et al. 1995). In addition, the dynamical stirring may lead to an increased mixing that could also expose larger amounts of dust to temperatures high enough ($\gtrsim 800$ K) to be crystallized.

In this paper we compare two carefully constructed samples of disks around single and binary stars with a narrow age spread to test the hypothesis that binary systems have disks with more processed dust and flatter structures. In §2 we describe our samples. The data reduction of the Spitzer spectra and of the 24 $\mu$m MIPS photometry is presented in §3. We summarize our results in §4, and in §5 discuss their implications on planet formation in single and binary systems.

2. SAMPLE DEFINITION

Testing whether stellar companions promote the first steps of planet formation requires (1) two coeval samples of disks around
single and binary stars with precisely determined multiplicity; (2) identical spectral type distributions for the two samples; (3) objects in regions with no diffuse PAH emission that could contaminate the dust emission features of the targets; and (4) disks with faint or no PAH emission features (for the same reason as [2]). The Taurus-Auriga star-forming region has a reasonably complete census of its pre-main-sequence stellar population and best meets our requirements among the nearby star-forming regions. To satisfy criteria (4) we selected disks around low-mass stars because they have an order of magnitude lower PAH emission than disks around intermediate-mass stars (Geers et al. 2006). The observed age distribution of low-mass stars in Taurus can be well approximated with a Gaussian centered at 1.6 Myr and a spread no larger than about 2–3 Myr (Hartmann 2001). This narrow age spread minimizes any possible trend of disk evolution with age. In summary, our sample of disks around single and binary stars is drawn from the Taurus-Auriga population of low-mass T Tauri stars (TTSs) with circumstellar disks and ages between ~1 and 3 Myr.

Because it is critically important to include only stars with known multiplicity, we first selected each target based on a combination of available high-resolution imaging and interferometry, spectroscopy, and radial velocity measurements (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1995; White & Ghez 2001). In this context, we refer to a star as single if it has no known companions with brightness above the detection limit within 10" (or ~1400 AU at the ~140 pc distance of the Taurus-Auriga star-forming region). The typical detection limit of high-resolution imaging surveys is 2–3 mag fainter than the primary star in the K band, which corresponds to a very low mass star of ~0.1 M⊙ at ~2 Myr according to the Baraffe et al. (1998) isochrones. Only a few binary star systems have been observed with techniques reaching higher contrast (se, e.g., the discovery of a brown dwarf companion to DH Tau by Itoh et al. 2005). The typical smallest separation resolvable with the imaging surveys is ~0.1'' (~10 AU), meaning that a few unresolved close binaries may have been classified as single. Of these, binaries with periods <100 days can only modestly contaminate our single-star sample, since their frequency in pre-main-sequence stars is 8%±3% (Mathieu et al. 2000). Due to the lack of general understanding of the separation distribution of close pre-main-sequence binaries, it is not possible to determine the exact level of contamination. However, the required infrared excess (see below) ensures circumstellar dust within a few AU, likely inconsistent with the presence of a close stellar companion. We also excluded all known spectroscopic binaries in Taurus (Mathieu 1994; Jensen & Mathieu 1997) from both the single and binary star samples. Our binary sample consists of stars with companions between ~0.1'' and 3'', thus covering the population of medium-separation stellar companions at projected separations between ~14 and 420 AU. After defining the samples, we searched for available near- and mid-infrared data (Kenyon & Hartmann 1995; Stassun et al. 2001; Hartmann et al. 2005; McCabe et al. 2006; Furlan et al. 2006) to select only those targets that have excess emission indicative of a circumstellar disk. These selection criteria resulted in a sample of mostly classical TTSs for the single and for the primary star in the multiple systems. Only CZ Tau and IQ Tau in our sample are classified as weak-lined TTSs (White & Ghez 2001; McCabe et al. 2006). The T Tauri types for the components of the binary sample are mostly classical, with the exception of FX Tau B, IS Tau B, V710 Tau B, and V807 Tau B, which are weak-lined TTSs (Duchêne et al. 1999; White & Ghez 2001; Hartigan & Kenyon 2003).
column (7) of Table 2. Resolved mid-infrared photometry is available for 11 out of 21 binary sources (McCabe et al. 2006). Another 8 sources have resolved $L$-band photometry (White & Ghez 2001), while the two closest binaries FO Tau and DF Tau have been resolved only in the $K$-band (White & Ghez 2001). For at least two-third of the binary sample, the Spitzer/IRS spectrum is dominated by the disk around the primary star as indicated by the near- and mid-infrared flux ratios of the primary and secondary components (col. [8] Table 2). We also note that our selection criteria did not exclude possibly more evolved disks such as transition disks. GM Aur and DM Tau in our list of single stars are among the best studied transition disks (see, e.g., Calvet et al. 2005).

