A DEEP SPITZER SURVEY OF CIRCUMSTELLAR DISKS IN THE YOUNG DOUBLE CLUSTER, h AND χ PERSEI

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ABSTRACT

We analyze very deep Infrared Array Camera and Multiband Imaging Photometer for Spitzer (MIPS) photometry of ∼12,500 members of the 14 Myr old Double Cluster, h and χ Persei, building upon our earlier, shallower Spitzer Cycle 1 studies. Numerous likely members show infrared (IR) excesses at 8 μm and 24 μm, indicative of circumstellar dust. The frequency of stars with 8 μm excess is at least 2% for our entire sample, slightly lower (higher) for B/A stars (later type, lower mass stars). Optical spectroscopy also identifies gas in about 2% of systems, but with no clear trend between the presence of dust and gas. Spectral energy distribution modeling of 18 sources with detections at optical wavelengths through MIPS 24 μm reveals a diverse set of disk evolutionary states, including a high fraction of transitional disks, though similar data for all disk-bearing members would provide constraints. Using Monte Carlo simulations, we combine our results with those for other young clusters to study the global evolution of dust/gas disks. For nominal cluster ages, the e-folding times (τ_e) for the frequency of warm dust and gas are 2.75 Myr and 1.75 Myr, respectively. Assuming a revised set of ages for some clusters, these timescales increase to 5.75 and 3.75 Myr, respectively, implying a significantly longer typical protoplanetary disk lifetime than previously thought. In both cases, the transitional disk duration, averaged over multiple evolutionary pathways, is ≈1 Myr. Finally, 24 μm excess frequencies for 4–6 M⊙ stars appear lower than for 1–2.5 M⊙ stars in other 10–30 Myr old clusters.

Key words: circumstellar matter – open clusters and associations: individual (NGC 869, NGC 884) – planetary systems – protoplanetary disks – stars: formation

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Planet formation around other stars provides a reference point for understanding the formation and early evolution of the solar system. Nearly all stars are born surrounded by optically thick disks of gas and dust (Adams et al. 1987; Strom et al. 1989; Hernandez et al. 2007b; Gutermuth et al. 2009), which comprise the building blocks of planets. Over time, dust grains in these protoplanetary disks settle toward the midplane and coagulate into larger, lower opacity bodies (Dullemond & Dominik 2005). Protoplanetary disk gas (and dust entrained in it) is drained by accretion onto the star (Hartmann et al. 1998). Hence, the frequency of detectable gas-rich dusty protoplanetary disks decreases with time (Hernandez et al. 2007b; Currie & Sicilia-Aguilar 2011).

By 10–20 Myr, the frequency of gas-rich dust disks has dropped effectively to zero. Few stars show infrared (IR) broadband excesses consistent with warm, optically thick protoplanetary disk dust (Silverstone et al. 2006; Currie et al. 2007a), cold gas from outer disk regions (Pascucci et al. 2006; Dent et al. 2013), or accreting gas from inner disk regions (Jayawardhana et al. 2006; Fedele et al. 2010). Optically thin, gas-poor debris disks have second-generation dust originating from planetesimal collisions (Wyatt 2008; Kenyon & Bromley 2008). They comprise most of the disk population at ages beyond 10 Myr (Rieke et al. 2005; Su et al. 2006; Carpenter et al. 2009a; Gaspar et al. 2013) and first emerge around stars nominally age-dated to 3–5 Myr (Carpenter et al. 2006; Currie et al. 2009; Currie & Kenyon 2009).

Stars with ages of several Myr to 10–20 Myr, therefore, clarify the timescale for and probe the structures of dissipating protoplanetary disks and the transition from these disks to debris disks. The most recent studies suggest an e-folding timescale of ∼3 Myr for protoplanetary disk dust and gas (Hernandez et al. 2007b; Fedele et al. 2010; Currie & Sicilia-Aguilar 2011). Fewer than ∼20% of such disks around stars of solar mass or greater remain at ∼5 Myr (Currie et al. 2009; Currie & Kenyon 2009).

The morphologies of protoplanetary disks at these intermediate ages also show evidence for significant evolution. Fewer disks are optically thick at all IR wavelengths, characteristic of nearly all million-year-old “primordial” disks. More disks exhibit reduced IR emission, consistent with inner disk clearing. As shown by spectral energy distribution (SED) modeling, many of these transitional protoplanetary disks have an optically thin inner hole/cavity that retains an optically thick outer disk (Calvet et al. 2005; Espaillat et al. 2007). Many other disks exhibit a reduced luminosity at IR to submillimeter wavelengths and likely represent a second evolutionary pathway, homologically depleted transitional disks (Currie et al. 2009), though this population is challenging to distinguish from some primordial disks with dust settling (Luhman et al. 2010; Currie & Sicilia-Aguilar 2011). Nevertheless, the relatively high frequency of the combined transitional disk population suggests that this phase, averaged over all pathways, comprises an appreciable fraction (e.g., 30%) of the total disk lifetime (Currie et al. 2009; Currie & Sicilia-Aguilar 2011), though the exact sizes of the transitional disk populations and relative lifetimes for different morphologies are still being debated (Muzerolle...
et al. 2010; Luhman et al. 2010; Currie & Sicilia-Aguilar 2011; Espaillat et al. 2014).

However, our understanding of protoplanetary disk and early debris disk evolution hinges on key, recently challenged assumptions about the samples comprising the above mentioned studies. In particular, while the relative ages of young clusters can be reliably determined, absolute ages are highly uncertain (see the discussion in Soderblom et al. 2014). Bell et al. (2013) and Pecaut et al. (2012) find that stars in many clusters nominally age-dated to 2–5 Myr and used to derive disk evolution timescales are about twice their nominal age. However, studies deriving the protoplanetary disk timescale and the transitional disk duration generally assume nominal, systematically younger ages (Hernandez et al. 2007b; Currie & Sicilia-Aguilar 2011).

Moreover, our knowledge about disk evolution is limited by poor constraints on the properties of disks around some kinds of stars at 10–20 Myr. Few protoplanetary disks remain around any stars age-dated at ∼10–20 Myr. Ensembles of such disks much larger than the populations of nearby clusters are needed to investigate the morphologies and relative frequencies of the longest-lived protoplanetary disks. While planets appear around stars as massive as 4.5 $M_\odot$ (Hatzes et al. 2005), studies focused on nearby clusters have only explored the disk populations around $M \lesssim 2–3 M_\odot$ (e.g., late B/early A type) stars. For any reasonable initial mass function (e.g., Miller & Scalo 1979), these massive stars are far less frequent than the AFGKM stars normally analyzed in disk evolution surveys. Therefore, extremely populous clusters at 10–20 Myr are required to investigate statistically the last vestiges of the protoplanetary disk phase and complete our understanding of the frequencies of debris disks around all types of planet-bearing stars.

The massive 14 Myr old Double Cluster, h and χ Persei, provides us with a valuable laboratory for studying disk evolution at 10–20 Myr. The large population of stars (∼12,500) in this region at a wide range of evolutionary states allows us to constrain the frequency and morphologies of the longest-lived protoplanetary disks. Additionally, h and χ Persei contains a large number of very early-type, massive stars (SpT $\leq$ B6, $M \geq 4 M_\odot$) relative to other nearby clusters, allowing us to investigate the disk populations of the most massive stars. Lastly, compared to most other clusters, the age of h and χ Persei is well constrained. A number of independent diagnostics such as pre-main-sequence isochrones, the main-sequence turnover, and the luminosity of M supergiants (Slesnick et al. 2002; Currie et al. 2010; Bell et al. 2013) independently point to an age of 14 Myr. Because the derived disk lifetimes are dependent on cluster age, precise knowledge of the age of h and χ Persei helps to clarify the protoplanetary disk lifetime as well as the relative frequency and morphology of long-lasting protoplanetary disks.

Previous Spitzer Space Telescope data for h and χ Per provide a first, but very limited, probe of the Double Cluster’s disk population (Currie et al. 2007a, 2007c, 2008a). Infrared Array Camera (IRAC) 3.6–8 μm data revealed many stars on the field with red colors consistent with disk emission, but was too shallow to detect the photospheres of stars less massive than about 1.3 $M_\odot$. Multiband Imaging Photometer for Spitzer (MIPS) 24 μm data identified many large-excess sources consistent with a plateau/peak in debris emission at 10–20 Myr for (some) stars more massive than the Sun due to icy debris disk evolution, which was verified by analyzing MIPS excesses in nearby regions also found in other studies (Currie et al. 2008a; Hernandez et al. 2007b; Chen et al. 2011). However, these data detected just 17 stars less than 3 $M_\odot$ with the most luminous debris emission and could not probe the photospheres of the most massive planet-bearing stars. Finally, at the time of these publications, membership lists for the Double Cluster were limited to post-main-sequence stars, Be stars, and the most massive main-sequence stars (e.g., Slesnick et al. 2002). The candidate member list from Currie et al. (2010) extending h and χ Per’s census to subsolar-mass stars was not yet available: warm dust and gas frequencies derived from Currie et al. (2007a, 2007b) are then prone to uncertainties due to contamination from non-members.

In this study, we present a deep photometric, IR study of h and χ Persei members using new IRAC and MIPS data from Spitzer and the membership list from Currie et al. (2010). The paper is organized as follows. In Section 2, we describe our data reduction techniques and quantify our completeness limits for both the IRAC and MIPS data. In Section 3, we identify and quantify the frequency of stars surrounded by warm and slightly cooler circumstellar dust, while Section 4 details a similar analysis of gas-rich disks. To further investigate the morphologies of disks around h and χ Persei stars, we then compare the SEDs of members with 8 μm and 24 μm excess to fiducial models representing a range of disk evolutionary states (Section 5). In Section 6, we combine our results with those of other clusters to constrain the lifetime of protoplanetary disks and the duration of the transitional disk phase. We conclude with a summary of our results, contrast them with other recent studies, and identify future work that can further constrain the h and χ Persei disk population and clarify key aspects of protoplanetary disk evolution in Section 7.

2. DATA

2.1. IRAC 3.6–8 μm Data

The IRAC (Fazio et al. 2004) observed h and χ Persei on October 30, 2008 (AOR IDs 2182740, 21828608, 21828096, 21828864, 21828352, and 2182912). Solar activity was normal to below average. Zodical emission ranged between ∼0.02 and 2 MJy sr$^{-1}$ from 3.6 μm to 8 μm. Image processing and photometry were performed separately for the short-exposure and long-exposure frames.

2.1.1. Image Processing and Photometry for Short-exposure Data

The short-exposure (0.6 s) corrected BCD (basic calibration data; CBCD) frames have very low source density, no diffuse mid-IR emission (e.g., nebulosity), and very few residual cosmic-ray hits. We processed these data using MOPEX (Makovoz 2005), applying an overlap correction and mosaicing the images. Photometry was performed using PhotVis (Gutermuth et al. 2004), a slightly modified GUI-based adaptation of the standard IDLPHOT aperture photometry package. We used a 2 pixel (2′) radius aperture, a sky annulus ranging between 2 and 6 pixels in radius, and the aperture corrections listed in the IRAC data handbook.

2.1.2. Image Processing and Photometry for Long-exposure Data

The source density for long-exposure data is significantly higher; the long-exposure data identify far more stars, including numerous AFGKM cluster members that are too faint (m[IRAC] $\geq$ 13) to be detected by the 0.6 s exposures (see Currie et al. 2007a; Currie 2008). To optimize our photometry,
and thus better insulate our results against photometric uncertainties, we adopt a more detailed approach to image processing and photometry.

Briefly, we first applied the Array-dependent Pixel Response correction (Quijada et al. 2004) to each CBCD frame and then mosaic the CBCD frames using MOPEX. We applied an overlap correction to each frame, masking pixels containing bright point sources and calculating each frame’s zero-point offset using iterative 3σ clipping to determine the frame’s background level.

To determine the distribution of pixel values for each position on the final mosaic, we interpolated values from individual frames using the drizzle algorithm with a “drizzle factor” of 0.1. Though very computationally expensive, the drizzle algorithm produced the most sharply defined point sources and did not introduce low-frequency pattern noise like that produced by bicubic interpolation. Outlier rejection was performed using the mosaic outlier and rmask mosaic modules. Final flux densities for each pixel were derived from the average value of the sigma-clipped stack of pixel values.

For photometry, we use a slightly modified version of the IDLPHOT aperture photometry package, improving the sky background determination, centroiding, and photometric error determination. To identify point sources, we set the detection threshold in each filter in the find.pro routine equal to three times the measured dispersion in the sky background (∼3σrms, avg). We apply pixel masks on the mosaic to remove the central pixels of all stars and the wings of bright stars from sky background determination. The adopted sky background is set to the median value, not the “mode.” As with the short-exposure data, we adopt a 2 pixel aperture, a 2−6 pixel sky annulus, and the aperture corrections from the IRAC data handbook. From the uncertainty in the sky background, photon noise, and read noise, we determine the photometric uncertainty, following Currie et al. (2008b).

