A Mid-infrared Study of Directly Imaged Planetary-mass Companions Using Archival Spitzer/IRAC Images

Raquel A. Martinez$^{1,2}$ and Adam L. Kraus$^1$

$^1$The University of Texas at Austin, 2515 Speedway, C1400, Austin, TX 78712, USA; raquel.martinez@utexas.edu
$^2$Department of Physics and Astronomy, 4129 Frederick Reines Hall, University of California, Irvine, CA 92697, USA

Abstract

The atmospheres and accretion disks of planetary-mass and substellar companions provide an unprecedented look into planet and moon formation processes, most notably the frequency and lifetime of circumplanetary disks. In our ongoing effort to leverage the extraordinary sensitivity of the Spitzer/Infrared Array Camera (IRAC) at 3.6, 4.5, 5.8, and 8.0 $\mu$m to study wide-planetary-mass and substellar companions near the diffraction limit, we present point-spread function fitting photometry of archival Spitzer/IRAC images for nine stars (G0 to M4+M7) in nearby star-forming regions or stellar associations that host companions at separations of $\rho = 1^\circ 17–12^\circ 33$. We detect all system primaries in all four IRAC channels and recover eight low-mass companions in at least one IRAC channel for our sample, five of which have not been resolved previously in IRAC images. We measure nonphotospheric [3.6]–[8.0] colors for four of the system companions (DH Tau, 2M0441 B, SR 12 c, and ROXs 42 B), confirming or discovering the presence of circumstellar or circum(sub)stellar disks. We detect fluxes consistent with photospheric emission for four other companions (AB Pic b, CHXR 73 b, IRXS J1609 b, and HD 203030 b) that are unlikely to host disks. Combined with past detections of accretion or disk indicators, we determine the global disk frequency of young (<15 Myr) wide companions with masses near the deuterium-burning limit to be 56% ± 12%.

Unified Astronomy Thesaurus concepts: Substellar companion stars (1648); Exoplanet detection methods (489); Exoplanet formation (492); Extrasolar gaseous giant planets (509); Brown dwarfs (185)

1. Introduction

Dedicated exoplanet-finding surveys, such as the NASA Kepler mission (Borucki et al. 2010), have revolutionized our understanding of mature planetary system populations, but the formation and evolutionary processes that lead to their properties are still not well understood. The detailed study of exoplanets on an individual basis is usually hindered by the close proximity of the exoplanet to its bright stellar host. The atmospheres of transiting exoplanets can be characterized via transmission spectroscopy (e.g., Deming et al. 2013; Kreidberg et al. 2014; Wakeford et al. 2017), but this limits the planetary systems that can be studied to those with semimajor axes <1 au. Systems with planets orbiting on wider orbits have been observed via spectroscopy behind adaptive optics (AO; Patience et al. 2010; Barman et al. 2011; Konopacky et al. 2013; Haffert et al. 2019; Petrus et al. 2020), but these observations are difficult and expensive. Direct-imaging surveys of nearby star-forming regions have found an interesting population of wide-orbit (>100 au) planetary-mass companions (<20 $M_{\text{Jup}}$; hereafter PMCs), such as IRXS J160929.1–210524 b (8 $M_{\text{Jup}}$, 330 au; Lafrenière et al. 2008), GSC 06214–00210 B (14 $M_{\text{Jup}}$, 330 au; Ireland et al. 2011), HD 106906 b (11 $M_{\text{Jup}}$, 650 au; Bailey et al. 2014), and USc01621 B (15 $M_{\text{Jup}}$, 2880 au; Chinchilla et al. 2020). These systems have far more favorable separations and contrasts for the detailed study of gas giant atmospheres on larger semimajor axes. In addition, at young ages, these systems also offer a unique view of moon-forming circumplanetary disks.

Most observations of directly imaged exoplanets and PMCs have been made in the near-infrared (1–3 $\mu$m). Self-luminous exoplanets and planetary-mass objects emit substantial amounts of energy in the mid-infrared, yet very few systems have been studied redward of the L band (3 $\mu$m). From the ground, mid-infrared observations of exoplanets and PMCs are technically challenging, while from space, many systems were discovered after the cryogenic mission of the Spitzer Space Telescope (Werner et al. 2004) ended in 2009 and/or fall near or inside its diffraction limit. Extending the wavelength coverage of these objects into the mid-infrared to better fit spectral energy distributions (SEDs) will lead to more precise estimates of their physical properties and further constrain models of substellar and exoplanet atmospheres (e.g., Leggett et al. 2008; Bonnefoy et al. 2010, 2014). Utilizing the available mid-infrared observations that do exist of these systems is crucial for planning additional follow-up observations with next-generation facilities like the James Webb Space Telescope (JWST).

PMCs also frequently harbor disks, mostly identified through accretion signatures (e.g., line emission in Hα, Paβ, and Brγ), red near-infrared colors, or mid-infrared excesses. Bowler et al. (2017) found 46% ± 14% of young (<15 Myr) substellar (<20 $M_{\text{Jup}}$) companions with existing moderate-resolution spectroscopy had detectable Paβ emission. This high disk frequency is comparable to that observed around isolated young substellar objects (Luhman et al. 2010; Esplin & Luhman 2017; Luhman & Esplin 2020), but it is not clear whether wide-orbit companion disks and isolated circum(sub)stellar disks have similar accretion rates, disk compositions, and grain size distributions. Observations of PMC disks at radio wavelengths...
have produced only upper limits, which suggests that the dust in PMC disks might actually be more compact and optically thick (e.g., Bowler & Hillenbrand 2015; MacGregor et al. 2017; Wolff et al. 2017), likely because of saturation.