### Table 2

| No. (1) | Source (2) | 2MASS J (3) | Adopted SpT* (4) | Separation (arcsec) (5) | SpT Reference (6) | Disk Configuration b (7) | Flux Ratio (Filter) (8) | Flux Ratio Reference (9) |
|---------|------------|-------------|-----------------|------------------------|-----------------|------------------------|-----------------------|------------------------|
| B1.............. CoKu Tau3 A-B | 04354093+2411087 | M1 | 2.05 | 1 | cp+cs | 4.7 (L) | 3 |
| B2.............. CZ Tau A-B | 04183158+2816585 | M1.5 | 0.32 | 1 | cp+cs | 1.71 (L) | 10 |
| B3.............. DD Tau A-B | 04183112+2816290 | M3+M3 | 0.56 | 2, 3 | cp+cs | 1.75 (N) | 10 |
| B4.............. DF Tau A-B | 04270280+2524223 | M0.5+M3 | 0.09 | 4, 3 | cp+cs | 1.6 (K) | 3 |
| B5.............. DK Tau A-B | 04304425+2601244 | K9+M1 | 2.30 | 1, 5 | cp+cs | 8.53 (SiC) | 10 |
| B6.............. FO Tau A-B | 04144928+2812305 | M2+M2 | 0.15 | 4, 3 | cp+cs | 1.7 (L) | 3 |
| B7.............. FS Tau A-B | 04220217+2657304 | M1+M4 | 0.23 | 4, 3 | cp+cs | 5 (L) | 3 |
| B8.............. FV Tau A-B | 04265352+2606543 | K5+K6 | 0.72 | 4, 2, 3 | cp+cs | 2.2 (N) | 10 |
| B9.............. FX Tau A-B | 04302961+2426450 | M1+M4 | 0.89 | 1, 5 | cp+cs | 2.8 (N) | 10 |
| B10............. GG Tau Aa-Ab | 04323034+1731406 | K7+M0.5 | 0.25 | 6 | cp+cs | 1.03 (N) | 10 |
| B11............. GH Tau A-B | 04303622+2409339 | M1.5+M2 | 0.31 | 3 | cp+cs | 1.45 (N) | 10 |
| B12............. GN Tau A-B | 04392090+2545021 | M2.5 | 0.33 | 7 | cp+cs | 1.53 (L) | 10 |
| B13............. HK Tau A-B | 04315056+2424180 | M1+M4 | 2.34 | 1, 5 | cp+cs | 30 (SiC) | 10 |
| B14............. HN Tau A-B | 04333935+1751523 | M5+M4 | 3.11 | 2 | cp+cs | 65 (L) | 3 |
| B15............. IS Tau A-B | 04336678+2699492 | K7+M4.5 | 0.22 | 8, 3 | cp+cs | 9 (L) | 3 |
| B16............. IT Tau A-B | 04335470+2613275 | K3+M4 | 2.39 | 5 | cp+cs | 2.95 (SiC) | 10 |
| B17............. RW Aur A-B | 05074953+3024050 | K1+K5 | 1.42 | 9, 5 | cp+cs | 13.63 (N) | 10 |
| B18............. UX Aur A-B | 04514737+3047134 | M7+M2 | 0.88 | 1, 5 | cp+cs | 2.07 (N) | 10 |
| B19............. V710 Tau A-B | 04315779+1821380 | M0.5+M2 | 3.17 | 2 | cp+cs | 12.7 (SiC) | 10 |
| B20............. V807 Tau A-B | 04303664+2409549 | K7+M3 | 0.3 | 4, 2, 3 | cp+cs | 3.6 (L) | 3 |
| B21............. V955 Tau A-B | 04420777+2523118 | K5+M1 | 0.33 | 3 | cp+cs | 5.6 (L) | 3 |

Note.—The 2MASS source name includes the J2000 sexagesimal equatorial position in the form: hhmmss+ddmmss (Cutri et al. 2003).