To select a final list of IRAC detections, we compared lists from the long- and short-exposure data. For sources brighter than magnitude 10.5 in the long-exposure data, we replaced the entries with those from the short-exposure data due to saturation (see also Currie et al. 2008b). By matching our catalog to the Two Micron All Sky Survey (2MASS) catalog, we fine-tuned the IRAC data astrometry and produce a combined list of IRAC sources with and without 2MASS counterparts. In all band merging between the IRAC channels and IRAC to MIPS/2MASS etc. we adopted a matching radius of 1′.

Figure 1 shows a color mosaic image produced from the IRAC [3.6], [4.5], and [8] filters (blue, green, and red).

2.1.3. IRAC Source Counts and Detection Limits

Figure 2 shows the distribution of IRAC magnitudes versus photometric uncertainties. Most sources follow a thin distribution in photometric uncertainty over the full range of magnitudes. However, for each filter, a second, sparser distribution lies on top of the main one; many sources have photometric uncertainties ∼0.1–0.2 mag even though the errors from photon noise can be ≤0.05 mag. Typically, these sources are located in regions of higher stellar density or near the point-spread function (PSF) wings of bright stars, and thus estimates of the local background flux are more uncertain.

Figure 3 displays the number counts in each IRAC band as a function of magnitude. In total, we detect ∼110,000, ∼120,000, ∼58,000, and ∼32,500 candidate point sources in the [3.6], [4.5], [5.8], and [8] filters, respectively. Of these, ∼76,000; ∼68,000; ∼31,000; and ∼23,000 are detected at the 3σ level (dashed line). Because they have matches in multiple IRAC or 2MASS filters, the vast majority of the candidate detections are confirmed: ∼80,000 in [3.6], ∼80,000 in [4.5], ∼34,000 in [5.8], and ∼21,000 in [8].

Compared to the data presented in Currie et al. (2007a, vertical gray lines), our new data are ∼1.5–3 mag deeper in each filter, clearly probing far deeper down the cluster mass function and detecting fainter background sources. The number counts peak at [3.6] ∼18, [4.5] ∼17.8, [5.8] ∼16.5, and [8] ∼15.5. Both the distribution of 3σ candidate detections and confirmed detections peak at substantially fainter limits.

2.2. MIPS 24 μm Data

2.2.1. Image Processing and Photometry

The MIPS (Rieke et al. 2004) imaged h and χ Persei on 2008 March 15–16, 2008 October 25–26, and 2009 March 26 and 29 as a part of General Observation Programs 40690 and 50664 (PI: Scott Kenyon). The program 40690 observations were focused on the cluster dominated regions with a typical integration time per pixel of 2000 s, while the program 50664 data imaged the low-density halo regions surrounding the h Persei and χ Persei centers with a typical integration time per pixel of 1000 s. Combined, these observations provide MIPS 24 μm data for point sources over a ∼0.4 deg² area, covering the core-dominated membership population and much of the known halo population.

Using the Data Analysis Tool pipeline, we processed individual BCD frames, removing latent image artifacts and bad pixels, and mosaiced the data using a standard outlier rejection similar to that used in the MOPEX reductions of our IRAC data. For point-source detection, we selected groups of pixels lying >3σ above the local background on the mosaic. Point-spread function fitting photometry was performed on detected sources.
Figure 2. Density plot of the magnitude vs. error distribution for IRAC data.

Figure 3. Number counts in the IRAC bands. The solid black lines identify all candidate detections, the dashed lines identify 5σ detections, and the dotted lines identify confirmed point sources (those with detections in multiple bands). The gray vertical lines identify where the source counts peak in Cycle 1 data presented by Currie et al. (2007a).
2.2.2. MIPS Source Counts and Detection Limits

The MIPS data contain 7583 point sources. Of these, 6174 are detected at a 5σ significance or better; 1098 (4270) have counterparts in the 2MASS (IRAC) data. The distribution of [24] versus σ([24]) is thicker than for the IRAC bands, largely due to the different survey depth from the two observing programs (Figure 4, left panel). The MIPS source counts peak at [24] ~ 11.25 for the shallower program 50664 data, while the deeper program 40690 data yield 5σ detections about a magnitude fainter in regions near the cluster centers. Compared to the MIPS data presented in Currie et al. (2008a; vertical gray line), our new data are then 0.75–1.75 mag deeper.

2.3. IRAC and MIPS Colors of All Detected Sources

Figure 5 displays the IRAC and MIPS colors for all targets detected in multiple bandpasses with photometric uncertainties less than 0.2 mag (~5σ). Our sample includes a well-defined distribution of objects centered on zero [3.6]–[8] color (top left panel), which widens from about 0.1 mag to 0.5–0.75 mag on the mosaiced data using model PSFs from the Spitzer Science Center Webpage.

Figure 4. Density plot of the magnitude vs. error distribution (left) and number counts (right) for MIPS 24 μm data. Symbols are the same as in Figures 1 and 2. The gray vertical line identifies where the source counts peak in data presented in Currie et al. (2008a).

Figure 5. IRAC/MIPS color–magnitude and color–color diagrams for objects detected in multiple bandpasses. Top left: [8]/[3.6]–[8] diagram showing a well-defined main locus of objects with approximately zero color, a population of weak, 0.25–1.5 mag excesses, and a dense population of objects with red colors ([3.6]–[8] ~ 1.5–4). Top right: [24]/[3.6]–[24] diagram showing more clearly the same three major populations: objects with zero color, a small weak-excess population ([3.6]–[24] ~ 0.5–4.5), and a dense strong-excess population ([3.6]–[24] ~ 4.5). Bottom left: [3.6]–[8]/[3.6]–[24] diagram showing that the objects with the strongest excesses in IRAC likewise have the strongest excesses in MIPS, while those with [3.6]–[24] ~ 0.5–4.5 include objects with and without IRAC excesses. Bottom right: J/[3.6]–[24] diagram showing that we only detect objects with zero [3.6]–[24] color down to a 2MASS J magnitude limit of ~12.5–13.
from \([8] = 12\) to \([8] = 15.5\). Our sample also includes a large population of objects with very red \([3.6]–[8]\) colors \((\gtrsim 1.5)\) consistent with those expected for young stellar objects (YSOs) or red, active galaxies (Gutermuth et al. 2008, 2009, see the Appendix of this work). The \([8]\) versus \([3.6]–[8]\) diagram also shows a smaller population of objects slightly redder \((\sim 0.25–1.5)\) than the main distribution of zero-color objects, consistent with the colors expected for highly reddened background stars; red, cool giants; Be stars; and pre-main-sequence stars with optically thin emission from remnant protoplanetary disks or warm debris disks (Currie et al. 2008a; Currie & Sicilia-Aguilar 2011; Kenyon & Bromley 2004). The sample’s distribution of [24] versus \([3.6]–[24]\) colors reveals the same kinds of populations: objects with zero color, many with very red \((\sim 4.5)\) MIPS colors, and a much smaller population of slightly red objects \((\sim 0.5–4.5)\).

The bottom panels of Figure 5 clarify the nature of the many objects with strong IRAC/MIPS excesses and the few with weaker excesses. The objects with strong excesses in one band (IRAC or MIPS) must, in general, be extremely red from 1 \(\mu\)m to 24 \(\mu\)m, given the dense clustering of objects at \([3.6]–[8.24] \approx 11.255,26\) (bottom left panel); the bottom right panel shows that these red objects preferentially have very faint J-band magnitudes. These colors are consistent with those either for YSOs or for active galaxies. Most of the objects with weaker 24 \(\mu\)m excesses appear to have very weak to negligible IRAC excesses, concentrated mainly along a narrow band from \([3.6]–[8.24] \approx 0.05\) to \([0.5,4.5]\), and have \(J \sim 12.5–16.5\), comparable to the near-IR brightnesses of AFGK members in \(h\) and \(\chi\) Persei (Currie et al. 2010).

2.4. Ancillary Data Establishing Cluster Members

To identify and characterize disks surrounding \(h\) and \(\chi\) Persei stars, we combine \(Spitzer\) data with optical/near-IR data for likely cluster members, updating the list from Currie et al. (2010) with a more accurate one of 13,956 stars (Table 1).

Optical spectroscopy confirms the stellar nature of sources, provides a better estimate of the stars’ intrinsic fluxes by yielding their extinctions, and reveals whether the stars show evidence for circumstellar gas accretion, which can be present for protoplanetary disks but is absent for debris disks. In total, 12,505 (~90%) of the optically selected cluster members have matches in our \(Spitzer\) data. We briefly review the sources of these ancillary data.

2.4.1. Optical and Near-infrared Photometry

Optical \(V_I\) photometry of \(h\) and \(\chi\) Persei stars was originally taken as a part of the MONITOR program (Aigrain et al. 2007) and covers \(\sim 0.6\) \(\text{deg}^2\) on the sky. We supplement this photometry with that from Slesnick et al. (2002), which was a shallower survey covering a wider, \(\sim 1\) \(\text{deg}^2\) area. Cluster stars with optical photometry range in mass from bright, \(\sim 15–20\) \(M_\odot\) supergiants to very faint, \(\sim 0.2\) \(M_\odot\) pre-main-sequence M stars (see Currie et al. 2010).

Near-IR \(JHK_s\)-band photometry is drawn from the 2MASS All-Sky Survey (Skrutskie et al. 2006). The survey has nominal 10\(\sigma\) limits of \(J = 15.8\) and \(K_s = 14.3\). However, the number counts of detections in the \(h\) and \(\chi\) Persei field suggest completion limits of \(J = 15.5\) and \(K_s = 15\) (Currie et al. 2007a), where the formal photometric uncertainties reach \(\sim 0.1\) mag and 0.2 mag, respectively.

2.4.2. Optical Spectroscopy: Identifying Accreting Stars

Finally, we add optical spectroscopy of \(h\) and \(\chi\) Persei stars. The survey presented in Currie et al. (2010) includes \(\sim 11,000\) stellar spectra with sufficiently high signal-to-noise to determine accurate spectral types. Currie et al. (2010) limited their membership analysis to spectroscopically observed stars with \(V\) band and 2MASS photometry (7465), which produced a list of 4702 members. Many other stars with spectra presented in Currie et al. (2010), but without optical photometry (and thus not analyzed for membership) may in fact be members of the Double Cluster and can be confirmed after obtaining new optical photometry.

Here, we consider evidence for stars accreting gas from protoplanetary disks among the entire set of spectra listed in Currie et al. (2010). We derive \(\text{EW}(\text{H}_\alpha)\) with SPTCLASS (Hernandez et al. 2004), which uses the standard IRAF routine \(sbands\). Manually comparing \(\text{EW}(\text{H}_\alpha)\) with SPTCLASS-derived estimates for this sample and for the previously reported sample from Currie et al. (2007b) shows excellent agreement.

Based on these measurements, we identify accretors from the subset of spectra not previously analyzed in Currie et al.

Table 1

| Member ID Number | Photometry Running Number | Spectroscopy Running Number | Membership Type | R.A. | Decl. | Numerical Spectral Type | V | \(\sigma(V)\) | I | \(\sigma(I)\) |
|------------------|---------------------------|-----------------------------|-----------------|------|------|-------------------------|---|------------|---|------------|
| 1                | 3                         | 174                         | 1               | 34.7691 | 57.1355 | 13.0                 | 7.1731 | 0.0001 | 6.6876 | 0.0001 |
| 2                | 16                        | 60                          | 3               | 34.6173 | 57.2084 | 11.5                 | 7.7866 | 0.0001 | 7.3575 | 0.0001 |
| 3                | 17                        | 11                          | 3               | 34.5962 | 57.0102 | 10.7                 | 7.8288 | 0.0001 | 7.4510 | 0.0001 |
| 4                | 30                        | 8                           | 3               | 34.4577 | 57.0904 | 10.5                 | 8.0183 | 0.0001 | 7.5970 | 0.0001 |
| 5                | 39                        | 69                          | 3               | 34.6996 | 57.0673 | 11.5                 | 8.2215 | 0.0001 | 7.6884 | 0.0001 |

Notes. The membership type has the following meaning: candidate members identified from \(1 = \) photometry, \(2 = \) spectroscopy, \(3 = \) photometry and spectroscopy. A zero for either the photometry or spectroscopy running number means that the source lacks either optical photometric or spectroscopic data. The spectroscopy running number corresponds to the running number from the combined photometry + spectroscopy table (Table 3), not the running number from Table 2. The optical photometry listed here comes from that obtained in Currie et al. (2010), which may be saturated for the brightest stars.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 6. Top: completeness at [8] and [24] for cluster members. We restrict our statistical analysis to stars with $V \leq 22$ at 8 μm and $V < 13$ at 24 μm. Bottom: $V$ vs. $\sigma([8])$ and $V$ vs. [8] for our sample. In the right-hand panel, the light gray dots identify stars with 5σ [8] detections. Nearly all stars with lower signal-to-noise ratios are fainter than $[8] = 15.5$.