In Martinez & Kraus (2019, hereafter Paper I), we presented an automated point-spread function (PSF) subtraction pipeline to leverage the Spitzer archive in the search for wide-orbit PMCs and identify excesses from circum(sub)stellar disks. Here we apply our infrastructure to the remaining sample of known wide-orbit PMCs. In Sections 2 and 3, we describe our sample and PSF-fitting framework. We present the results of our image analysis and pipeline performance in Section 4. Finally, in Section 5, we consider the mid-infrared photometry of the wide companions in our sample in the context of other young low-mass stars and brown dwarfs and discuss the global disk frequency of PMCs.

2. Sample and Spitzer Observations

In Paper I, the sample of wide companion systems was chosen to test the feasibility of recovery via PSF subtraction over a broad range of separations and contrast ratios. Here we constructed a new sample to include other low-mass companions with potentially planetary mass that plausibly fit within those detection limits. We then identified systems with archival Spitzer/Infrared Array Camera (IRAC; Fazio et al. 2004) observations from its cryogenic mission. Six of the companions have not been resolved in Spitzer/IRAC, while three companions have had IRAC photometry reported in the literature previously. Seven of the systems belong to the young star-forming regions or stellar associations of Taurus, Carina, Chameleon, Upper Scorpius, and ρ Ophiuchus, while two are young field objects. We target the young field objects because their lower distances provide good sensitivity to both mass and projected separation.

IRAC operated with four filters in the mid-infrared: 3.6, 4.5, 5.8, and 8.0 μm. The IRAC detector has 256 × 256 pixels with a pixel scale of 1′′/22. We work with IRAC’s cryogenic-phase corrected basic data (BCD) and uncertainty files. All data were reduced with the Spitzer Science Center software pipeline version S18.25.0. We used the high-precision astrometry measurements of the companions from previous high-contrast AO observations as priors in our Markov Chain Monte Carlo (MCMC) fits (see Section 3).

The combined sample primary properties are given in Table 1, and the system properties are given in Table 2. The specific details about the Spitzer/IRAC programs and data products are listed in Table 3.

3. Data Analysis

Previous analyses of Spitzer/IRAC images searched for wide-orbit PMC systems by taking advantage of IRAC’s well-behaved PSF wings at >λ/D (e.g., Janson et al. 2015; Durkan et al. 2016; Baron et al. 2018). Our framework is optimized for probing the IRAC PSF at 1–5 λ/D, where companion identification is difficult because the PSF is undersampled at the native 1′′/22 pixel scale. Classical PSF modeling techniques, such as locally optimized combination of images (Laflènire et al. 2007) or principal component analysis, require more pixels to adequately model the primary star PSF. We use the framework described in Paper I to model the PSFs of the system components in the IRAC images. To summarize, we use the point-response function (or effective PSF; Hoffman 2005) developed by the Spitzer science team to generate model PSFs at any position on the IRAC detector. We then fit a two-source PSF model in each image, performing an MCMC analysis using a Metropolis–Hastings algorithm with Gibbs sampling. The PSF model is described by seven parameters: the x-pixel coordinate of the primary centroid (x), y-pixel coordinate of the primary centroid (y), image background (b), peak pixel value of the primary (p), projected separation (ρ), position angle (PA), and contrast (Δm). In addition, image pixel values greater than 90% of the saturation limit were masked. We adopt priors on separation and PA from past high-resolution imaging results, listed in Table 2.
The MCMC analysis is conducted in two stages to determine image-specific parameters \((x, y, \rho, \Delta m)\) separately from system-specific parameters \((n, \rho, PA, \Delta m)\). We ran four MCMC chains with 140,000 steps each, discarding the first 10% of each chain as “burn-in.” The weighted average median \((x, y)\)-centroid, \(\rho\), \(PA\), and \(\Delta m\) generated by the MCMC fit are used to create individual PSF models of each system component from which aperture photometry using a 10″ radius is measured. The zero-points of IRAC channels 1–4 are 280.9 ± 4.1, 179.7 ± 2.6, 115.0 ± 1.7, and 64.9 ± 0.9 mag, respectively.

Some members of the sample have nearby neighbors with flux that could influence the results of the pipeline fit. The neighbors of DH Tau, 2MASS J04414565+2301580 and 2MASS J04414489+2301513 (hereafter 2M0441 A and 2M0441 B), and CHXR 73 are within 15″ of the primary centroid and unsaturated. We use the same PSF model described above to fit and subtract each neighbor within each individual IRAC image prior to being put through the pipeline. SR 12 is ∼25″ away from a bright and saturated young stellar object, 2MASS J16272146±2441430 (YLW 13B). Although this object is well outside of the pipeline-fitting region, the wings of its flux can still affect the PSF-fitting results. For this system, we use the high dynamic range PSF from Marengo et al. (2006) to model this bright neighbor and subtract off its contaminating flux (Figure 1).

After the MCMC runs, stacked residual images are created by combining individual residual images after the primary PSF has been subtracted, placing each on a final grid with a pixel scale five times smaller than the original IRAC pixel scale of 1″/22, shifting to a common origin, and rotating so that north is up and east is left. The PSF subtraction occurs on the original data, not on mosaicked or subsampled images, because of the complicated nature of the IRAC PSF and because subsampling the images prior to PSF fitting would introduce covariance between adjacent pixels. We perform aperture photometry on these subsampled stacked residual images to determine detection limits around each primary. We use apertures with radii equal to the FWHM in each channel (1″/66, 1″/72, 1″/88, and 1″/98). The FWHMs are larger than the IRAC pixel scale (1″/22); thus, all covariant pixels contribute to the measured aperture flux.