* The second spectral type, when available, is for the secondary star.

b Here “cp” stands for circumprimary disk, and “cs” stands for circumsecondary disk. These disk configurations have been determined via resolved optical and infrared photometry; see § 2 for details.

Flux ratios are calculated as primary/secondary. In parenthesis we provide the filter at which the flux ratio has been calculated (the SiC filter is centered at 11.8 μm; McCabe et al. 2006).

References.—(1) Leinert et al. 1993; (2) Hartigan et al. 1994; (3) White & Ghez 2001; (4) Cohen & Kuhi 1979; (5) Duchêne et al. 1999; (6) White et al. 1999; (7) White & Basri 2003; (8) Martin et al. 1994; (9) Mundt & Giampapa 1982; (10) McCabe et al. 2006.

3. DATA REDUCTION

We use the low-resolution Spitzer spectra around the 10 μm silicate emission feature to characterize the degree of dust processing in single and binary systems. Observations at wavelengths longer than ~20 μm are necessary to trace the evolution of the disk structure. For this, we prefer to use the MIPS 24 μm photometry that is available for all (except 6) targets, rather than the spectra acquired with the Long-Low module of the IRS, which is lacking for 14 targets. In the following we describe the data reduction of the Spitzer IRS spectra and 24 μm MIPS photometric data.

3.1. Spitzer IRS Low-Resolution Spectra

The IRS data presented in this paper have been acquired as part of the IRS/GTO program (Furlan et al. 2006) and became available to the community at the end of the year 2005. Only six of the objects we selected (CY Tau, DS Tau, FM Tau, IS Tau, V710 Tau, and V807 Tau) were observed in staring mode, with the targets placed in two nod positions along the spatial direction of the slit at 1/3 and 2/3 of the slit length. On all the other targets, a 2 × 3 step mapping observation was carried out: the three steps were chosen to be separated by three-quarters (for SL) or half

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**Fig. 1.** Histogram of the spectral types for the single and binary systems. The spectral type distribution of the single stars and of the primary stars in the binary sample are almost identical. [See the electronic edition of the Journal for a color version of this figure.]
of the slit width in the dispersion direction, and the two steps were separated by one-third of the slit in the spatial direction. The exposure time at each nod position was 6 s for all targets, with the exception of V710 Tau, which had a 14 s exposure time per nod.

We downloaded the low-resolution IRS data that were processed with the SSC pipeline S13.2.0. Our data reduction starts from the droopres intermediate data product and follows the steps outlined in detail in Bouwman et al. (2007). In brief, we first subtracted the pairs of imaged spectra acquired along the spatial direction of the slit in order to correct for the background emission and stray light. Then we replaced bad pixels by interpolating over neighboring, good pixels. Although for our analysis we use only the SL data, we also extracted the LL part of the spectra for comparison with the MIPS 24 μm photometry where both data sets are available. Spectra were extracted from the background-subtracted pixel-corrected images using a 6.0 pixel and 5.0 pixel fixed-width aperture in the spatial direction for the SL (5.2–14 μm) and LL (14–35 μm) modules, respectively. The low-level fringing at wavelengths >20 μm was removed using the irsfringe package (Lahuis & Boogert 2003).

Because peak-up images were not acquired for the majority of the sources, targets may not have been positioned accurately at the center of the slit. We determined the actual position of each source during extraction by finding the peak emission of the wavelength-collapsed source profile. Once the spectra are extracted for each order, nod and cycle, we computed a mean spectrum for each order and assigned as uncertainty at each wavelength the 1 σ standard deviation of the distribution of the data points.

The absolute flux calibration was done using order-based spectral response functions created within the Formation and Evolution of Planetary Systems (FEPS) Spitzer Legacy program (Hines et al. 2005; Meyer et al. 2006; Bouwman et al. 2007). The advantages of this spectral response function over the standard SSC BCD calibration are (1) the use of a larger number of calibrators from the FEPS program, (2) the spectral response function is order and nod-position based, and (3) it is a one-dimensional spectral response function, allowing a better rejection of bad pixels. The estimated absolute flux calibration uncertainty is around 10% (Bouwman et al. 2007) and is propagated to the flux uncertainties assigned at each wavelength. The calibrated spectra are shown in Figure 2.