2.5. Combined Spitzer and Ground-based Sample Characteristics

2.5.1. IRAC and MIPS Completeness

To select point sources with dust emission, we rely on the 8 μm IRAC data and the 24 μm MIPS data. Within the far more sensitive [3.6] and [4.5] IRAC images, we detect nearly all (90%–95%) cluster members from $V \sim 6$ ([3.6] $\sim$ [4.5] $\sim$ 3–5) to $V = 24$ ([3.6] $\sim$ [4.5] $\sim$ 17–17.5). Members lacking detections fall outside of the IRAC coverage. Thus, the ratio of the detection frequencies at [8] ([24]) and [4.5] provide a robust estimate of the completeness at 8 μm (24 μm). Figure 6 shows the result.

Figure 6 (top panels) assesses our sample completeness. Our 8 μm completeness diverges from 100% at $V > 17$ and drops below 50% by $V = 22$. Our 24 μm completeness drops from a maximum value of $\sim$80% at $V = 11$%–25% by $V = 13$. In Section 4, we derive statistics for disk emission in a given filter only for h and χ Persei stars where we detect at least 25% of the sample. Thus, at 8 μm, we focus on stars brighter than $V = 22$. At 24 μm, we derive statistics for stars brighter than $V = 13.5$.

The bottom panels of Figure 6 assess the level to which the 5σ cutoff that we will impose for analyzing our IRAC detections (Section 3) may bias our results. For stars with $V = 11$–19, 19–20, 20–21, and 21–22, the typical [8] photometric uncertainties are $\sigma([8]) \approx 0.05$–0.1, 0.1, 0.15, and 0.175, respectively. For these $V$ magnitude bins, the percentage of stars detected at better than a 5σ level at [8] is 99.5%+, 95%, 86.3%, and 76%, respectively. We obtain similar results for $V$ versus [24] and $\sigma([24])$.

2.5.2. Masses of Spitzer-detected h and χ Persei stars

Double Cluster members targeted by Spitzer cover a wide range of optical/IR brightness, spectral types, and thus stellar masses. To estimate the typical stellar masses corresponding to an h and χ Persei star of a given optical brightness, we use two sets of isochrones—Baraffe et al. (1998) for stars less than 1.4 $M_\odot$ and Palla & Stahler (1999) for more massive stars. To map between the stars’ effective temperatures predicted from these isochrones and spectral type and median V-band magnitude, we first adopt the effective temperature scale listed in Currie et al. (2010).8 We compute the median V-band magnitude

8 Note that the stellar mass sampling from the Palla & Stahler (1999) isochrones is quite coarse, and thus values for the upper main sequence in h and χ Persei are less precisely determined than for the pre-main sequence. However, we opt to use these isochrones since they yield an age for other young associations—specifically, Upper Scorpius—that can agree with the age derived from Baraffe et al. (1998; cf. Preibisch et al. 2002). Other isochrones with better sampling may yield spurious stellar mass-dependent age spreads (Currie et al. 2010). Furthermore, while the sampling in mass is coarse, the resultant sampling in spectral type and V-band magnitude is not (see Table 3). We will further discuss stellar ages in Section 6.

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Figure 7. Color–magnitude diagram identifying IR-excess sources (diamonds) and negative outliers (gray dots) compared to the full distribution of \( h \) and \( \chi \) Persei sources. The solid lines identify the median color for a given [8] or [24] magnitude and the dashed lines separate objects whose colors are consistent with bare photospheres in a given passband and those deviating from this distribution by more than \( \sim 3\sigma \). The vertical dashed lines in the top left and bottom left panels depict the typical colors for blue protoplanetary disks in Taurus drawn from Figure 5 in Luhman et al. (2010).

### Table 2

| ID | R.A.   | Decl.  | SpT   | V    | \( \sigma(V) \) | [3.6] | \( \sigma([3.6]) \) | [4.5] | \( \sigma([4.5]) \) | [5.8] | \( \sigma([5.8]) \) | [8]  | \( \sigma([8]) \) | [24] | \( \sigma([24]) \) |
|----|--------|--------|-------|------|-----------------|-------|---------------------|-------|-------------------|-------|-------------------|------|-------------------|------|-------------------|
| 2  | 34.6173| 57.2084| 11.5  | 7.866| 0.0001          | 7.480 | 0.002               | 7.475 | 0.002             | 7.427 | 0.002             | 7.339| 0.004           |
| 3  | 34.5962| 57.0102| 10.7  | 7.829| 0.0001          | 7.974 | 0.003               | 7.975 | 0.002             | 7.867 | 0.001             | 7.861| 0.038           |
| 4  | 34.4577| 57.0904| 10.5  | 8.018| 0.0001          | 8.260 | 0.002               | 8.248 | 0.002             | 8.210 | 0.001             | 8.187| 0.032           |
| 5  | 34.6996| 57.0673| 11.5  | 8.221| 0.0001          | 7.979 | 0.002               | 7.881 | 0.002             | 7.717 | 0.001             | 7.578| 0.001           |
| 7  | 34.7002| 57.2855| 12.0  | 8.378| 0.0001          | 8.569 | 0.002               | 8.583 | 0.002             | 8.570 | 0.002             | 8.552| 0.048           |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

for stars of a given mass/spectral type directly for BAF stars since such stars are well sampled from our spectroscopic survey (Currie et al. 2010) and are on/very near the main sequence; thus, the adopted \( T_{\text{eff}} \) scale should match that of field dwarfs. For lower mass stars poorly probed by our spectroscopic survey, we simply adopt a distance of 2.34 kpc and a mean Double Cluster reddening of \( E(B-V) = 0.54 \) (derived mostly from BAF stars). From these assumptions, we determine the predicted \( V \)-band magnitude for these lower mass, later type stars.

Table 3 shows the expected spectral type and \( V \)-band magnitudes for cluster members with different stellar masses. Stars with \( V \approx 12, 13, 15, 18, 19, 20, \) and 22 typically have spectral types of SpT \( \approx \) B2.5, B4, A1.5, K0, K3, K5, and M1.5, respectively. Adopting our hybrid Palla & Stahler/Baraffe 14 Myr isochrone to map between spectral type/\( T_{\text{eff}} \) and stellar mass, stars with these spectral types typically have stellar masses of \( M_{\star} \approx 6, 5, 2, 1.2, 1.1, 0.95, \) and 0.6 \( M_{\odot} \). Thus, given our IRAC/MIPS completeness limits, we will later only derive the 8 \( \mu \)m excess frequency for stars with \( M_{\star} \approx 0.6–6 \) \( M_{\odot} \) and the 24 \( \mu \)m excess frequency for stars with \( M_{\star} \approx 4–6 \) \( M_{\odot} \) (Section 3.2 and 3.3).

### 3. Circumstellar Dust in Disks Around \( h \) and \( \chi \) Persei Stars

Table 2 lists photometry for all \( \sim 12,500 \) \( h \) and \( \chi \) Persei members with Spitzer data. Here, we first examine the Spitzer colors for cluster members to identify stars with evidence of circumstellar dust. Next, we quantify the frequency of warm dust emission at 8 \( \mu \)m and set limits on the population of members with slightly cooler dust emission probed by MIPS 24 \( \mu \)m data. For all analyses, we restrict our sample to stars with 5 \( \sigma \) detections.

#### 3.1. IRAC and MIPS Colors: Evidence for Warm Circumstellar Dust Emission

Figure 7 displays the IRAC/MIPS color–magnitude diagrams for \( h \) and \( \chi \) Persei members. The members-only distributions...
clearly differ from those of the population of all objects, as they include very few objects with extremely red IRAC and MIPS colors (i.e., \([3.6]–[8] > 2\), \([3.6]–[24] > 5\)). As shown in the Appendix, the objects with very red colors are most consistent with being polycyclic aromatic hydrocarbon (PAH)-emission galaxies or active galactic nuclei, whereas our members-only sample shares little to no overlap with the range of galaxy colors. There may be some other bona fide, hitherto unidentified cluster members with circumstellar disks among our full sample of Spitzer-detected sources. However, focusing only on those objects previously identified as members via optical photometry/spectroscopy allows us to derive statistics on the Double Cluster’s disk population with significantly less extragalactic contamination.

The top panels of Figure 7 show the IRAC \([8]\) versus \([3.6]–[8]\) and \([8]\) versus \([4.5]–[8]\) distributions for cluster members. The main locus of colors for cluster members is centered roughly about zero with a dispersion that broadens from \(\pm 0.05–0.06\) mag to \(\pm 0.75\) mag for the faintest stars detected at the 5σ level. The distributions exhibit some evidence of a gap in the excess population at \([8] = 11\), where excess sources brighter than this limit all have \([3.6]–[8] < 0.9\), while fainter excess sources include some with slightly redder colors. Still, the vast majority of fainter stars with colors redward of the main locus exhibit \([3.6]–[8]\) colors \(\sim 1\) mag or less.

To provide a comparison with our sample, we overplot \([3.6]–[8]\) colors typical of blue protoplanetary disks in Taurus from Figure 5 in Luhman et al. (2010, vertical line). Our sample includes over 10,000 stars and the cluster is only slightly older than clusters/moving groups containing some stars with optically thick, near-IR luminous disks (e.g., TW Hya, Upper Scorpius). Nevertheless, we identify very few stars whose \([3.6]–[8]\) colors overlap with the range of colors typical for protoplanetary disks. Instead, IRAC excesses for nearly all \(h\) and \(\chi\) Per stars are comparable to the level of emission from the two varieties of transitional disks (Currie et al. 2009; Currie & Sicilia-Aguilar 2011) and warm debris disks indicative of terrestrial planet formation (Kenyon & Bromley 2004; Currie et al. 2007c; Rhee et al. 2007; Lisse et al. 2009).

The MIPS colors (bottom panels) show similar trends. Here, the distributions of \([3.6, 4.5]–[24]\) colors broaden from ~0.05 mag at the bright end again to a wider distribution for the faintest stars detected at [24]. Stars brighter than ninth magnitude have excesses up to ~2–2.5 mag. While many stars fainter at [24] likewise exhibit these weak excesses, they also include some with \([3.6, 4.5]–[24] = 3–5.5\), comparable to the 24 μm excesses exhibited by the most luminous debris disks (Rieke et al. 2005; Low et al. 2005; Currie et al. 2008a) and some transitional disks (Currie & Sicilia-Aguilar 2011). Few stars have \([3.6]–[24]\) colors overlapping with most Taurus stars.

Figure 8 further elucidates the IR-excess population for \(h\) and \(\chi\) Persei. As shown in the left-hand panel, most of the stars with 24 μm excess emission have nearly zero color at \([3.6]–[8]\), though most of the ones with the largest 24 μm excesses are likewise red at \([3.6]–[8]\). All of the MIPS-detected stars with \([3.6]–[8]\) excesses have clear 24 μm excesses. Thus, there are many more stars with excesses at [24] than at [8]; stars with bona fide [8] excesses are virtually certain to have excesses at [24] as well, although they may fall below our [24] detection limit.

The right-hand panel of Figure 8 further demonstrates that for much of our sample, we are only identifying the stars with the most luminous 24 μm excess emission. From the results in Section 2.5, the 24 μm data only reach the photospheres of B-type stars. Any later-type stars detected in this band must have excess emission.

### 3.2. IRAC-excess Emission from Warm Dust

#### 3.2.1. Identifying IRAC-excess Sources

To identify stars with statistically significant excess emission at 8 μm, we follow methods similar to those described in Hernandez et al. (2006) and later work, defining the threshold for an IR-excess source based on the source color compared to the intrinsic dispersion of colors at a given magnitude. The Double Cluster members analyzed here have [8] magnitudes as bright as approximately fifth magnitude and as faint as \(\sim [8] = 15.5\), where the former’s photometric errors are negligible and the latter’s are as large as 0.2 mag. While the IRAC colors for young stellar photospheres show little variation for stars earlier than mid-M (see Luhman et al. 2010; Pecaut & Mamajek 2013), binarity could, in principle, artificially redden the system by up to \(\approx 0.05\) mag (e.g., see Table 13 in Luhman et al. 2010). Additionally, while reddening for most Double Cluster members falls within a range of \(E(B−V) = 0.4–0.7\) with a median value of 0.52–0.56, Currie et al. (2010) identified some stars best modeled as being far more heavily reddened and some with low reddening. Given various IR extinction laws (Indebetouw et al. 2005; Sicilia-Aguilar et al. 2011).
2005; Flaherty et al. 2007), this range in reddening could induce a spread in color of up to \(\approx 0.05-0.06\) mag in \([3.6, 4.5]-[8]\). Finally, the IRAC detector also suffers small gain variations across the field depending on whether bright point sources landed on a given pixel in the observations taken immediately prior (Knutson et al. 2007), and small errors in centroiding position due to bright nearby stars may also affect flux and background determinations.