To evaluate the sensitivity of our PSF-fitting framework to substellar companions in the IRAC images of our sample, we performed aperture photometry on the stacked images before and after PSF subtraction. We measured the flux inside 100 randomly drawn apertures of radius 1 FWHM at FWHM/4 (0″/42, 0″/43, 0″/47, and 0″/50) intervals radially outward from the primary star. The mean and standard deviation of these fluxes are used to determine the limiting flux and then converted into Spitzer/IRAC magnitudes to obtain 4σ limits. With ∼36, 34, 28, and 25 independent apertures in a search radius of 10″ around a primary star, the probability of measuring a spurious >4σ signal is 0.003%.

We then convert our detection limit curves into mass detection limits using the BT-Settl evolutionary models of Allard et al. (2012) at the reported literature ages and Gaia parallactic distances of our sample systems. For a given target, the companion height above (or below) the 4σ detection limit at that radius can be used to infer the systematic uncertainty due to residual primary PSF structure in our modeling framework photometry. For example, if the photometry measured for a companion is equal to the 4σ limit, its systematic flux uncertainty would be 25%, or ∼0.24 mag, while a 5σ detection would have a systematic flux uncertainty of 20%, or ∼0.20 mag. For all contrast and photometry measurements hereafter, we list this systematic uncertainty in addition to the statistical uncertainty from our MCMC fits.

4. Results

4.1. Detections

Our reprocessing of the IRAC images yielded detections in one or more filters for eight out of our sample of nine substellar companions. The one system whose companion was not detected, GJ 504, had the brightest primary \((K_s = 4.03\) mag) and largest expected contrast (>12 mag), but we are still able to assess a robust upper limit. We present the final system parameters as determined by our pipeline in Table 4. The contrasts reported are marginalized values of the parameters as measured by our MCMC fits, and we list both statistical and systematic uncertainties. Any further analysis we perform with this output adds the uncertainties in quadrature. The projected separations and PAs reflect the input priors from previous AO measurements.
imaging such that the information in the Spitzer/IRAC images is entirely devoted to measuring companion contrast. The IRAC magnitudes for the primary stars and substellar companions are calculated from the PSF models, assuming the median MCMC fit parameters, and are included in Table 5.

In Figure 2, we present example pipeline results for an individual system, AB Pic. We show stacked images of the original data and final system model, as well as stacked residual images after the PSF models are subtracted. Subtracting the primary star PSF, a statistically significant positive residual is seen at the expected position of AB Pic b. This residual disappears after subtracting the best-fit system PSFs, indicating that it is a robust detection across all IRAC filters.

Not all companions were detected in every IRAC channel. Generally, companions were not detected or had less constrained photometry in channel 3 (5.8 μm), suggesting a possible PSF mismatch between templates and data in that channel. CHXR 73 b was detected in channels 1, 2, and 4; ROXs 42B b was detected in channels 2 and 4; and 1RXS J1609 b also had the largest 24 μm contrast improvements. In addition, companions that were detected in other channels may have been missed in channel 3.

Table 5 contains a list of companions that were detected in those filters. We also show the intrinsic photospheric mid-infrared color–magnitude sequences from the BT-Settl models of Allard et al. (2010, 2014; Bowler & Hillenbrand 2015, and references therein). Mid-infrared excess has been identified for both pairs (Luhman et al. 2010; Adame et al. 2011; Bulger et al. 2014), indicating that at least one component of each binary harbors a circum(sub)stellar disk. We readily confirm this excess with our pipeline in the Spitzer images, but determining the mid-infrared flux contributions from the individual components of 2M0441 B is beyond the scope of this paper.

### 4.2. Detection Limits and Mass Sensitivity

Our PSF-fitting results yield sensitive upper limits on the companions that we did not detect, as well as the presence of additional companions in these systems. We present the contrast and mass limits reached in the PSF-subtracted images as a function of radial separation in Tables 6 and 7 and show the channel 4 detection limits in Figure 5 (see Section 3 for the details of the detection limit calculation).

Our detection limit curves show that prior to PSF subtraction, detectable companion contrasts plateau past 8″, corresponding to projected physical separations of ~150 au for the closest sample member (17.5 pc; GJ 504) and ~1600 au for the furthest (191.0 pc; CHXR 73). Within 8″, detectable contrasts improve by as much as 7 mag in channel 1 and 5.5 mag in channel 4.

While we do not detect the companion of GJ 504 in the images, we can place a limit on its L [8 μm] color using previous AO imaging results in the L band from Skemer et al. (2016) and our work. We find L [8 μm] < 8.43 mag.
4.3. SED Fits

Optical and near-infrared photometry from the literature can be used with our new Spitzer/IRAC mid-infrared photometry to analyze the SEDs of our sample systems. We fit system components with solar-metallicity BT-Settl model atmospheres (Allard et al. 2012) spanning effective temperatures between 1000 and 7000 K ($\Delta T_{\text{eff}} = 100$ K) fixed at either $\log g = 3.5$ (2M0441 B, CHXR 73, and ROXS 42B b) or $\log g = 4.0$, which is appropriate for young dwarfs according to BT-Settl evolutionary models. We convolve the model atmospheric spectra with filter transmission profiles to generate synthetic photometric measurements and find the $\chi^2$-minimizing scale factor between the model and observed photometry for each object. We also fit $E(B-V)$ as a free parameter using the extinction curve of Fitzpatrick (1999) in steps of 0.01 mag.

In Figure 6, we show the SED fits for the systems in our sample. We show our new Spitzer/IRAC photometry as red stars and the literature photometry used in our fits as blue squares. We also include the best-fit BT-Settl model for the primary and companion in gray. In Table 5, we list all of the photometry used in each SED fit for each system, in addition to our measured photometry from the pipeline parameters. In Table 8, we summarize the properties found from our fits. We discuss the SED fits of specific systems in Section 4.4 and interpret potential companion mid-infrared excesses further in Section 5.