We checked the absolute flux calibration of the IRS SL module using the published IRAC 8 μm photometry by Hartmann et al. (2005) and Luhman et al. (2006), whose data were acquired in two different campaigns, 2004 February–March and 2005 February, respectively. Eleven sources have IRAC 8 μm magnitudes from both campaigns, while 5 more sources have only magnitudes from 2004 February (Hartmann et al. 2005), and 14 more sources only from 2005 February (Luhman et al. 2006). The mean difference in the IRAC 8 μm fluxes for the 11 sources observed in both campaigns is 16%, much larger than the IRAC absolute flux calibration accuracy of a few percent (Reach et al. 2005). The largest deviations are for FV Tau, DL Tau, and DO Tau, whose 8 μm IRAC fluxes decreased by factors of 33%, 23%, and 23%, respectively.
respectively, in a year baseline. These differences are likely due to intrinsic stellar variability. The IRS 8 \( \mu m \) fluxes integrated over the IRAC 8 \( \mu m \) spectral response curve agree on average within \( \sim 10\% \) of the published IRAC photometry, which is within the estimated IRS flux calibration uncertainty. We also verified that our spectra agree very well with those published by Furlan et al. (2006), who adopted a different data reduction.

3.2. Spitzer 24 \( \mu m \) Photometry

MIPS 24 \( \mu m \) (hereafter MIPS24) data are available in the Spitzer archive for all but six of the targets we selected (specifically DM Tau, DS Tau, GG Tau, HN Tau, RW Aur, and UY Aur). The majority of the MIPS data have been acquired as part of the Taurus Spitzer Legacy Program (PI: D. Padgett) in 2005 February–March (PID 3584) and March 2007 (PID 30816) using the MIPS scan-map operational mode. V710 Tau and GM Aur are not covered by these programs but have data from the c2d Spitzer Legacy Program (PI: N. Evans; PID 173) and the GTO program, respectively (PI: G. Fazio; PID 37). We downloaded the post-BCD MIPS 24 \( \mu m \) products processed through the SSC pipelines S14.4.0 or later. In the case of photometry mode (only for V710 Tau), the SSC product is an averaged and registered single image, while in the case of scan maps (for all other sources), the product is a distortion-corrected mosaic image.\(^3\) The 24 \( \mu m \) post-BCD images generated from pipeline versions later than S14 have improved flat-field corrections and are suitable for photometry at an accuracy of 10\% (see § 9.1 of the MIPS Data Handbook v3.2; link in footnote 3), sufficient for the purposes of this study.

Aperture photometry was done using IDP3 (Schneider & Stobie 2002). The centroid of the aperture was found by fitting a Gaussian to each source. We used an aperture radius of 6.6 pixels (2.7 pixels) and background annulus from 20\" to 32\". We opted for this intermediate aperture radius among those suggested by the Spitzer Science Center in order to include the emission from both binaries (as in the IRS spectra) and to exclude the emission from companions at >10\" from some of the single stars (see note to Table 1). To recover the total flux we then applied the proper aperture correction of 1.648.\(^4\) DO Tau, GK Tau, FS Tau, and FV Tau have 24 \( \mu m \) fluxes \( \geq 1.6 \) Jy and are thus saturated in the 3 s exposures acquired within the Taurus Spitzer Legacy Program. For these sources, as well as for the six targets that lack MIPS24 data, we computed the 25 \( \mu m \) flux (integrated flux from 23.5 to 26.5 \( \mu m \)) from our SL 6 \( \mu m \) flux and the \( n_{0.25} \) spectral indices from Table 4 of Furlan et al. (2006).\(^5\) We show in § 4.2 that our results are not affected by the use of 25 \( \mu m \) fluxes instead of 24 \( \mu m \) fluxes for these 10 objects. For the sources that have both MIPS24 observations and LL data, we find that our aperture photometry agrees within about 10\% with the IRS 24 \( \mu m \) flux integrated over the MIPS24 spectral response curve. Table 3 summarizes the MIPS24 or the IRS25 fluxes for our sample of single and binary systems.