Therefore, instead of defining our threshold for an IR-excess source based on intrinsic photometric errors, we empirically derive the spread in photospheric colors and identify excess sources as statistical outliers. For each color–magnitude diagram (e.g., \([8]\) versus \([3.6]-[8]\)), we first divide the distribution into 0.5 mag bins and derive the median color and standard deviation for each bin. We then use a quadratic interpolation to determine the median color and standard deviation at each magnitude. Nonlinearly, we identify \(3\sigma\) outliers as those with evidence for IR excess. To be conservative, we include an additional 0.06 mag buffer to account for color variations due to binarity and differences in reddening, an amount that also roughly corresponds to the spread in IRAC color for the brightest cluster members with negligible photometric errors.

Thus, IR-excess sources are defined as those with color \(\geq\) median(color) + \(3 \times \sigma_{\text{color}} + 0.06\). The empirically derived dispersion in color is always greater than the quadrature-added uncertainties in the photometric measurements. Compared to the criterion previously used in Currie et al. (2007a), our threshold is less stringent for brighter stars but far stricter for faint stars since it varies as \(3 \times \sigma_{\text{empir}}\), not \(1 \times \sigma_{\text{phot}}\).

We first compute the frequency of the IRAC-excess population as a function of the stars’ \(V\) - and \(I\)-band photometry. We restrict our analysis to stars brighter than \(V = 22\), where our completeness drops well below 50% (see Section 2.5). Furthermore, the percentage of stars whose \([8]\) detections whose high photometric uncertainties (\(\sigma([8]) > 0.2\)) preclude us from considering them here grows to 14%–24% for \(V = 20-22\). Therefore, our excess frequencies for the faintest stars (\(V = 20-22\)) are significantly more uncertain than for brighter stars.

Second, we compute the frequency of the IRAC-excess population as a function of the spectral types derived in Currie et al. (2010). Stars with \(V \approx 20-22\) typically correspond to K5–M1 stars (see Table 3). Therefore, only our excess frequencies for stars earlier than mid-K are robust against completeness/photometric biases.

### 3.2.2. Frequency of IRAC-excess Sources

Figure 9 shows the frequency of the IRAC-excess population as a function of \(V, I\), and spectral type. Overall, 263 \(h\) and \(\chi\) Persei members or \(~2.2\%\pm0.3\%\) show evidence for \(8\) \(\mu\)m excess likely due to warm dust. From \(V = 14\) to our completeness limits, the frequency of warm dust appears to steadily rise from \(~0.5\%–1\%\) (e.g., \(3.5\)/502 and \(11/955\) at \(V = 14–15\) and \(15–16\), respectively) to \(~3\%\) (e.g., \(23/843\) at \(V = 19–20\) and \(~4\%–5\%\) \(9/193\) at \(V = 21–22\)). The IRAC-excess frequency versus \(I\) shows similar trends. The frequency as a function of spectral type appears roughly flat from \(A0\) to \(G5\) at \(~1.5\%\), but rises to \(3.5\%\) for \(K\) stars, albeit with considerable uncertainty.

If we consider all stars regardless of evolutionary status (black dots in all figure panels), the frequency of warm dust for the brightest stars (\(V < 11, I < 10, B0–B5\)) is as high as in any magnitude/spectral bin covering lower mass stars. However, many of these stars are known Be stars or other post-main-sequence stars whose apparent IRAC excess is likely due to free–free emission or to warm dust from a circumstellar excretion disk and not a circumstellar accretion disk or debris disk connected to planet formation. To estimate the frequency of solely circumstellar disks related to planet formation, we then trim our sample of known Be stars, giants, and supergiants using lists of such stars from Currie et al. (2010), Marsh-Boyer et al. (2012), and from the SIMBAD database. In the latter case, various sources contribute to the Be star and (supergiant) identifications (Bragg & Kenyon 2002; Slesnick et al. 2002).

The revised IRAC-excess frequencies show that nearly all of the previously identified excess sources are in fact Be stars or post-main-sequence stars. With these stars removed, the excess frequencies for the brightest, earliest stars are \(~1\%–1.5\%\), comparable to or slightly smaller than their frequencies for slightly fainter, later and (presumably) lower mass stars (\(~1.5\%–2\%\)). Thus, in agreement with previous results (Currie et al. 2007a; Currie 2008), we identify a slight brightness/spectral-type dependent frequency of warm dust indicating that dusty circumstellar disks are less frequent around the most massive stars (\(M \sim 1.5–5\) \(M_{\odot}\)).

### 3.3. MIPS-excess Emission from Cooler Dust

To quantify the frequency of stars with MIPS excesses, we follow the same procedure used in Section 3.2.1 to flag IRAC-excess sources, defining the excess sources as those whose \(K_s\)–[24], \([3.6]–[24]\), or \([4.5]–[24]\) colors are redder than the median color by more than \(3\sigma+0.06\). Overall, we identify 152 \(h\) and \(\chi\) Persei stars with evidence for excess emission at 24 \(\mu\)m. As explained in Section 2.5, we restrict our analysis to stars with \(V \leq 13.5\) due to the poorer MIPS completeness compared to IRAC.

Following Section 3.2.1, we also derive the frequency in terms of spectral type and mass, using the rough conversion between the \(V\) magnitude and these two properties as listed in Table 3.
Figure 9. Frequency of 8 μm excess emission from disks vs. V-band magnitude (top), I-band magnitude (bottom left), and (numerical) spectral type (bottom right). As described previously, the numerical spectral type has the following formalism: 10 = B0, 11 = B1,..., 68 = M8. All plots report frequencies including and excluding post-main-sequence stars like giants and Be stars whose excess emission is likely not indicative of planet formation.

Because of poorer sampling in mass and \( T_{\text{eff}} \) from the Palla & Stahler (1999) isochrones and the large number of post-main-sequence stars dominating spectral types B0 and B1, we restrict the range of spectral types considered to B2–B6. The corresponding mass range is \( M_\star = 4–6 \, M_\odot \).

Figure 10 displays the frequency of MIPS 24 μm excess emission as a function of V magnitude, spectral type, and mass for these massive, early-type stars. About 5% of these stars show evidence for MIPS-excess emission from cooler dust compared to the 1%–3% that show IRAC-excess emission over the same range in V magnitude (~12–13.5), spectral type (~mid B), and mass (4–6 \( M_\odot \)) (see Figure 9). Although there is a slight decline in excess frequency with increasing V magnitude and later spectral types, the error bars are large enough to easily be consistent with no trend, indicative of a constant frequency of MIPS-excess emission. Any (small) correction for confusion with faint galaxies will not change this conclusion.

4. CIRCUMSTELLAR GAS IN DISKS AROUND h AND \( \chi \) PERSEI STARS

4.1. Identifying Accreting h and \( \chi \) Persei Stars

Our criteria for identifying possible accreting systems follows White & Basri’s (2003) spectral-type-dependent threshold based on the observed H\( \alpha \) equivalent width. For the stars with spectral types of K0 and later, the EW(H\( \alpha \)) provides a robust measure of accretion (White & Basri 2003). Nominally, for K0–K7 stars, we identify those with EW(H\( \alpha \)) ≥ 3 Å as accretors. For K7–M2.5 (M2.5–M5.5) stars, EW(H\( \alpha \)) ≥ 5 Å (20 Å) are flagged as accretors. These criteria are similar to those adopted in Currie & Kenyon (2009), but are more precise than those adopted for h and \( \chi \) Persei stars in Currie et al. (2007b), where stars with EW(H\( \alpha \)) > 5–10 Å were identified as candidate accretors.

It is more difficult to identify possible accretors among the AFG-type stars, which comprise the bulk of our spectroscopic sample. Within this group of intermediate-mass stars, much larger H\( \alpha \) emission line fluxes are required to produce EW(H\( \alpha \)) > 3 Å (e.g., White & Basri 2003). While these stars have additional clear accretion signatures (i.e., U-band excess, optical veiling, H\( \alpha \) emission; Calvet et al. 2004), they lack a clear EW(H\( \alpha \)) criterion for separating weakly accreting stars from chromospherically active ones using low-resolution spectroscopy. Because H\( \alpha \) absorption is often much broader than the absorption lines in later type stars, some stars show clear emission line reversals even though EW(H\( \alpha \)) < 3 Å (Dahm 2008; Currie & Kenyon 2009). Devising a reliable metric for identifying accreting AFG stars is beyond the scope of this paper; thus, for AFG stars, we nominally adopt the same EW(H\( \alpha \)) threshold applicable for K0–K7 stars and simply flag the few others showing core line reversal and H\( \alpha \) clearly in emission (no matter what the equivalent width).

Table 4 lists the 42 new candidate accreting stars and 30 previously identified candidate accretors from Currie et al. (2007b). Of these 72 objects, 47 (51) are among our members with Spitzer (optical) photometry. Three were initially rejected in Currie et al. (2010) as likely members.

Despite the preferential sampling in favor of BAF stars, most of the new candidate accretors are G0 or later (38/42). Of the BAF stars listed in Table 4, two have H\( \alpha \) in absorption, and thus formally are not identified as accretors. However, they have a strong core emission line reversal. These include a B9 star, which
may be the earliest known accreting star older than 10 Myr. While the \( H_\alpha \) equivalent widths generally are far smaller than for 1–5 Myr old T Tauri stars, and thus more indicative of low accretion rates (White & Basri 2003; Dahm 2008), three early K stars have much stronger emission (\( \text{EW}(H_\alpha) = 25–83 \) Å) reminiscent of their younger counterparts. As our spectroscopic sample is very incomplete for the h and \( \chi \) Persei mid-K to M star population (Currie et al. 2010), it is unclear whether any of the kinds of stars comprising most members of the youngest star-forming regions show frequent \( H_\alpha \) emission indicative of accretion in the Double Cluster.

4.2. Frequency of Accreting h and \( \chi \) Persei Stars

Figure 11 shows that the accretion frequency for likely h and \( \chi \) Persei members with optical spectra is highest for GK stars (\( M \sim 0.8–1.3 M_\odot \)) and lowest for earlier stars (\( M > 1.4 M_\odot \)). Our sample of accretors includes two F-type stars, while all the remaining accretors are G0 or later. As a result, the accretion frequency is consistent with zero from the earliest stars through F5, while the frequency rises above 2% for G0–K5 stars, peaking at \( \sim 3.3% \) for late G stars. This trend is consistent with a stellar mass-dependent frequency of gas accretion (Currie & Kenyon 2009), although our criteria for identifying accretors may slightly underestimate this population around the earliest (BA) stars. The frequency is lower for K5–M0 stars, although here again our sampling is poor.

4.3. Accretion and Circumstellar Dust Emission

Recent results imply that the frequency of dust and gas in protoplanetary disks in most young clusters decreases on a timescale of \( \sim 3 \) Myr (Hernandez et al. 2007b; Currie & Kenyon 2009; Fedele et al. 2010; Currie & Sicilia-Aguilar 2011). However, the presence of dust in older, \( \sim 10–20 \) Myr old clusters does not necessarily imply detectable protoplanetary disk gas and vice versa. Many disks around 10–20 Myr old stars with dust emission are instead optically thin, gas-poor debris disks (Chen & Kamp 2004; Roberge et al. 2005; Lisse et al. 2008, 2009). Conversely, at least some disks showing evidence for protoplanetary disk gas lack strong broadband IR-excess emission from dust that would be detectable in our sample (Currie et al. 2007b; Bittner et al. 2010). While preliminary results showed a weak correlation between protoplanetary disk gas and IR excess in h and \( \chi \) Persei stars, our expanded sample of accretors and more precise IR photometry allows us to reinvestigate this connection.

Figure 11 compares the \( H_\alpha \) equivalent width to the [3.6]–[8] color among our sample of candidate accretors. Most strikingly, the distribution of IR colors appears nearly symmetrical about zero for a range of \( \text{EW}(H_\alpha) \) with only one to two outliers. This result is in slight contrast with previous studies of h and \( \chi \) Persei’s accreting population (Currie et al. 2007b), which found a very weak correlation between \( H_\alpha \) equivalent width and \( 8 \) \( \mu \)m excess. Specifically, Currie et al. (2007b) derive a Spearman rank correlation coefficient of \( r_s = 0.60 \) across their full dynamic range in \( H_\alpha \) equivalent width (\( |\text{EW}(H_\alpha)| = 0–50 \) Å). Conversely, over the same dynamic range, we derive a Spearman rank correlation coefficient of \( r_s = 0.046 \) implying that the relationship between protoplanetary disk gas and IR excess cannot be described by a monotonic function. The disagreement is probably due to (1) poorer photometric precision in the Currie et al. (2007a) IRAC data and (2) the decision in Currie et al. (2007b) to use \( K_s–[8] \) instead of [3.6]–[8] as a tracer of warm dust, where the former exhibits...
Table 4 (Continued)

| R.A.      | Decl.  | ST  | EW(H₂) | [3.6]-[8] | [4.5]-[8] |
|-----------|--------|-----|--------|-----------|-----------|
| 34.4520   | 57.3922| 51.6| −19.40 | −99.000   | −99.000   |
| 34.6519   | 57.0209| 46.0| −11.59 | 0.126     | 0.179     |
| 35.3151   | 57.0772| 52.5| −26.40 | 0.017     | −99.000   |
| 35.4112   | 57.4461| 53.9| −59.50 | −99.000   | −99.000   |
| 35.5489   | 57.0786| 57.4| −47.32 | 0.678     | 0.431     |
| 34.6662   | 57.1706| 25.0| 0.00   | 0.078     | 0.056     |

Notes. The numerical spectral type has the following formalism: 10 = B0, 11 = B1, . . . 68 = M8. The equivalent width of H₂ is listed in units of angstroms. Spitzer/IRAC photometry at [3.6] and [8] are from this paper.

a much stronger spectral type dependence (cf. Luhman et al. 2010).