4.4. Notes on Two Individual Systems

Our reprocessing of the IRAC images yielded detection of all nine primaries and eight substellar companions, five of which have not been resolved in the IRAC filters. We describe two systems in more detail in the following sections.

4.4.1. DH Tau

DH Tau is a protoplanetary disk host with spectral type M1 (Herbig 1977; Watson et al. 2009). It is an actively accreting classical T Tauri star with previously detected mid-infrared excess (Valenti et al. 1993; Meyer et al. 1997; Luhman et al. 2006, 2010). It hosts a substellar companion at a projected separation of $\rho = 2.3$ ($\sim 310$ au at its Gaia distance of $\sim 135$ pc; Itoh et al. 2005; Wallace et al. 2020; Bailey-Jones et al. 2021). The companion mass was initially estimated to be $\sim 30-50 M_{\text{Jup}}$, but comparison of its bolometric luminosity to newer evolutionary models revealed a lower mass of $\sim 11 M_{\text{Jup}}$ (Luhman et al. 2006; Kraus et al. 2014a; Bowler 2016), closer to the planet–brown dwarf boundary. Hydrogen emission lines and a UV continuum excess indicate active accretion onto DH Tau B (Bonnefoy et al. 2014; Zhou et al. 2014). Emission from the circum(sub)stellar disk has not been detected at mm wavelengths (Wu et al. 2020), but recently, van Holstein et al. (2021) detected near-infrared linear polarization signals originating from DH Tau B indicating the presence of circum(sub)stellar material.

We resolve DH Tau B and measure its mid-infrared photometry in all IRAC channels (see Figure 3 for channel 2 detection). As we described in Section 4.3 and show in Figure 6, we use Hubble Space Telescope optical (Zhou et al. 2014), Two Micron All Sky Survey (2MASS) near-infrared (Cutri et al. 2003), and the Spitzer/IRAC 3.6 $\mu$m photometry measured in this work to analyze the SEDs of DH Tau A and B. The best-fitting model for DH Tau A is $T_{\text{eff}} = 2600 \pm 100$ K and $E(B-V) = 1.27 \pm 0.06$ mag; for DH Tau B, the best-fitting model is $T_{\text{eff}} = 1800 \pm 50$ K and $E(B-V) = 0.00 \pm 0.03$ mag. The 8 $\mu$m photometry for DH Tau B disagrees with the best-fitting model at 3.8$\sigma$. We find the mid-infrared color of DH Tau B to be [3.6]–[8.0] = 2.19 $\pm$ 0.66 mag, which is discrepant with the Luhman et al. (2010) empirical color of an M9 dwarf atmosphere at the 2.7$\sigma$ level.
Table 4
Best-fit System Properties of Detected Companions

| 2MASS (Primary) | Other Name (Companion) | Separation (arcsec) | PA (deg) | $\Delta[3.6]$ (mag) | $\Delta[4.5]$ (mag) | $\Delta[5.8]$ (mag) | $\Delta[8.0]$ (mag) |
|----------------|------------------------|---------------------|----------|---------------------|---------------------|---------------------|---------------------|
| J04294155+2632582 | DH Tau B               | 2.22 ± 0.18         | 137.30 ± 1.5 | 5.74 ± 0.24 ± 0.56 | 5.30 ± 0.17 ± 0.42 | 4.79 ± 0.16 ± 0.31 | 4.38 ± 0.15 ± 0.19 |
| J04414565+2301580 | 2M0441 Bab             | 12.35 ± 0.01        | 237.4 ± 0.1  | 2.67 ± 0.01 ± 0.01 | 2.43 ± 0.01 ± 0.01 | 2.16 ± 0.01 ± 0.01 | 1.78 ± 0.01 ± 0.01 |
| J06191291–5803156 | AB Pic b               | 5.52 ± 0.09         | 175.4 ± 0.3  | 6.34 ± 0.06 ± 0.08 | 5.98 ± 0.07 ± 0.09 | 5.65 ± 0.26 ± 0.09 | 5.58 ± 0.16 ± 0.20 |
| J11062877–7737331 | CHXR 73 b              | 1.24 ± 0.03         | 228.5 ± 3.8  | 3.63 ± 0.04 ± 0.12 | 3.79 ± 0.06 ± 0.04 | ...                 | 2.92 ± 0.12 ± 0.08 |
| J16093030–2104589 | 1RXS J1609 b           | 2.14 ± 0.11         | 27.0 ± 0.6   | ...                 | 6.04 ± 0.15 ± 0.17 | ...                 | ...                 |
| J16271951–2441403 | SR 12 c                | 8.62 ± 0.05         | 164.8 ± 0.6  | 5.83 ± 0.07 ± 0.08 | 5.08 ± 0.03 ± 0.06 | 5.05 ± 0.07 ± 0.13 | 4.16 ± 0.03 ± 0.12 |
| J16311501–2432436 | ROXs 42B               | 1.17 ± 0.03         | 263.6 ± 4.8  | ...                 | 5.08 ± 0.56 ± 0.24 | ...                 | 4.55 ± 0.11 ± 0.10 |
| J21185820–2613500 | HD 203030 b            | 12.025 ± 0.004      | 108.69 ± 0.02 | 8.27 ± 0.01 ± 0.63 | 7.88 ± 0.01 ± 0.27 | 6.97 ± 0.02 ± 0.20 | 6.84 ± 0.02 ± 0.21 |

*Note.* If an entry in $\Delta m$ is missing, the companion was not detected in that channel.
### Table 5
Photometry for Sample Systems