4. RESULTS

4.1. Strength and Shape of the 10 \( \mu m \) Feature

The 10 \( \mu m \) silicate emission feature traces silicate dust in the optically thin layer of circumstellar disks out to about 1 AU from

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\(^3\) Available at http://ssc.spitzer.caltech.edu/mips/dh/mipsdatahandbook3.2.pdf.

\(^4\) See http://ssc.spitzer.caltech.edu/mips/apercorr/.

\(^5\) Most of these sources are so bright that they were observed only with the IRS high-resolution module. Therefore, we could not compute 24 \( \mu m \) fluxes from the LL data we reduced.

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**TABLE 3**

| No. (1) | Source (2) | \( F(24 \mu m) \) (mJy) (3) | \( F(25 \mu m) \) (mJy) (4) | Comments (5) |
|--------|------------|-----------------------------|-----------------------------|--------------|
| S1...... | AA Tau     | 525                         | ...                         | ...          |
| S2...... | BP Tau     | 666                         | ...                         | ...          |
| S3...... | CI Tau     | 997                         | ...                         | ...          |
| S4...... | CW Tau     | 1445                        | ...                         | ...          |
| S5...... | CX Tau     | 296                         | ...                         | ...          |
| S6...... | CY Tau     | 123                         | ...                         | ...          |
| S7...... | DE Tau     | 677                         | ...                         | ...          |
| S8...... | DH Tau     | 316                         | ...                         | ...          |
| S9...... | DL Tau     | 965                         | ...                         | ...          |
| S10..... | DM Tau     | ...                         | 320                         | MIPS24       |
| S11..... | DN Tau     | 424                         | ...                         | ...          |
| S12..... | DO Tau     | ...                         | 2951                        | MIPS24 saturated |
| S13..... | DP Tau     | 1281                        | ...                         | ...          |
| S14..... | DS Tau     | ...                         | 303                         | MIPS24       |
| S15..... | FM Tau     | 462                         | ...                         | ...          |
| S16..... | FN Tau     | 1047                        | ...                         | ...          |
| S17..... | FZ Tau     | 1057                        | ...                         | ...          |
| S18..... | GI Tau     | 1006                        | ...                         | ...          |
| S19..... | GK Tau     | ...                         | 1699                        | MIPS24 saturated |
| S20..... | GM Aur     | 746                         | ...                         | ...          |
| S21..... | IP Tau     | 277                         | ...                         | ...          |
| S22..... | IQ Tau     | 544                         | ...                         | ...          |
| S23..... | LkCa 15    | 398                         | ...                         | ...          |
| B1...... | CoKu Tau3  | 327                         | ...                         | ...          |
| B2...... | CZ Tau     | 1232                        | ...                         | ...          |
| B3...... | DD Tau     | 1575                        | ...                         | ...          |
| B4...... | DF Tau     | 945                         | ...                         | ...          |
| B5...... | DK Tau     | 1286                        | ...                         | ...          |
| B6...... | FO Tau     | 529                         | ...                         | ...          |
| B7...... | FS Tau     | ...                         | 2112                        | MIPS24 saturated |
| B8...... | FV Tau     | ...                         | 2344                        | MIPS24 saturated |
| B9...... | FX Tau     | 420                         | ...                         | ...          |
| B10..... | GG Tau     | ...                         | 1266                        | no MIPS24    |
| B11..... | GH Tau     | 379                         | ...                         | ...          |
| B12..... | GN Tau     | 536                         | ...                         | ...          |
| B13..... | HK Tau     | 823                         | ...                         | ...          |
| B14..... | HN Tau     | ...                         | 2988                        | no MIPS24    |
| B15..... | IS Tau     | 228                         | ...                         | ...          |
| B16..... | IT Tau     | 264                         | ...                         | ...          |
| B17..... | RW Aur     | ...                         | 2012                        | no MIPS24    |
| B18..... | UY Aur     | ...                         | 5918                        | no MIPS24    |
| B19..... | V710 Tau   | ...                         | 245                         | ...          |
| B20..... | V807 Tau   | 476                         | ...                         | ...          |
| B21..... | V955 Tau   | 546                         | ...                         | ...          |