5. SPECTRAL ENERGY DISTRIBUTION
MODELING OF DISK-BEARING STARS

The analysis in Section 3 as well as previous work from Currie et al. (2007a, 2008a) demonstrates that h and ch Persei includes a small population of stars with (1) warm, terrestrial zone dust identifiable from broadband 8 μm excess emission and (2) very strong (≥3 mag) excess emission at 24 μm that in many cases is likely due to cooler dust. As our observations are not sensitive to (pre-)main-sequence stars lacking broadband 8 μm excess but producing modest 24 μm excesses (~0.25–1.5 mag) more typical around stars of comparable age (Chen et al. 2011), we cannot identify cooler debris disks and many homologically depleted transitional disks. Typical cold debris disks yield negligible broadband excesses at 24 μm and will also not be detected around h and ch Persei stars. While our study does not probe the full extent of the disk population, we still can analyze data for stars with IRAC and MIPS excesses or those that are accreting and compare the emission to that predicted for disks covering a range of evolutionary states. The disks around such stars represent those that are least evolved and provide an upper limit to the relative frequency of normal protoplanetary disks at 14 Myr.

5.1. Disk Terminology and Classification Method

Following Currie & Sicilia-Aguilar (2011), we consider three different classes of disks:

1. Primordial disks. We identify optically thick primordial disks, characteristic of disks in the youngest star-forming regions (Gutermuth et al. 2009), generally as those with excess emission above our model disk limit from 4.5 μm to 24 μm.

2. Transitional disks with inner holes/gaps. We identify transitional disks with inner holes as those with photospheric emission or weak excess emission through 5.8 μm, but emission in excess of our fiducial model at 24 μm, indicative of a positive λFₜ slope from 8 to 24 μm and optically thick outer disk emission at 24 μm. Those with gaps like LkCa 15’s may appear to have emission comparable to an optically thick disk at some near-IR wavelengths but have a steep flux slope (α ≈ −3) from the near- to mid-IR (e.g., through 8 μm) due to an absence of dust between a hot optically thick population near the dust sublimation radius and a cooler optically thick population at AU-scale distances.
3. Warm debris disks/homologously depleted transitional disks. Objects with weak excess, consistently lying below our fiducial disk model have SEDs comparable to homologously depleted transitional disks in Taurus, the Corona Australis, IC 348, and other young star-forming regions (Currie & Sicilia-Aguilar 2011) and warm debris disks (Currie et al. 2007c, 2008b; Rhee et al. 2007). For all stars modeled here with spectra, none are shown to be accreting and thus none have clear evidence for circumstellar gas. However, our optical spectra were obtained at low resolutions, where weakly accreting disks may not be identifiable and/or may be difficult to flag. Although h and χ Persei’s age may favor objects in this category as having warm debris disks (Currie et al. 2007c, 2008a), the case is not clear-cut. Thus, to be conservative, we note that these objects may be either warm debris disk-bearing stars or those surrounded by homologously depleted transitional disks.

Note that our identification of candidate homologously depleted transitional disks is simpler than in Currie & Sicilia-Aguilar (2011) who focus on nearby clusters with richer IR data sets. Specifically, they used Taurus optical to submillimeter data to identify the range of disk masses covered by optically thick primordial disks. In addition to the criteria listed above, they then required homologously depleted disks to have disk masses below the Taurus optically thick disk range. Some range in IR colors (e.g., $K_s =8$ versus $K_s =24$) includes both primordial disks and transitional disks, but for clusters much more distant than Taurus (e.g., NGC 2362, h and χ Perseii), we lack far-IR/submillimeter data that is required to estimate a disk mass. Therefore, based on the Taurus modeling results, they correct for the frequency of transitional disks derived from IR SED modeling alone (as in this paper) by the “contamination rate” of primordial disks with the same IR-excess emission. We do not introduce such a correction factor here since (1) it is small to begin with and does not alter our results presented later and (2) very few stars we model have IR colors that, based on Taurus data, correspond to multiple disk states.

5.2. Models Used to Classify Disks

5.2.1. Fiducial Disk Model Comparisons

We first compare the SEDs of disk-bearing h and χ Persei stars to geometrically flat, optically thick reprocessing disk models to conservatively identify those disks with a reduced optical depth of emitting dust ($\tau_{\text{IR}} < 1$); i.e., transitional disks. Following Currie & Sicilia-Aguilar (2011), we adopt models produced from the Whitney–Monte Carlo radiative transfer code (Whitney et al. 2003a, 2003b; Robitaille et al. 2006). The models assume no flaring ($H/r = \text{constant}$), no accretion, and no protostellar envelope emission. The disks are optically thick to their own radiation over spatial scales relevant to our study ($r < 5–10$ AU) even for disks over an order of magnitude lower mass than that which we nominally adopt ($0.05 M_\odot$).

As shown in Currie & Sicilia-Aguilar (2011) and in other earlier publications (e.g., D’Alessio et al. 2006; Kenyon & Hartmann 1987), making the disk flared instead of flat or considering accretion can only result in a more luminous disk and a higher transitional disk frequency. Therefore, our fiducial model represents a conservative limit separating the bluest, lowest-luminosity primordial disks from transitional disks.

5.2.2. Model SED Fitting

As a separate investigation, we model source SEDs using the grid of radiative transfer disk models from Robitaille et al. (2006). As our data are limited to detections at $\lambda \lesssim 24 \mu m$, these model comparisons cannot investigate the mass of emitting dust in the disks (Currie & Sicilia-Aguilar 2011), and our disk classification scheme does not turn on whether or not the disk is flared. Instead, we simply use these model comparisons to investigate whether each source’s best-fit models require an inner hole substantially larger than the dust sublimation radius. Thus, they can show whether some disks we find lack inner holes (primordial disks, homologously depleted transitional disks) based on fiducial comparisons nevertheless are best fit by disk models with inner holes.

To identify the best-fitting disk models, we restrict ourselves to those models satisfying the $\Delta\chi^2$ criterion of $\chi^2-\chi^2_{\text{best}} < 3$, where $\chi^2$ refers to the minimum $\chi^2$ per data point (see also Currie & Sicilia-Aguilar 2011; Currie et al. 2009; Ercolano et al. 2009). We adopt a reddening uncertainty of 10% and a distance uncertainty of 10 pc. To be conservative, we set the division between a disk requiring an inner hole and one without at 10 times the dust sublimation radius.

5.3. Results for Disks with Excesses in Multiple Bandpasses

From our sample of $\approx270$ stars with IR excess, 18 show clear excesses at both 8 $\mu m$ and 24 $\mu m$, are later than B5 (fainter than $J = 13$), and thus not likely post-main-sequence stars, which can therefore be compared in more detail to disk models. One of these—α = 34.7824, δ = 57.2346—was previously identified in Currie et al. (2007c, 2008a), labeled as “Source 5” since it was the fifth candidate h and χ Persei member with excesses in multiple IRAC bands, and modeled by comparing its SED to predictions from terrestrial planet formation calculations (Kenyon & Bromley 2004) and a simple model assuming two, single-temperature blackbodies. The other 17 targets listed are new detections.

Of the 18 sources, 7 have optical spectroscopy from Currie et al. (2010). The remaining 11 lack optical spectroscopy and thus do not have a confirmed spectral type or extinction estimates. To determine the appropriate $T_{\text{eff}}$ for these 11/18 stars, we first fit the V and $I$ photometry to predicted colors for h and χ Per stars for a range of extinctions using intrinsic dwarf colors and reddening laws listed in Currie et al. (2010). The seven other targets had previously derived spectral types and extinctions from Currie et al. (2010). We used these spectral types and extinctions as a starting point and explored whether alternative estimates provided a better fit to the optical/near-IR photometry. Our derived values agree with these previous determinations to within one subclass in spectral type and $\sim10\%$ in reddening, supporting the parameters derived in Currie et al. (2010).

5.3.1. Results for Fiducial Disk Model Comparisons

Table 5 records the known or derived spectral types and reddening values along with IRAC/MIPS colors, and disk types

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10 Inclination likewise has a negligible effect except for nearly edge-on cases (Currie & Sicilia-Aguilar 2011).

11 Note again that this mismatch in numbers is largely driven by our poor sensitivity at MIPS 24 $\mu m$. 
of the 18 h and χ Persei stars with IRAC and MIPS excesses that we model. Figure 12 displays a typical model comparison with the model spectral type for the photosphere (Bb) and the disk (Disk) directly plotted along with its J2000 coordinates. We display an atlas of all modeled sources in the Appendix.

Table 5 (second column from the right) records the best-fit disk inner radius for our sources using the Robitaille et al. (2006) grid. Figure 13 displays example analysis results: the set of best-fit SEDs (left panel) and distribution of disk inner radii (right panel) for the eighth excess source in our list (α = 34.9447, δ = 57.1925). In most cases, our results based on fiducial model comparisons and model fitting agree. Primordial disks and homologously depleted transitional disks identified from fiducial model transitional disks, are not best fit by a disk model with an inner hole. Disks with weak IRAC excess, but much stronger MIPS 24 μm excesses, are best fit by disk models with large (Rdisk > 10 Rsub) inner holes.

SED modeling suggests that we may be slightly underestimating the population of transitional disks with inner holes. Three sources, identified as having homologously depleted transitional disks/warm debris disks, are best fit by a disk model with an Rdisk > 10 Rsub hole. Two of these sources are early-type (B8.5, A5) stars with very weak, debris disk-like excess emission (0.2–0.6 mag in the IRAC bands; 1.6–1.75 mag in MIPS): the inner holes identified by SED modeling may instead reflect the location of debris belts. The third of these (F5.9) has a 4.7 mag excess in MIPS 24 μm characteristic of only the most luminous debris disks (e.g., HR 4796A; Chen & Kamp 2004) and many transitional disks with inner holes (cf. Currie & Sicilia-Aguilar 2011). One source identified as having a primordial disk from fiducial model comparisons is best fit by a disk model with a 30 Rsub inner hole.

In summary, our h and χ Persei disk analysis shows evidence for substantial evolution, even among the protoplanetary disk population. Fiducial model comparisons and SED fitting reveal a large fraction of transitional disks, either those with inner holes or ones that are homologously depleted, compared to primordial disks.
5.4. Results for Accreting Disks

In addition to our modeling of members with IRAC and MIPS excesses, we also briefly compare the SEDs of accreting members identified in Section 4 to the same fiducial disk model. While accreting circumstellar disks are often associated with optically thick “primordial” disks that are typical of the youngest star-forming regions, Figure 14 shows that the situation is more complicated. The star with weaker Hα emission (|EW(Hα)| = 5.3 Å left panel) clearly has weaker warm dust emission relative to the optically thick, geometrically flat disk limit. The other star, the outlier in Figure 11 (right panel), has significantly stronger Hα emission (|EW(Hα)| = 47.3 Å) but still has IRAC-excess emission from dust lying at or below the flat disk limit (Figure 14, right panel). The SEDs of the remaining accreting stars that also maintain an IRAC excess, resemble the left-hand panel star, as the strength of the excess is always weaker than the flat, optically thick disk limit.

Therefore, even the long-lived accreting protoplanetary disks in h and χ Persei show evidence of significantly reduced broadband IR dust emission more indicative of transitional disks than the optically thick primordial disks that dominate the youngest star-forming regions like Taurus. In the next section, we compare the frequency and morphologies of disks in h and χ Persei to those in other clusters in a global analysis of disk evolution from 1 Myr to 20 Myr.

6. THE h AND χ PERSEI DISK POPULATION IN CONTEXT: EMPIRICAL CONSTRAINTS ON DISK EVOLUTION AND PLANET FORMATION

6.1. Methodology and Goals

Comparing the disk population in h and χ Persei to that for clusters/associations of comparable or younger ages allows us to constrain how the frequency of warm circumstellar dust and gas changes with time (see Hernandez et al. 2007b; Fedele et al. 2010; Currie & Sicilia-Aguilar 2011). Circumstellar dust and gas comprise the building blocks of planetary cores and gaseous envelopes (Pollack et al. 1996; Kenyon & Bromley 2009); dust may also be second generation, produced via collisions between planetesimals in young debris disks (Wyatt 2008; Kenyon & Bromley 2008). Modeling the time evolution of dust and gas then sets some limits on the timescale for converting these raw materials into gas giant planets and/or the early time evolution of debris disks (Rieke et al. 2005; Sue et al. 2006; Currie et al. 2008a, 2009; Chen et al. 2011, 2012).