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| F775W   | ...                     | 20.2 ± 0.03                | 1    |
| F850LP  | ...                     | 18.0 ± 0.02                | 2    |
| J       | 9.76 ± 0.02             | 15.71 ± 0.05               | 2, 3 |
| H       | 8.82 ± 0.02             | 14.96 ± 0.04               | 2, 3 |
| K       | 8.17 ± 0.02             | 14.19 ± 0.02               | 2, 3 |
| [3.6]   | 7.58 ± 0.02             | 13.32 ± 0.24 ± 0.56        | This work |
| [4.5]   | 7.21 ± 0.02             | 12.51 ± 0.17 ± 0.42        | This work |
| [5.8]   | 7.10 ± 0.02             | 11.89 ± 0.16 ± 0.31        | This work |
| [8.0]   | 6.76 ± 0.02             | 11.13 ± 0.15 ± 0.19        | This work |

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| 2MASS J04294155+2632582 (DH Tau) |                      |                             |      |
| J        | 7.78 ± 0.02             | 13.15 ± 0.24 ± 0.56        | This work |
| H        | 8.46 ± 0.02             | 14.69 ± 0.04               | 2, 3 |
| K        | 7.60 ± 0.02             | 14.02 ± 0.02               | 2, 3 |
| [3.6]   | 7.38 ± 0.02             | 13.05 ± 0.24 ± 0.56        | This work |
| [4.5]   | 6.97 ± 0.02             | 12.30 ± 0.17 ± 0.42        | This work |
| [5.8]   | 6.76 ± 0.02             | 11.97 ± 0.16 ± 0.31        | This work |
| [8.0]   | 6.19 ± 0.02             | 10.90 ± 0.02 ± 0.01        | This work |
| J        | 9.16 ± 0.02             | 16.21 ± 0.02 ± 0.01        |      |

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| J        | 12.10 ± 0.01            | 16.10 ± 0.01               | 4    |
| H        | 10.10 ± 0.02            | 14.42 ± 0.03               | 2    |
| K        | 9.85 ± 0.02             | 13.73 ± 0.03               | 2    |
| [3.6]   | 9.59 ± 0.02             | 12.76 ± 0.02 ± 0.01        | This work |
| [4.5]   | 9.48 ± 0.02             | 11.89 ± 0.02 ± 0.01        | This work |
| [5.8]   | 9.32 ± 0.02             | 11.48 ± 0.02 ± 0.01        | This work |
| [8.0]   | 9.19 ± 0.02             | 10.96 ± 0.02 ± 0.01        | This work |

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| J        | 12.04 ± 0.02            | 16.10 ± 0.01               | 4    |
| H        | 10.10 ± 0.02            | 14.42 ± 0.03               | 2    |
| K        | 9.85 ± 0.02             | 13.73 ± 0.03               | 2    |
| [3.6]   | 9.59 ± 0.02             | 12.76 ± 0.02 ± 0.01        | This work |
| [4.5]   | 9.48 ± 0.02             | 11.89 ± 0.02 ± 0.01        | This work |
| [5.8]   | 9.32 ± 0.02             | 11.48 ± 0.02 ± 0.01        | This work |
| [8.0]   | 9.19 ± 0.02             | 10.96 ± 0.02 ± 0.01        | This work |

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| J        | 15.07 ± 0.01            | ...                        | 4    |
| H        | 13.49 ± 0.1             | ...                        | 4    |
| K        | 12.51 ± 0.1             | ...                        | 4    |
| [3.6]   | 11.81 ± 0.1             | ...                        | 4    |
| [4.5]   | 11.47 ± 0.1             | ...                        | 4    |
| [5.8]   | 9.91 ± 0.02             | ...                        | 2    |
| [8.0]   | 9.02 ± 0.02             | ...                        | 2    |
| K        | 8.67 ± 0.02             | ...                        | 2    |
| J        | 16.99 ± 0.07            | ...                        | 14   |
| H        | 15.88 ± 0.06            | ...                        | 14   |
| K        | 15.01 ± 0.05            | ...                        | 14   |
| [3.6]   | 8.38 ± 0.02             | >12.29                     | This work |
| [4.5]   | 8.38 ± 0.02             | 13.44 ± 0.56 ± 0.24        | This work |
| [5.8]   | 8.28 ± 0.02             | >12.37                     | This work |
| [8.0]   | 8.28 ± 0.02             | 12.82 ± 0.11 ± 0.10        | This work |

| Filter   | Primary Magnitude (mag) | Secondary Magnitude (mag) | Ref. |
|----------|-------------------------|----------------------------|------|
| J        | 9.92 ± 0.03             | 17.85 ± 0.12               | 2, 3 |

**Note.** When two uncertainties are listed, the first is a statistical uncertainty based on the rms between images, and the second is a systematic uncertainty based on the PSF subtraction of the primary. If an entry is missing, that filter was not used in the component’s SED fit.

**References.** (1) Zhou et al. (2014); (2) Cutri et al. (2003); (3) Itoh et al. (2005); (4) Chambers et al. (2016); (5) Hog et al. (2000); (6) Gaia Collaboration et al. (2018); (7) Chauvin et al. (2005); (8) Hubble Legacy Archive; (9) Luhman et al. (2006); (10) Skemer et al. (2016); (11) Epchtein et al. (1997); (12) Wu et al. (2015); (13) Lachapelle et al. (2015); (14) Kraus et al. (2014a); (15) Miles-Páez et al. (2017); (16) Metchev & Hillenbrand (2006).
Using the dereddened $K$-band photometry from Itoh et al. (2005) and our channel 4 detection, DH Tau B’s infrared color is $K-[8.0] = 2.93 \pm 0.24$ mag, which is discrepant from an M9 atmosphere at the 8.0$\sigma$ level. This red color indicates a clear mid-infrared excess consistent with the presence of a circumstellar disk.