Note.—The absolute photometric uncertainty is expected to be \( \sim 10\% \). This uncertainty includes both the internal random and the absolute calibration uncertainty; see text for details.
We first fit a third-order polynomial$^6$ to the spectral data outside the 10 μm silicate emission feature (between 6 and 8 μm and between 12 and 14 μm) and then normalize our spectra to the fitted continuum. This normalization ensures that the shape of the spectral features remains identical to the original one (e.g., van Boekel et al. 2005). Figure 3 shows the band strengths for our sample of single (circles) and multiple (squares) systems. The main question we want to answer in this paper is whether the population of disks around single stars statistically differ in terms of dust processing from the population of disks around binaries. In other words, do either of the two populations have more processed dust in their disks than the other? To answer this question we apply the Kolmogorov-Smirnov (hereafter K-S) test (see, e.g., Press et al. 1993) and the Mann-Whitney U (hereafter MWU) test (see, e.g., Walpole & Myers 1985) on the peak-over-continuum and the flux ratios (F11.3/F9.8 and F8.6/F9.8) presented in Figure 3. The K-S and the MWU tests are both non-parametric tests with the null hypothesis that two samples are drawn from the same distribution. Similarly, the MWU test does not reveal any statistically significant difference in the degree of grain growth and crystallinity of the single and binary samples: the probability that both samples could have been drawn from the same distribution. Generally, the MWU test does not reveal any statistically significant difference in the degree of grain growth and crystallinity of the single and binary samples: the probability that both samples could have been drawn from the same distribution.

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$^6$ A third-order polynomial gives smaller residuals in the spectrum minus fitted continuum than a first, a second, or a fourth order polynomial. We also verified that the results discussed in this section do not change when using lower or higher order polynomials to fit the continuum.
Dust Settling

Coagulation models show that if the dust grains in the upper layers of a flared disk become sufficiently large, they will gravitationally settle toward the mid-plane of the disk, resulting in a flattened disk geometry (e.g., Schräpler & Henning 2004; Nomura & Nakagawa 2006). Thus, one way to search for grain growth is to evaluate the flaring of circumstellar disks. While the shape of the 10 μm feature is sensitive to the presence of grains of a few microns in size in the disk upper layer, the disk flaring should probe the overall grain population of larger grains (e.g., Dullemond & Dominik 2004). To evaluate the disk flaring we use the ratio of fluxes at two different mid-infrared wavelengths. This procedure is justified by two facts: (1) the continuum flux emitted from the surface layer of the disk becomes proportional to the disk flaring at radial distances from solar-type stars of 0.4 AU or larger (Chiang & Goldreich 1997), and (2) these radial distances are probed by mid-infrared observations.

We integrate the flux of our SL infrared spectra in two wavelength bands, one shortward and one longward of the 10 μm silicate emission feature: 5.4–6.0 μm (central wavelength 5.7 μm) and 12.5–14.0 μm (central wavelength 13.25 μm). In addition, we use the MIPS24 photometry (or the IRS25 flux when MIPS is not available; see Table 3) to trace the disk flaring out to a few AU from the central star. The calculated flux ratios are shown in Figure 7, and histograms are presented in Figure 8. Larger flaring is indicated by higher ratios of long-wavelength continuum to short-wavelength continuum flux from the dust disk. These plots show that both single and binary systems have a large variety of disk structures. [See the electronic edition of the Journal for a color version of this figure.]
disk structures, with no preference for any structure in the two samples. The K-S and the MWU probabilities that the flux ratio distributions for single and binary stars come from the same parent population are higher than 0.1, confirming that the distributions of disk flaring for the two samples are not statistically different (the same result holds when excluding the sources with IRS25 fluxes).

5. DISCUSSION

Our study shows a large diversity in the 10 μm silicate emission features and SED slopes of T Tauri disks. We found that neither the dust processing nor the disk flaring correlates with the multiplicity of the sources. These results are particularly interesting for two aspects that will be discussed below.