In this section, we combine h and χ Persei data with that from other clusters to explore the timescale for protoplanetary disk evolution and the properties of debris disks, especially those around high-mass stars (4–6 M☉). Although we use specific, absolute (and hence uncertain) ages to describe the clusters, our arguments are chiefly based on the relative ages and the evolutionary sequence they establish, which Soderblom
et al. (2014) argue are robust. Table 6 lists the clusters and ages for various characteristic dust/gas regimes. Due to the extreme sample size of h and χ Persei stars, we achieve robust estimates of the warm dust and gas fractions at ~10–15 Myr.

First, we follow Currie & Sicilia-Aguilar (2011), using a Monte Carlo simulation to predict the frequency of circumstellar dust and gas from protoplanetary disks for various characteristic dust/gas evolution e-folding timescales. We then identify the timescale that best matches the data using a simple reduced \( \chi^2 \) criterion. We use the best-fitting dust evolution timescale as input for a second Monte Carlo simulation tracing the relative frequency of transitional disks with time for various bulk transition disk timescales ranging between 0.1 Myr and 1 Myr using the subset of well-characterized clusters in Currie & Sicilia-Aguilar (2011)—Taurus, the Corona Borealis Cluster, IC 348, NGC 2362, η Cha—and h and χ Persei. Finally, we explore debris disk evolution for stars with masses of \( \sim 4-6 M_\odot \), a mass range not previously studied, by comparing the frequency of MIPS-excess sources in h and χ Persei to those for members of the Sco-Cen Association (Upper Scorpius, Lower Centaurus Crux, and Upper Centaurus Lupus; Chen et al. 2011, 2012). All data probing dust evolution come from Spitzer observations, whereas data probing gas evolution originate from various ground-based spectroscopic surveys.

While our data probing circumstellar dust draw from Spitzer/IRAC observations only, some differences between each cluster sample impede our ability to set more robust limits on the typical timescale for protoplanetary disks to disappear. For instance, the completeness limits for each cluster data set are different. This is especially true for h and χ Persei, which is more distant than the other clusters analyzed here. Although our methods for identifying excess sources follow those standard in the literature (Hernandez et al. 2007b), there may still be small differences between methods used to find disk-bearing stars among the clusters we analyze.

With these caveats in mind, we focus simply on understanding the typical evolution timescales for warm dust and gas and how these timescales change depending on the assumed ages for clusters. For example, recent work by Pecaut et al. (2012) argues that Upper Scorpius may be about twice as old as its nominal 5 Myr age (Preibisch et al. 2002), although other work seems to indicate results intermediate between these extremes (Bowler et al. 2011). Bell et al. (2013) reinvestigate the ages of many young clusters—e.g., IC 348, σ Orionis, and NGC 2362—often used to define these evolutionary timescales and argue that cluster ages have generally been underestimated. However, Bell et al. (2013) find an age for χ Persei (14.5 Myr) in excellent agreement with previous estimates (14 Myr; Currie et al. 2010).

To bracket the error range for young cluster ages (Soderblom et al. 2014), we fit for the warm dust and accretor fractions for the clusters in Figure 15. While our data probing circumstellar dust draw from Spitzer/IRAC observations only, some differences between each cluster sample impede our ability to set more robust limits on the typical timescale for protoplanetary disks to disappear. For instance, the completeness limits for each cluster data set are different.

### Table 6

 Frequencies of Warm Circumstellar Dust and Gas from Spitzer Surveys

| Name     | Nominal Age (Myr) | Revised Age (Myr) | Disk Fraction | Accretion Fraction | References |
|----------|-------------------|-------------------|---------------|--------------------|------------|
| NGC 1333| 1                 | ...               | 0.83 ± 0.11   | ...                | 1          |
| ρ Oph   | 1                 | ...               | ...           | 0.50 ± 0.16        | 2          |
| Taurus  | 1.5               | ...               | 0.63 ± 0.09   | 0.59 ± 0.09        | 2.3        |
| NGC 7129| 1.5               | ...               | 0.54 ± 0.14   | ...                | 4          |
| NGC 2068/71| 2                | ...               | ...           | 0.61 ± 0.09        | 5          |
| Cha I   | 2                 | ...               | 0.44 ± 0.08   | ...                | 2          |
| IC 348  | 2.5               | 6                 | 0.47 ± 0.12   | 0.33 ± 0.06        | 2.6        |
| σ Orionis| 3                 | 6.4, 7.4          | 0.36 ± 0.04   | 0.30 ± 0.05        | 7, 8       |
| NGC 6231| 3                 | ...               | ...           | 0.15 ± 0.05        | 8          |
| Tr37    | 3.5               | ...               | 0.48 ± 0.05   | ...                | 9          |
| NGC 2362| 5                 | 12, 3.3           | 0.20 ± 0.03   | 0.05 ± 0.05        | 10, 11     |
| Upper Sco| 5                 | 10                | 0.19 ± 0.05   | 0.07 ± 0.02        | 2, 12      |
| OB1b    | 5                 | ...               | 0.17 ± 0.04   | ...                | 13         |
| η Cha   | 6                 | ...               | 0.40 ± 0.14   | 0.27 ± 0.19        | 14, 15     |
| NGC 6531| 7.5               | ...               | ...           | 0.08 ± 0.05        | 8          |
| TWA 8   | 8                 | ...               | ...           | 0.06 ± 0.06        | 15         |
| 25 Orionis| 8.5              | ...               | 0.06 ± 0.023  | 0.06 ± 0.02        | 7, 16      |
| NGC 2169| 9                 | ...               | 0.09 ± 0.03   | ...                | 17         |
| NGC 7610| 9.8               | 12.6, 5.3         | 0.04 ± 0.04   | 0.02 ± 0.02        | 9          |
| β Pic MG| 12                | ...               | ...           | 0.04 ± 0.13        | 15         |
| h and χ Persei| 14             | ...               | 0.022 ± 0.002 | 0.017 ± 0.003     | This work  |
| Tuc-Hor | 27                | ...               | ...           | 0.040.08           | 15         |
| NGC 6644| 46                | ...               | ...           | 0.040.04           | 8          |

**Notes.** Nominal ages, revised ages from Bell et al. (2013) with empirical disk and accretor fractions for the clusters in Figure 15. **References.** (1) Gutermuth et al. 2008; (2) Mohanty et al. 2005; (3) Hernandez et al. 2007b; (4) Gutermuth et al. 2004; (5) Flaherty & Muzerolle 2008; (6) Lada et al. 2006; (7) Hernandez et al. 2007a; (8) Fedele et al. 2010; (9) Sicilia-Aguilar et al. 2006; (10) Dahm & Hillenbrand 2007; (11) Currie et al. 2009; (12) Carpenter et al. 2006; (13) Hernandez et al. 2005; (14) Megeath et al. 2005; (15) Jayawardhana et al. 2006; (16) Briceno et al. 2007; (17) Jeffries et al. 2007; (18) this work.

6.2. Evolution of Warm Dust from Inner Disks

Figure 15 plots the frequency of warm dust emission (as probed by Spitzer/IRAC) for our sample, where we focus on...
clusters with ages between 1 and 15 Myr. The best-fit timescale is 2.75 Myr. We obtain similar results regardless of whether we focus on all clusters or just those nominally younger than 10 Myr. While this timescale best reproduces our combined sample there are clearly outliers, most notably Trumpler 37 and 10 Myr. While this timescale best reproduces our combined sample when nominal ages are adopted clearly underpredicts the accretion frequency.

The middle panel displays a model with a slightly longer timescale ($\tau_{\text{PD}} = 3.25$ Myr), which together with 2.75 Myr bracket the value considered by Currie & Sicilia-Aguilar (2011). The near-quadrupling of the reduced $\chi^2$ as the model timescale increases to 3.25 Myr is largely due to the inability of the model to reproduce the dust frequencies found in regions such as $\sigma$ Orionis (Hernandez et al. 2007b), Upper Scorpius (Carpenter et al. 2006), and NGC 2362 (Dahm & Hillenbrand 2007; Currie et al. 2009).

Adopting revised ages for clusters listed in Bell et al. (2013) and Pecaut et al. (2012) clearly yields a longer timescale (right panel) for warm dust in disks. Our best-fit timescale ($\chi^2 \sim 2.4$) more than doubles to 5.75 Myr, a result driven by some of the same regions ($\sigma$ Orionis, Upper Scorpius, and NGC 2362) whose frequencies determine the best-fit timescale for nominal ages. When assuming the revised cluster ages of Bell et al. (2013), the 2.75 Myr timescale found to best fit the combined sample when nominal ages are adopted clearly underpredicts the disk frequencies for IC 348, $\sigma$ Ori, Upper Sco, and NGC 2362 ($\chi^2 \sim 22$). For $h$ and $\chi$ Persei, however, an intermediate timescale may be more consistent.

6.3. Evolution of Protoplanetary Disk Gas

Our results for circumstellar gas evolution mimic the general trends found in the above section for dust (Figure 16). The best-fit accretion timescale adopting nominal cluster ages is 1.75 Myr ($\chi^2 \sim 1.4$), slightly smaller than our nominal dust timescale and marginally consistent with previous analyses (Fedele et al. 2010). The predicted gas disk frequency as a function of time well matches the combined sample with the possible exception of $\rho$ Oph where it overpredicts the accretion frequency slightly older ($t > 5$ Myr) regions like $\eta$ Cha and 25 Ori, where it underpredicts the accretion frequency.

As with dust, the revised cluster ages for many clusters significantly extend the gas disk lifetime. Our best-fit value is $\tau_{	ext{g}} = 3.75$ Myr, more than a factor of two longer than the timescale we obtain from nominal cluster ages. Taken literally, adopting revised cluster ages yields gas disk timescales slightly shorter than warm dust lifetimes, in slight contrast to previous results finding similar lifetimes for gas and dust (Fedele et al. 2010; Currie & Kenyon 2009). Although sample-specific biases in how disk dust and gas may instead be responsible for these differing gas and dust lifetimes, the more basic result is robust: the revised cluster ages would more than double the gas and warm dust lifetimes.

6.4. Transitional Disk Evolution

Figure 17 compares transitional disk frequencies derived for Taurus, the Coronet Cluster, IC 348, NGC 2362, and $\eta$ Cha from Currie & Sicilia-Aguilar (2011) with those derived here for our limited $h$ and $\chi$ Persei sample. Lines denote predicted transitional disk frequencies from our Monte Carlo simulations for a range of bulk transitional disk durations ranging between 0.1 Myr and 2 Myr assuming a protoplanetary disk lifetime of 2.5 Myr for nominal cluster ages (left) and 6 Myr for revised ages (right). For $h$ and $\chi$ Persei, the error bars correspond to upper and lower limits for the transitional disk frequency determined from whether stars with weak excesses are considered to be homologously depleted transitional disks or warm debris disks. For other clusters, the error bars likewise reflect ambiguities in interpreting the properties of the most weakly emitting disks (see the discussion in Currie & Sicilia-Aguilar 2011).

Despite uncertainties in inferring the properties of many disks, our analysis clearly points to a transitional disk phase that lasts $\approx 1$ Myr when averaged over entire cluster samples and all possible pathways: transitional disks with holes/gaps depleted in dust that clear from the inside-out and those that deplete homologously. For revised ages for IC 348, NGC 2362 and other clusters, this trend is even stronger. For all cases, the transitional disk phase lasts on average approximately one-fourth to one-third of the total protoplanetary disk lifetime. Our results are consistent with recent detailed studies of transitional disk frequencies (Currie & Sicilia-Aguilar 2011; Currie et al. 2009).

Many sources in the oldest clusters—i.e., NGC 2362, $h$ and $\chi$ Per—identified as having homologously depleted transitional disks may instead have warm debris disks. Nevertheless, considering primordial disks and transitional disks with inner holes alone for these clusters still point to an extended transitional disk duration. For NGC 2362 and $h$ and $\chi$ Persei, we would still derive transitional disk fractions of five-ninths and six-eighths, respectively (see Currie & Sicilia-Aguilar 2011 for NGC 2362;
Figure 16. Frequency of accreting protoplanetary disks in 1–20 Myr old clusters adopting nominal cluster ages (left) and considering revised cluster ages from Bell et al. (2013; right). The solid lines depict the predicted accretor frequency vs. time for the best-fit curve to the data. The dotted line in the right panel shows the predicted curve for a 1.75 Myr lifetime compared with the best-fit value of 3.75 Myr.