We use our 3.6 $\mu$m photometric measurement, DH Tau’s Gaia parallactic distance (133.3 pc; Bailer-Jones et al. 2021), and Taurus’s adopted age of $\tau \sim 2$ Myr to estimate the mass of DH Tau B to be $M = 17 \pm 6 M_{\text{jup}}$, consistent with previous mass determinations ($M = 18 \pm 4 M_{\text{jup}}$; Kraus et al. 2014a).

4.4.2. AB Pic

AB Pic is a K2 star originally considered a member of the Tucana–Horologium association ($\tau \sim 40$ Myr; Song et al. 2003; Kraus et al. 2014b; Bell et al. 2015). Torres et al. (2008) later reassessed AB Pic to be a member of Carina, another young moving group (YMG) with an age of $\tau \sim 30$ Myr (e.g., Bell et al. 2015; Miret-Roig et al. 2018). Recently, Booth et al.

Figure 2: Stacked images of AB Pic across all four IRAC channels (rows) after it has gone through the PSF-fitting pipeline. All fits were conducted within the CB7CD images at the native plate scale, but to convey the full data set, the images here were generated by combining individual frames after they had been rescaled to 0.24 pixel$^{-1}$ ($\sim 5 \times$ smaller than the original IRAC pixel scale), shifted to a common origin, and rotated so that north is up and east is left. The first and second columns show the original IRAC data of AB Pic and the median two-source PSF model, respectively, displayed with a logarithmic color scale (leftmost color bar). The third column shows the residuals left behind after only the primary PSF model is subtracted from the data. The fourth column shows the residuals left behind after the two-source PSF model is subtracted from the data. Both the third and fourth columns are displayed with a linear color scale (rightmost color bar) and 3$\sigma$ and 5$\sigma$ contours overlaid with solid and dotted lines, respectively. The standard deviation of the pixel values is displayed in the lower left corner of the fourth column in units of DN s$^{-1}$. After subtracting the primary star PSF, a statistically significant positive residual is seen at the expected position of AB Pic b. This residual disappears after subtracting the best-fit system PSFs, indicating that it is a robust detection across all IRAC filters.

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Figure 3. Stacked images of DH Tau, CHXR 73, 1RXS J1609, and ROXs 42B, the other four systems besides AB Pic (shown in Figure 2) with companions that are newly resolved in this work. The first and second columns show the original IRAC data and the median two-source PSF model, respectively, displayed with a logarithmic color scale (leftmost color bar). The third column shows the residuals left behind after only the primary PSF model is subtracted from the data. The third column is displayed with a linear color scale (rightmost color bar) with 3σ and 5σ contours overlaid with solid and dotted lines, respectively. For each panel, north is up, and east is left.
Figure 4. Color–magnitude diagram for our sample detected in both channel 1 (3.6 μm) and channel 4 (8.0 μm). For comparison, we include young >M7 brown dwarf members of the Taurus (triangles; Esplin & Luhman 2017) and Upper Scorpius (squares; Luhman & Esplin 2020) star-forming regions. Orange symbols represent disk-free members, while red symbols denote disk-bearing members. We also include field brown dwarfs from Dupuy & Liu (2012), indicated by asterisks. The M3.6 was determined from Gaia EDR3 parallactic measurements (Bailer-Jones et al. 2021) of each system primary. The primary components are indicated as filled stars, while substellar companions are indicated as filled circles. Also displayed are the intrinsic photospheric [3.6]–[8.0] colors from BT-Settl models of Allard et al. (2012) at 1, 10, 100, and 500 Myr (dashed lines). Not shown are the companions to GJ 504 and 1RXS J1609, which were not detected in either channel 1 or channel 4.

4.5. Companions with Previous IRAC Photometric Measurements

4.5.1. 2M0441 AB

Esplin et al. (2014) reported IRAC photometry of $m_{[4.5]} = 9.48 \pm 0.02$, $m_{[8.0]} = 9.37 \pm 0.03$, and $m_{[12]} = 9.22 \pm 0.03$ mag for 2M0441 A in channels 2–4 (channel 1 is saturated). For 2M0441 B, they reported $m_{[4.5]} = 12.26 \pm 0.02, m_{[8.0]} = 11.88 \pm 0.02, m_{[12]} = 11.53 \pm 0.03$, and $m_{[16]} = 11.00 \pm 0.03$ mag. Our pipeline IRAC photometry agrees with these prior measurements within the error bars, and through our PSF-fitting procedure that masks saturated pixels, we are able to recover a channel 1 magnitude for the primary that is consistent with its overall SED shape.

4.5.2. HD 203030

Miles-Páez et al. (2017) observed HD 203030 with Spitzer/IRAC (Program ID 40489) at two distinct epochs to utilize roll subtraction to obtain photometry of HD 203030 b that was minimally contaminated by its host bright stellar halo. No photometry is reported for HD 203030, but they did report IRAC photometry of $m_{[3.6]} = 14.99 \pm 0.02$, $m_{[4.5]} = 14.73 \pm 0.02$, $m_{[5.8]} = 14.39 \pm 0.05$, and $m_{[8.0]} = 14.15 \pm 0.04$ mag for HD 203030 b. We initially fit the first-epoch long-exposure images of HD 203030 and found that our channel 1 pipeline photometry of $m_{[3.6]} = 15.01 \pm 0.40$ mag agreed with their measurement, but we measured higher fluxes for all other channels ($m_{[4.5]} = 14.63 \pm 0.26$, $m_{[5.8]} = 13.84 \pm 0.20$, and $m_{[8.0]} = 13.44 \pm 0.21$ mag). No ground-based photometry at wavelengths greater than 3 μm has been reported in the literature.