5.1. Medium-Separation Binaries and Planet Formation

A stellar companion induces tidal forces in a disk that become particularly strong at resonance points. Resonant interactions result in the excitation of density waves that can truncate a disk and act to modify the binary eccentricity (see, e.g., Lubow & Artymowicz 2000 for a review). Theoretical calculations of binary-disk interactions predict that circumstellar disks will be truncated at 0.2–0.5 times the binary semimajor axis a, with the exact values depending on eccentricity, mass ratio, and disk viscosity (Artymowicz & Lubow 1994). These theoretical expectations are supported by millimeter observations of binaries, tracing the optically thin dust emission and thus the total disk mass in the system. There is evidence for a diminished millimeter flux (hence disk mass) among the 1–100 AU binaries in comparison to wider binaries or single stars (see, e.g., Mathieu et al. 2000 for a review). This result is qualitatively consistent with the circumstellar disks of medium-separation binaries being tidally truncated at 0.2–0.5a. Two-thirds of our sources have stellar companions between 0.1″ and 1″, with a mean projected separation of 0.4″ or 56 AU at the distance of Taurus. Therefore, the typical truncation radius for disks in our sample is >11–28 AU, well outside the location of Jupiter and Saturn in our solar system. Even in other systems these outer radii are found to be devoid of giant planets (e.g., Kasper et al. 2007). This fact suggests that the formation of terrestrial and giant planets may proceed undisturbed in disks around medium-separation binaries even if these disks are constrained in size.

Early investigations of young TTs found no significant difference in the frequency of near- and mid-infrared excess emission between single and binary star systems (e.g., Simon & Prato 1995; Jensen et al. 1996). With the 60 μm IRAS flux probing dust ≤10 AU from the central star, these measurements demonstrate that binary systems have disks as often as single stars do. Recently, Monin et al. (2007) analyzed the separation distributions of binaries with and without disks and found no statistical difference. Since most of their binaries have projected separations >20 AU, their result shows that medium- and wide-separation binaries do not have a significant effect on the circumstellar disk lifetime. Our work indicates that these disks also evolve in a similar way. The extent of dust processing in the disk surface layer and the degree of dust settling in binary disk systems do not statistically differ from those in disks around single stars. This suggests that the first few Myr of disk evolution in the terrestrial (and maybe out to the giant) planet-forming region are not affected by medium-separation stellar companions. Whether the disk evolution proceeds undisturbed for tens of millions of years until planets are fully formed cannot yet be assessed observationally. Bouwman et al. (2006) estimate a mean disk dispersion timescale of ~5 Myr for close (≤4 AU) binaries, in contrast to a timescale of ~9 Myr for single-star systems. They argue that the time available to form planets in close binary systems is considerably shorter than that in disks around single stars, which may inhibit planet formation. The only two medium-separation binaries in their sample hint at a disk dispersal timescale comparable to that of single stars, suggesting a similar disk evolution for single and medium-separation binary systems over the first ~10 Myr.

Exoplanet surveys offer us a glimpse into the frequency and properties of giant planets in multiple star systems. Recently, Eggenberger & Udry (2007) reported 42 planets orbiting binary and multiple stars (see their Table 1). Bonavita & Desidera (2007) analyze a subsample of radial velocity planet host stars with uniform planet detectability and demonstrate that the overall frequency of giant planets in binaries is not statistically different from that of planets in single stars. However, they find indications for a lower frequency of radial velocity planets in the subgroup of close- and medium-separation binaries (<50–100 AU). In a complementary study, Desidera & Barbieri (2007) find that the mass distribution of planets in binaries with separations <300–500 AU is statistically different from that around wider binaries and single stars: massive planets in short-period orbits are found predominantly around close- and medium-separation binaries. Taken together, the results from the frequency and properties of exoplanets suggest that a stellar companion with separation less than a few hundred AU affects giant planet formation and/or the subsequent migration. Numerical simulations seem to support this notion. Kley (2000) shows that a fairly eccentric (e = 0.5) stellar companion at 50–100 AU enhances the growth rate of a Jupiter-mass planet embedded in a circumstellar disk and makes its inward migration more rapid. Recently, Kley & Nelson (2007) confirmed these trends by following the evolution of a 30 M⊕ protoplanet in a disk truncated by a stellar companion at 18.5 AU and e = 0.36, such as the γ Cep binary system. Our study shows that the early evolution of protoplanetary disks surrounding binary stars is similar to that in single stars, indicating that the differences in the exoplanet properties arise in the later stages of their formation and/or migration.