Figure 17. Relative frequency of transitional disks vs. time in Taurus, the Coronet Cluster, IC 348, NGC 2369, and η Cha as in Currie & Sicilia-Aguilar (2011) updated to include h and χ Persei and to consider nominal (left) and revised (right) cluster ages from Bell et al. (2013). For each case, we overplot predicted transitional disk frequencies from our parametric model, adopting a typical protoplanetary disk lifetime of 2.5 Myr (left) and 6 Myr (right). In both cases, the duration of the transitional disk phase is significantly longer than 0.1 Myr and more comparable to ∼1 Myr.

6.5. Frequency of Dust Around 4–6 M⊙ Stars

Although the relatively shallower depth of MIPS compared to IRAC for stellar photospheres means we have far weaker constraints on the presence of cooler dust producing 24 μm excess emission, the MIPS data are deep enough that we can compare frequencies for massive stars to those for similar stars in other clusters. Figure 18 compares the frequency of dust around 4–6 M⊙ stars to those for the Sco-Cen subgroups: Upper Scorpius (5–10 Myr), Upper Centaurus Lupus (16 Myr), and Lower Centaurus Crux (17 Myr). To derive frequencies for Sco-Cen we focus on B2–B6 stars and simply compare the number flagged as excess sources in Carpenter et al. (2009b) and Chen et al. (2012), trimming out Be stars and post-main-sequence objects.

All samples exhibit a very low frequency of 24 μm excess from disks around 4–6 M⊙ stars, ranging between 0% and ∼7% (0/4 for Upper Sco, 0/8 for LCC, and 1/14 for UCL). The small sample sizes and small numbers of excess sources preclude us from identifying any trend in 24 μm excess frequency versus time as has been found for 1.5 M⊙ stars (Currie et al. 2008b). However, these massive stars exhibit lower MIPS 24 μm excess frequencies than do 1–2.5 M⊙ stars at 10–30 Myr for many clusters (∼25%–50% Currie et al. 2008b; Forbrich et al. 2008; Chen et al. 2011, 2012).

7. DISCUSSION

7.1. Summary of Results

We present new constrains on the time evolution of planet forming disks from new, deep IRAC and MIPS photometry of ∼12,500 stellar members of the Double Cluster, h and χ Persei, deeper at 8 μm and 24 μm by ∼1.5 mag compared to previous studies (Currie et al. 2007a, 2008a). Relative to regions of a similar age, the Double Cluster contains a large sample of stars, which is vital for producing robust statistical estimates of the frequency of warm dust and gas.

Our study yields the following primary results:

1. The frequency of warm dust, as probed by IRAC 8 μm excess, is on the order of ∼2%–3% for the sample as a whole, increasing from near zero for mid-B stars to ∼4%–5% for subsolar-mass stars.
2. Although the MIPS 24 μm data are not sufficiently deep to conduct a similar analysis for all h and χ Persei members, they provide the first constraints on the disk frequency for the region’s most massive planet-bearing stars (4–6 M⊙).
About ~3%-8% of these massive stars have MIPS 24 μm excesses, lower than the MIPS 24 μm frequencies found for 1–2.5 M_⊙ stars in other clusters.

3. The frequency of accretion among h and χ Persei stars is ~2%, comparable to the warm dust frequency. Similarly, the accretion frequency may be higher for later type, lower mass stars. We do not find evidence for a correlation between the presence of warm dust and accreting gas.

4. SED modeling of h and χ Persei stars with IRAC and MIPS excesses allows us to investigate the morphology of rare disks with warm dust at 10–15 Myr. Our modeled stars have disks exhibiting a wide range of evolutionary states. In particular, a large fraction of disks appear to have SEDs consistent with transitional disks, indicative of a rather extended transitional disk duration.

5. We combine our results for h and χ Persei to those for other clusters to conduct a global analysis of disk evolution in young clusters. Assuming nominal cluster ages, we derive characteristic e-folding timescales of 2.75, 1.75, and 1 Myr for the warm dust lifetime, gas lifetime, and transitional disk duration. Assuming alternate cluster ages (Bell et al. 2013; Pecaut et al. 2012), these timescales increase to 5.75, 3.75, and 1.5 Myr, respectively. Thus, the protoplanetary disk phase may last significantly longer than previously thought.

7.2. Comparisons with Earlier Studies

7.2.1. Earlier Studies of the Disk Population of h and χ Persei

This study builds upon analyses of Cycle 1 IRAC and MIPS Spitzer and ground-based data, which comprised the first studies of circumstellar disks around stars in the Double Cluster (Currie et al. 2007a, 2007b, 2007c, 2008a). Over an area comparable to this study, Currie et al. (2007a) identified about 5000 (7000) stars detected in the IRAC [8] ([4.5]) filters and located near previously known members of h and χ Per, used 2MASS All-Sky Survey data to select stars whose near-IR color–magnitude diagram positions were plausibly consistent with those for 2.3 kpc distant stars, and studied the frequency of warm IRAC-excess emission by comparing photometry derived from 2MASS K_s to IRAC flux densities. Currie et al. (2007c) identified a subsample of stars with IRAC excesses in multiple bands, added in preliminary MIPS photometry, and compared the stars’ SEDs to model predictions for warm debris disks whose dust is indicative of active terrestrial planet formation. Currie et al. (2007b) identified about two dozen stars whose color–magnitude diagram positions were consistent with values expected for h and χ Persei members and whose H_2 equivalent widths were consistent with estimates for accreting objects. Finally, Currie et al. (2008a) present a full analysis of MIPS data for h and χ Persei, modeled systems with strong MIPS-excess emission, and compared MIPS 24 μm excesses around BAF stars from multiple regions to investigate the time evolution of 24 μm debris emission.

The data analyzed in our study differ from previous data in several important respects. Our IRAC data are significantly deeper, with completion limits roughly 2 mag deeper in [8]; at the completion limits for the Cycle 1 data, our photometric errors are ~3 times smaller. We achieve similar increases in survey depth at MIPS 24 μm. While Currie et al. (2007b) draw from a preliminary analysis of 5000 stars with optical spectroscopy, our study incorporates the full sample. These previous studies either focused on all 2MASS-detected objects in the field or relied on very preliminary photometric cuts to focus on candidate members. Our study uses the candidate membership list from Currie et al. (2010) based on extremely deep optical photometry and optical spectroscopy to remove background stars from our analysis.

Our results modify some previous conclusions about h and χ Persei’s disk population. Currie et al. (2007a) found that few (~2%-3%) stars have excesses at multiple IRAC bands, though the frequency of such excesses rose toward fainter stars likely representative of later, lower mass stars. We derive similar frequencies at 8 μm near our survey depth limit. For brighter stars probed by Currie et al. (2007a), our frequencies are lower likely because our criterion for differentiating between an IR-excess source and a bare stellar photosphere is more conservative and based on the observed dispersion of IRAC colors as a function of magnitude. While our accretor frequency agrees with the rough estimates previously reported by Currie et al. (2007b), we fail to confirm the trend between IRAC excess and H_2 excesses around χ Persei’s disk population. Currie et al. (2007c, 2008a) identify stars with weak IRAC excesses as candidate terrestrial planet-forming systems. A full analysis of the optical spectroscopy sample and the IRAC data together demonstrates that h and χ Persei contains a mixed disk population: sources with evidence for gas but no dust, dust but no evidence for gas, and those with evidence for both. It is likely that many (most?) of our weak IRAC-excess sources are terrestrial planet forming systems, since such systems are found around more nearby, better studied stars (Rhee et al. 2007; Lisse et al. 2008). However, to be conservative, we remain agnostic as to the state of these systems: they could either be warm debris disks or homologously depleted transitional disks.

Finally, we did not reinvestigate the “rise and fall” of 24 μm emission from debris disks around BAF stars. Although a full analysis of these targets within the context of debris disk evolution will be left for a future paper, studies published subsequent to Currie et al. (2008a) support a more limited version of our previous results. For example, Carpenter et al. (2009a) find evidence for a peak in debris emission around F stars at ~10–15 Myr but do not find a similar trend for earlier or later type stars. Focusing only on planet mass (by accounting for the different mapping between spectral type and mass versus age), Chen et al. (2011) find evidence for an increase in debris emission at 15–20 Myr (the age of the older Sco-Cen subgroups) around 1.5 M_⊙ stars. However, this behavior is not seen so clearly for solar-mass stars, nor for 2–2.5 M_⊙ stars.
While Currie et al. (2008a) and later Kenyon & Bromley (2008) interpret a peak in debris emission within the context of oligarchic growth in icy planetesimal swarms, Chen et al. (2011) argue that the debris luminosities for solar-mass stars are higher than predicted in debris disk evolution models. The distribution of debris disk temperatures as a function of stellar mass and age also may hint at key effects not explicitly considered in the Kenyon & Bromley (2008) models such as planetesimal belt sculpting by massive planets (e.g., Chen et al. 2014).

7.2.2. The Lifetime of Protoplanetary Disks and Timescale for Gas Giant Planet Formation

This work provides a quantitative, updated comparison to earlier estimates of the lifetime of warm dust and gas in protoplanetary disks and an assessment of how stellar age uncertainties affect derived lifetimes. From ground-based L’ data of many clusters, Haisch et al. (2001) compare disk frequencies to a simple linear fit and estimate that half of all protoplanetary disks disappear by ~3 Myr and nearly all disappear by 6 Myr. Based on deeper Spitzer/IRAC data able to detect the stellar photosphere of subsolar-mass stars and at wavelengths where disk excess is more easily identifiable (see the discussion in Ercolano et al. 2009), Hernandez et al. (2007b) estimate a typical lifetime of ~3 Myr as well. Fedele et al. (2010) match frequencies of gas and dust to an exponential decay function; Currie & Sicilia-Aguilar (2011) match the dust frequency to Monte Carlo simulation predictions with an exponential decay probability distribution function as in this work. In all cases, the results are similar: a protoplanetary disk gas and dust lifetime of ~2.5–3 Myr for most stars (see also Mamajek 2009; Jayawardhana et al. 2006), slightly shorter (longer) for early-type higher mass (mid-M) stars (see Carpenter et al. 2006; Currie & Kenyon 2009).

Assuming nominal cluster ages, we derive fairly similar results, though we, like Fedele et al. (2010), formally favor a slightly longer e-folding timescale for dust than gas (τ_dust ~ 2.75 Myr and τ_gas ~ 1.75 Myr). This may be due to some mixing of disk populations, e.g., some of the warm dust may be from terrestrial zone debris emission, not protoplanetary disk dust, so that our protoplanetary disk frequency is underestimated. Alternatively, surveys may be failing to identify some stars whose weak optical emission lines and veiling from accretion are best identified from high-signal-to-noise, high-resolution echelle spectra (see Dahm 2008).

Our results support and quantify Bell et al.’s (2013) assertion that alternate ages derived for many young clusters would significantly lengthen the inferred lifetimes for protoplanetary disk dust. As expected, the gas disk lifetime is also longer. Bell et al. (2013) quote a “half-life” of disks of ~2–5 Myr and report a 10%–20% disk fraction at 10–12 Myr. Assuming that the disk lifetime decays as an exponential function and including slightly different samples (i.e., Upper Scorpius instead of the more distant ω, Ori), our Monte Carlo analysis yields largely similar results for dust: t_dust ~ 5.75 Myr and a dust fraction of ~10%–20% at 10–12 Myr and then <5% at later ages. While the gas disk lifetime we derive is shorter (~3.75 Myr) it is still more than twice as long as the one we derive assuming nominal cluster ages.

At present, it is not yet clear which set of ages is correct (Soderblom et al. 2014), although older ages derived for main-sequence stars in Upper Scorpius are more consistent with ages derived for the region’s post-main-sequence population (see Pecaut et al. 2012). Thus, these different estimates should be understood to bracket possible values. While the stars we focus on are predominately solar to slightly subsolar in mass, the disk lifetime may be even longer for the latest stars and highest mass brown dwarfs: for ~10 Myr old Upper Scorpius, Luhman & Mamajek (2012) still find that one-fourth of all mid-M stars show evidence for warm circumstellar dust.

A revised, more lengthy characteristic protoplanetary disk lifetime would have important consequences for planet formation, especially for gas giants. For instance, wide separation super-Jovian mass planets discovered through direct imaging (Marois et al. 2008) are extremely difficult to form via standard core accretion models (Pollack et al. 1996), yet at least some of them have properties (e.g., mass ratio/separation; C/O abundances) suggesting that they may have formed this way (Currie et al. 2011; Konopacky et al. 2013). Modifications to core accretion models (Lambrechts & Johansen 2012; Kenyon & Bromley 2009) are required to account for these cores within the nominal, short protoplanetary disk lifetime. With the exception of ROXs 42B (Currie et al. 2014), the host stars for these planet–mass companions are older than either the nominal or revised protoplanetary disk lifetimes. Thus, a longer disk lifetime relaxes the constraints placed on planet formation by core accretion as well.