To explore this discrepancy further, we use our pipeline infrastructure to fit all of the IRAC images available simultaneously for each exposure time, as well as the individual epochs separately. In the 1 s exposures, the primary is not saturated, and we measure its photometry to be $m_{[3.6]} = 6.64 \pm 0.02$, $m_{[4.5]} = 6.68 \pm 0.02$, $m_{[5.8]} = 6.63 \pm 0.02$, and $m_{[8.0]} = 6.63 \pm 0.02$ mag across the IRAC channels for the first epoch and $m_{[3.6]} = 6.66 \pm 0.02, m_{[4.5]} = 6.68 \pm 0.02, m_{[5.8]} = 6.64 \pm 0.02$, and
$m_{[8.0]} = 6.63 \pm 0.02$ mag for the second. The IRAC photometry is consistent with the Band 1 (3.5 $\mu$m), 2 (4.0 $\mu$m), and 3 (12.0 $\mu$m) mid-infrared photometry reported in the AllWISE catalog (Cutri et al. 2021; $W_1 = 6.66 \pm 0.07$, $W_2 = 6.63 \pm 0.02$, $W_3 = 6.63 \pm 0.02$). In the 26.8 s exposures, our pipeline measures $m_{[3.6]} = 6.73 \pm 0.02$, $m_{[4.5]} = 6.76 \pm 0.02$, $m_{[5.8]} = 6.88 \pm 0.02$, and $m_{[8.0]} = 6.61 \pm 0.02$ mag across the IRAC channels for the first epoch and $m_{[3.6]} = 6.80 \pm 0.02$, $m_{[4.5]} = 6.79 \pm 0.02$, $m_{[5.8]} = 6.69 \pm 0.02$, and $m_{[8.0]} = 6.61 \pm 0.02$ mag for the second, suggesting a systematic uncertainty of 0.1–0.2 mag for the brightness of the primary when its PSF core is saturated. This variation is still smaller than the ~0.5–0.7 mag discrepancy between our photometric measurements for the companion and those of Miles-Páez et al. (2017), indicating that if there is an issue in our analysis, it comes when fitting the companion and after the primary PSF has been subtracted.

The intrinsic photospheric colors of late M and L dwarfs are typically determined by combining photometric observations with parallax measurements (e.g., Patten et al. 2006; Luhman et al. 2010; Filippazzo et al. 2015; Faherty et al. 2016). An L7.5 field dwarf should have $K_* = [3.6] = 1.13$, $[3.6]–[4.5] = –0.02$, $[4.5]–[5.8] = 0.32$, and $[5.8]–[8.0] = 0.23$ mag in the IRAC channels, according to Dupuy & Liu (2012). Both [3.6]–[4.5] colors measured for HD 203030 b by Miles-Páez et al. (2017) and in this work are ~0.3–0.4 mag redder than expected, although consistent with younger planetary-mass objects (e.g., Filippazzo et al. 2015; Faherty et al. 2016; Liu et al. 2016). In the other channels, the colors measured by Miles-Páez et al. (2017) agree with a field L7.5 photosphere, while our photometry continues to be significantly redder. Miles-Páez et al. (2017) measured [3.6]–[8.0] = 0.84 ± 0.04 mag, which is ~0.3 mag redder than expected but still within the upper envelope of the rms scatter of the Dupuy & Liu (2012) sample. We measure [3.6]–[8.0] = 1.57 ± 0.45 mag. This color excess could potentially indicate the presence of a circum(sub)stellar disk if confirmed, but given the disagreement with Miles-Páez et al. (2017), such an interpretation should be treated with caution.

To test if this color excess might emerge from our reduction procedures, in Figure 7, we show the stacked image output for our pipeline fits of the first epoch of long-exposure IRAC images. A significant positive residual is present at the expected location of HD 203030 b when only the primary PSF is subtracted, and no significant structure remains at that location when both primary and companion PSFs are

### Table 6

| 2MASS        | Distance (pc) | Ch. | $M$ (mag) | Exp. Time (s) | Contrast (mag) at $\rho =$ (arcsec) |
|--------------|--------------|-----|-----------|--------------|----------------------------------|
| J04294155+2632582 | 133.3        | 1   | 1.96      | 0.4          | 4.79 4.49 4.36 4.46 5.08 5.76 6.46 6.23 6.45 6.22 |
| J04414565+2301580 | 122.9        | 1   | 4.13      | 0.6          | 3.19 2.15 1.87 1.64 2.43 5.72 7.90 7.53 7.63 7.59 |
| J06191291–5803156 | 50.1         | 1   | 3.39      | 0.4          | 6.90 6.26 6.37 6.96 7.23 7.79 7.33 7.66 7.57 7.38 |
| J11062877–7737331 | 190.0        | 1   | 3.35      | 0.4          | 5.63 4.59 5.83 5.78 6.54 6.34 6.29 6.32 6.14 6.04 |
| J13164653+0925269 | 17.6         | 1   | 2.62      | 1.0          | 4.73 4.55 4.45 4.60 5.19 5.88 6.65 6.84 7.01 7.34 |
| J16093030–2104589 | 137.8        | 1   | 3.07      | 10.4         | 6.16 5.88 5.45 5.09 5.59 6.39 7.02 7.28 7.18 6.99 |
| J16271951–2441403 | 112.5        | 1   | 2.84      | 10.4         | 4.64 4.38 4.29 4.02 4.69 5.74 6.59 7.06 7.09 7.77 |
| J16311501–2432436 | 145.4        | 2   | 2.55      | 0.4          | 6.16 5.88 5.01 5.29 5.40 6.85 7.33 7.18 7.28 7.28 |
| J21185820+2613500 | 39.2         | 1   | 3.76      | 26.8         | 4.70 4.25 4.13 4.36 4.77 6.89 7.56 7.73 7.66 7.66 |
| J21185820+2613500 | 39.2         | 2   | 3.79      | 26.8         | ... 4.78 5.57 4.66 4.11 4.09 5.62 7.36 7.24 7.69 7.69 |
| J21185820+2613500 | 39.2         | 3   | 3.91      | 26.8         | 1.66 1.26 1.18 1.27 1.42 2.18 3.86 6.55 7.49 7.22 7.22 |
| J21185820+2613500 | 39.2         | 4   | 3.64      | 26.8         | 3.28 3.05 3.05 3.15 3.38 3.90 6.85 6.40 6.66 6.98 6.98 |
subtracted, though in channels 3 and 4, there appears to be a slight oversubtraction. The maximum pixel value at the location of HD 203030 b prior to PSF subtraction is 0.1359 subtracted, though in channels 3 and 4, there appears to be a slight oversubtraction. The maximum pixel value at the location of HD 203030 b prior to PSF subtraction is 0.1359 and 0.2507 DN s\(^{-1}\), respectively, in those channels. After PSF subtraction, that pixel value is \(-0.0058\) and \(-0.0237\) DN s\(^{-1}\), or 4\% and 9\% of the initial pixel value. If the oversubtraction is uniform for all pixels in an aperture, this would result in a maximum flux overestimation of 0.05 and 0.10 mag in channels 3 and 4, still not enough to explain the differences between our IRAC photometry and that of Miles-Páez et al. (2017). The assumption of uniform oversubtraction across an aperture is unrealistic, though, and we proceed with an empirical approach to better estimate our uncertainties.