Whether terrestrial planet formation is also affected by medium-separation binaries cannot yet be addressed observationally. Our study shows that the initial dust processing is not impacted by the presence of a stellar companion. Based on the fact that the build-up of planetesimals as large as the ~500 km Vesta has occurred in the first 3.8 ± 1.3 Myr of the solar nebula (Kleine et al. 2002), it is reasonable to speculate on the basis of our study that the formation of planetesimals in binary and single systems proceed along, if not on, identical avenues. Another indication supporting this suggestion comes from the finding of a similar incidence of debris disks in Gyr old single and binary stars (Trilling et al. 2007). If the debris dust is produced by colliding asteroids, then the similar rate of debris dust in binaries implies that planetesimal formation is not inhibited by the presence of stellar companions. Recent simulations of the later stages of terrestrial planet formation show that rocky planets can form in a wide variety of binary systems (Quintana & Lissauer 2007). The binary periastron is the most important parameter in limiting the number of forming planets and their range of orbits. Quintana & Lissauer (2007) show that binaries with periastron ≥10 AU, comprising most of the medium-separation binaries investigated in this paper, can form terrestrial planets over the entire range of orbits allowed for single stars. As a result, more than 50% of the binary systems in the Milky Way (Duquennoy & Mayor 1991) are wide enough to allow the formation of Earth-like planets.
5.2. The Diversity in Silicate Features and SEDs

Although small-sample statistics suggested a correlation between stellar multiplicity and initial dust processing (Meeus et al. 2003; Sicilia-Aguilar et al. 2007), our study demonstrated that medium-separation stellar companions do not appreciably affect the growth and crystallization of dust in circumstellar disks. Given the criteria applied to select our samples, we can also exclude that age, spectral type, and stellar environment can account for the large variety of observed silicate emission features and SED slopes in our study. There may be several other factors contributing to this diversity, which will be fully explored in an upcoming paper. Here we briefly mention two of them, turbulence and initial conditions.

Turbulence in circumstellar disks not only drives the accretion of gas onto the central star but also replenishes the disk atmosphere with more grains that can be larger in size. If the grains inferred from the 10 μm silicate emission feature reflect the level of disk turbulence, the strength of the features should depend on the stellar accretion rates. Sicilia-Aguilar et al. (2007) note that stars with strong features tend to have large accretion rates in their sample of several Myr old intermediate- and low-mass stars. This trend may be the result of turbulence determining the grain population in the disk atmosphere. Alternatively, the trend could be due to the more massive stars (which have typically larger accretion rates) in their sample heating a larger disk area and thus producing stronger silicate emission features (see, e.g., Kessler-Silacci et al. 2007). The tentative correlation seen in the sample of Sicilia-Aguilar et al. (2007) needs to be confirmed using a larger and more homogeneous sample of stars with well-determined accretion rates.

Different initial conditions for the collapsing cores may also leave their imprints on the formation and evolution of circumstellar disks. This possibility has been explored by Dullemond et al. (2006) to explain crystallization of dust grains in the early stages of disk evolution. In their model the level of crystallinity depends crucially on the rotation rate of the collapsing cloud core, because this determines the radius at which the infalling matter reaches the disk: rapidly rotating clouds would evolve into disks with low crystallinity, and slowly rotating clouds into disks with high crystallinity.

6. SUMMARY

In this paper we explored the effect of a stellar companion on the initial growth and settling of dust grains in circumstellar disks. We constructed two large samples of disks around single and binary TTSs with a narrow age spread and a spectral type distribution for the single stars identical to that of the primary stars in the binary sample. We used the strength of the 10 μm silicate emission feature derived from Spitzer IRS spectra as a proxy for grain growth and the SED slope of circumstellar disks as a proxy for dust settling. Our results can be summarized as follows:

1. There is no statistically significant difference between the distribution of 10 μm silicate emission features from single and binary systems.

2. The distribution of disk flaring is indistinguishable between the single and binary system samples.

These results show that stellar companions at projected separations of ≥10 AU do not appreciably affect the degree of crystallinity nor the degree of grain growth. Based on the combination of these and other results, we argue that the formation of planetesimals and possibly terrestrial planets is not inhibited in a circumstellar disk perturbed by a medium-separation stellar companion.

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