7.2.3. Duration of the Transitional Disk Phase

Our analyses support previous results (Currie et al. 2009; Currie & Sicilia-Aguilar 2011) finding that the transitional disk phase lasts longer than proposed in most early studies (Skrutskie et al. 1990; Wolk & Walter 1996), closer to 1 Myr than 0.1 Myr. In contrast, a few recent studies that use empirical breaks in IR colors alone arrive at somewhat shorter durations (Luhman et al. 2010; Luhman & Mamajek 2012). The major drawback with these other recent studies is that IR colors alone do not accurately distinguish between normal protoplanetary disks and disks that are becoming optically thin, since the color space between the two populations overlaps (Merin et al. 2010; Currie & Sicilia-Aguilar 2011). Thus, a criterion for identifying transitional disks based on perceived breaks in IR colors will underestimate this population’s size and, in turn, underestimate the transitional disk duration.

To alleviate these shortcomings, Currie & Sicilia-Aguilar (2011) adopt the SED modeling-driven criteria described in their Section 4.2 and briefly summarized in Section 5.2 in this work. While Luhman & Mamajek (2012) rightly note that theoretical models are imperfect and have degeneracies, Currie & Sicilia-Aguilar (2011) explicitly addressed these issues by treating their classifications probabilistically. For instance, the intrinsic distribution of their modeling grid in disk mass is heavily biased toward high masses. Their SED modeling

12 While every age derivation is model dependent, arguably the least model-dependent age-dating method (Li depletion) likewise favors systematically older ages for regions previously age-dated to 10 Myr (e.g., Binks & Jeffries 2014).

13 For example, many “gapped” transitional disks (e.g., LkCa 15, UX Tau, MWC 758) have “normal” IR colors but large, ~20 AU wide cavities indicative of disk clearing and likely opened by infant planets (Espaillat et al. 2010, 2012; Andrews et al. 2011; Dodson-Robinson & Salyk 2011). Since these disks have experienced significant structural evolution, they cannot be considered “primordial” as claimed in Luhman & Mamajek (2012), since disks are not born with 50 AU scale gaps in large dust. Homologically depleted transitional disks likewise overlap in some IR color space with normal protoplanetary disks.
identifies many transitional disks in spite of this strong prior in favor of classifying a disk as primordial.14

The key addition used in Currie & Sicilia-Aguilar’s (2011) classifications—a disk mass limit separating some transitional disks from primordial disks—is justified. Our ignorance of the dust opacity and assumed (not measured) dust-to-gas ratios for many disks precludes an absolute calibration of disk masses (Currie & Sicilia-Aguilar 2011). However, since disk masses for both primordial disks and (candidate) transitional disks were derived self-consistently, we can identify whether or not homologously depleted transitional disks have relatively lower masses. Although Currie & Sicilia-Aguilar’s (2011) adopted limit (0.1% × \(M_\star\)) was typically just above the detection limit for most of the submillimeter data we considered (Andrews & Williams 2005), nearly all of the optically thin disks in Andrews & Williams (2005) were detected, and Currie & Sicilia-Aguilar (2011) modeled all of them anyway. Candidate homologously depleted disk masses can then be compared to the mass distribution for primordial disks.15

In summary, detailed modeling of very young nearby clusters like Taurus, coarser modeling of populous older regions like NGC 2362 and h and \(\chi\) Persei, and statistical analyses of multiple clusters support a more lengthy transitional disk duration of \(\approx 1\) Myr. Averaged over entire clusters and over all possible disk clearing mechanisms, transitional disks occupy about one-fourth to one-third of the total disk lifetime. As shown in this paper, the upwardly revised ages for clusters in Bell et al. (2013) and Pecaut et al. (2012) only serve to strengthen the argument in favor of a more extended transitional disk duration.

7.3. Future Work

The Double Cluster, h and \(\chi\) Persei, provides an excellent laboratory with which to study stellar evolution from the pre-main sequence to post-main sequence (Currie et al. 2010; Bell et al. 2013; Slesnick et al. 2002) and circumstellar disks at an age probing the protoplanetary to debris disk transition (this work; Currie et al. 2007a, 2008a). Currie et al. (2010) highlighted several key areas of future research on h and \(\chi\) Per’s stellar population, and here we list future avenues of research to study its disk population.

1. Disk evolution as a function of environment. As noted in Currie et al. (2010), the coverage area for optical spectra is substantially larger than that for the optical photometry we combine it with to establish a list of members, meaning that there could be many more stars associated with the halo population of h and \(\chi\) Perseus (Currie et al. 2007a) that we have yet to identify. A wide-field optical photometric survey would identify additional candidate members of h and \(\chi\) Persei. Furthermore, because our Cycle 1 Spitzer data (and, to a lesser extent, the data we present here) were obtained over a similarly large area, we could compare the frequency of warm dust/gas between stars in the low-density regions to those in the cluster-dominated regions to better understand how disk evolution depends on the circumstellar environment. Recent studies indicate that disk lifetimes may be significantly longer for extremely tenuous associations (Fang et al. 2013), or much shorter in extremely dense globular cluster-like environments (Thompson 2013). The Double Cluster allows us to study the environmental dependence of the frequency of warm dust in disks within a single coeval region.

2. The disk properties of sub-bolometric mass stars. Our current spectroscopic sample does not well probe the h and \(\chi\) Perseus disk later than \(\sim\)mid-G (see Figure 6 in Currie et al. 2010). In addition to identifying low-mass (candidate) members, optical spectroscopy such as with MMT/Hectospec (and later Binospec) or LBT/MODS could measure accretion diagnostics (e.g., H\(_2\)) that will allow us to better characterize the properties of the faintest stars with IRAC and MIPS excesses. In principle, we could see whether all such stars show evidence for accretion or, like the stars studied here, include both stars showing evidence for gas (protoplanetary disks) and those lacking evidence for gas (candidate debris disk-hosting stars).

3. Observations of the h and \(\chi\) Persei disk population with JWST. Finally, the James Webb Space Telescope (JWST) should provide a significant advance in our understanding of the Double Cluster’s disk population. In particular, while Spitzer/IRAC data are highly sensitive to photospheric emission/weak excesses around sub-bolometric mass stars, our sensitivity further into the IR is far poorer, as MIPS is only sensitive to the photospheres of early/mid-B stars (see Section 2.5).

In contrast, MIRI with JWST has a 50\(\times\) smaller beam size and a predicted 5\(\sigma\) 2500\,s sensitivity of 28\,mJy at 25.5 \(\mu\)m, or roughly 2 mag fainter than our typical MIPS 24\,\(\mu\)m limits, capable of detecting the photosphere of early A stars in the Double Cluster. Sensitivity gains at slightly shorter wavelengths (e.g., 20\,\(\mu\)m) are even more substantial, allowing us to study disks around even lower mass stars. The far superior mid-IR sensitivity of JWST/MIRI then means that we will better be able to put a study of h and \(\chi\) Per’s disk population on a more comparable footing to other less populous, but much closer regions (e.g., Sco-Cen; \(\sigma\) and \(\lambda\) Orionis).

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APPENDIX

A.1. Expected Levels of Extragalactic Contamination of h and χ Persei Members

From our line of sight, h and χ Persei is an extremely populous cluster projected out of the galactic plane by ~200 pc, and the Spitzer data reaches completeness limits of ~51 μJy at [8], making extragalactic contamination of at least one cluster member very likely. To assess the probable frequency of contamination as a function of wavelength and magnitude, we use the IRAC number counts derived for the Bootes field from Fazio et al. (2004) and the MIPS 24 μm counts derived from Papovich et al. (2004). In Fazio et al. (2004), the number counts are differential, estimating the number of galaxies per magnitude in half-magnitude bins.16

16 Thus, the differential number counts at $m_{\text{IRAC}} = 15.5$ are defined from galaxies with $m_{\text{IRAC}} = 15.25–15.75$. To compute the number of galaxies expected with $m_{\text{IRAC}} = 15.25–15.75$, we must multiply by the bin width of 0.5 mag.

We estimate the frequency of galactic contamination using the following relation:

$$N_{\text{contamination}} = \pi \times r_m^2 \times N_g \times N_{\text{star}} / A,$$

where $r_m$ is the matching radius (1′), $N_g$ is the number of galaxies in a square degree, and $N_{\text{star}}$ is the number of members in our survey area, $A$. Here, $N_{\text{star}}$ is the subset of ~13,960 probable cluster members located within the IRAC/MIPS fields: ~12,000 for IRAC and ~9600 for MIPS. The survey area covers ~0.5 deg$^2$ in the IRAC 8 μm filter and 0.4 deg$^2$ in MIPS-24.

From the IRAC 8 μm differential number counts at $m_{\text{IRAC}} = 14, 15, 15.5,$ and 16 yields, we then expect the following number of members contaminated by galaxies on our IRAC mosaics as a function of magnitude: ~4, 9, 22, and 31 galaxies with magnitudes of $m_{[8]} = 14, 15, 15.5,$ and 16, respectively. The IRAC color–magnitude diagram for [8] versus $[3.6, 4.5]–[8]$ implies that a member must have $[3.6, 4.5]–[8] \gtrsim 0.75$ to be flagged as an excess source for the faintest objects detected at 5σ at [8]. Our faint detection limit is at $m_{[8]} \approx 15.5$, so galaxies as faint as $m_{[8]} \sim 16.25$ can contaminate a member, making it appear as bright as $m_{[8]} = 15.5$ and giving it a $[3.6, 4.5]–[8]$ color $\gtrsim 0.75$. Thus, galaxies in the $m_{[8]} = 16$ bin ($m_{[8]} = 15.75–16.25$) are the faintest ones that could...
Figure 20. Atlas of h and χ Persei stars with clear excesses in IRAC and MIPS bandpasses compared to photometric predictions for a bare stellar photosphere (solid line) and an optically thick, flat reprocessing disk (dashed line).

(A color version of this figure is available in the online journal.)
possibly contaminate a member’s photometry. Summing from $m[8] = 12$ to 15.5 (16), we expect 47 (78) members to have IRAC photometry contaminated by a galaxy.

The density of galaxies brighter than $[24] = 11.25$ is expected to be $\sim 10^7 \text{ sr}^{-1}$ (cf. Papovich et al. 2004). Over our 0.4 deg$^2$ MIPS area, we expect $\sim 1200$ galaxies brighter than this limit. Adopting $N_{\text{star}} = 9600$ and an area of $A = 0.4 \text{ deg}^2$, we predict that 18 members are contaminated from galaxies brighter than $[24] = 11.25$. As depicted in Figure 7, the number of excess sources at 8 and 24 $\mu$m is significantly larger than the number of expected extragalactic contaminants.

A.2. Extragalactic Contamination of the $h$ and $\chi$ Persei IRAC/MIPS-excess Population

Not all galaxies measurably affect the observed mid-IR colors of the stars they contaminate if the stars are much brighter than the galaxies in the IRAC bands, as many have near zero IRAC color (see Figure 1 in Stern et al. 2005). However, broad-line active galactic nuclei (BL-AGNs) and PAH-emission galaxies both have very red IRAC colors (Gutermuth et al. 2008). Member contamination by these galaxies can mimic the presence of a disk. Here we compare the distribution of IRAC
colors for members to those expected for BL-AGN and PAH-emission galaxies using color–color diagrams as in Gutermuth et al. (2008, 2009).

Active star-forming galaxies (e.g., BL AGNs) have very red [5.8]–[8] colors due to strong PAH emission. Gutermuth et al. (2008, 2009) define regions in [4.5]–[5.8]/[5.8]–[8] and [3.6]–[5.8]/[4.5]–[8] diagrams where these galaxies reside and removed objects located within as contaminants. We first focus on PAH-emission galaxies, defining the region of likely contamination is essentially absent when we restrict our analyses according to our criteria and to Gutermuth et al.’s. However, by adopting the Stern et al. (2005) adopted colors for PAH-emission galaxies are ∼0.5 and 0.7 mag redder in [5.8]–[8] and [4.5]–[8]. However, they cover all of the Boötes-field PAH galaxies shown in Gutermuth et al. and thus should be acceptable for targeting this specific type of contaminant.

To compare our member colors to those expected from AGN contaminants, we simply adopt the boundaries listed in Stern et al. (2005):

\[ 5.8]–\[8] \gtrsim 1.5, \]
\[ [4.5]–[5.8] \leq 3 \times ([5.8]–[8] − 1.5), \]
\[ [4.5]–\[8] \gtrsim 1.7, \]
\[ [3.6]–[5.8] \leq (2/3.5) \times ([5.8]–[8] − 1.3). \]

Compared to the criteria in Gutermuth et al. (2008, 2009), our adopted colors for PAH-emission galaxies are ~0.5 and 0.7 mag redder in [5.8]–[8] and [4.5]–[8]. However, they cover all of the Boötes-field PAH galaxies shown in Gutermuth et al. and thus should be acceptable for targeting this specific type of contaminant.

Figure 19 contains an atlas of h and χ Persei stars modeled.

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