The number of resolution elements in the stacked residual images is about 1220, 780, 470, and 250 for IRAC channels 1, 2, 3, and 4, respectively. Thus, we would expect 3, 2, 1, and \(<1\) spurious 3\(\sigma\) outliers in the residual images for each channel. For HD 203030, it appears that there are more outliers than expected from noise, but many are aligned with the PSF structures most visible for the brightest primaries of our sample. We note that in channel 2, the large residual to the lower right is a background object (\(\pi = 0.56 \pm 0.12\) mas; Gaia Collaboration et al. 2018). The HD 203030 b residual is present in all channels, bolstering confidence in the detections that do not fall upon PSF structure.

To estimate a systematic uncertainty from PSF modeling, we consider the rms of flux values measured within apertures of 1 FWHM radius at the radial separation of the companion around HD 203030 when calculating the detection limit in the PSF-subtracted images. In channel 3, we find the rms to be 3.26 DN s\(^{-1}\), which is 19.9\% of the flux measured for HD 203030 b. Similarly, in channel 4, we find the rms of the flux values to be 9.25 DN s\(^{-1}\), or 24.0\% of the measured flux of the companion. We therefore conclude that there is no clear evidence of systematic errors in our PSF fit, as the overluminosity would be a 4\(\sigma\)–5\(\sigma\) effect for each of the [5.8] and [8.0] filters, which sample the IRAC PSF in different ways. However, it is unlikely that this discrepancy can be resolved without further observations to independently determine its mid-infrared brightness.

### 4.5.3. SR 12

Observations of SR 12 were a part of the Spitzer c2d Legacy survey (Evans et al. 2009) that imaged five nearby molecular clouds with the IRAC and MIPS instruments. Various studies (e.g., Cieza et al. 2007, 2009; Gutermuth et al. 2009; Günther et al. 2014; Esplin & Luhman 2020) have reported IRAC...
photometry for SR 12 AB from these data, ranging from 8.16 – 8.27 mag at 3.6 $\mu$m, to 8.16 – 8.25 mag at 4.5 $\mu$m, to 7.99 – 8.12 mag at 5.8 $\mu$m, to 8.03 – 8.12 mag at 8.0 $\mu$m, with typical uncertainties between 0.02 and 0.06 mag. Our pipeline photometry for SR 12 AB agrees with these previous measurements within the uncertainties in channels 1, 3, and 4, though our measurement is $\sim 0.06$ mag brighter in channel 2.

The c2d IRAC photometry for SR 12 c is $m_{[3.6]} = 13.65 \pm 0.08$, $m_{[4.5]} = 13.60 \pm 0.03$, $m_{[5.8]} = 13.20 \pm 0.28$, and $m_{[8.0]} = 12.50 \pm 0.37$ mag (Cieza et al. 2007; Alves de Oliveira et al. 2010; Günther et al. 2014). Our channel 1 and 2 photometry is significantly discrepant ($m_{[3.6]} = 13.99 \pm 0.11$, $m_{[4.5]} = 13.18 \pm 0.07$ mag), but we are able to constrain SR 12 c’s channel 3 and 4 photometry to $m_{[5.8]} = 13.09 \pm 0.15$ and $m_{[8.0]} = 12.17 \pm 0.13$ mag.

SR 12 c has a spectral type of M9–L0 (e.g., Kuzuhara et al. 2011; Bowler et al. 2014; Santamaría-Miranda et al. 2018); thus, its photosphere should have a $K_s$-[3.6] color of $\sim 0.6$–0.7 mag based on empirical measurements of late M dwarfs (e.g., Patten et al. 2006; Luhman et al. 2010). Kuzuhara et al. (2011) reported ground-based photometry of $K_s = 14.57 \pm 0.03$ mag with their discovery of SR 12 c. Combining this $K_s$-band measurement with our IRAC channel 1 photometry gives $K_s-[3.6] = 0.58 \pm 0.11$ mag, consistent with a detection of an M9 photosphere. We also measure $[3.6]-[8.0] = 1.82 \pm 0.17$ mag, which indicates that the companion harbors a disk. Santamaría-Miranda et al. (2018) identified numerous emission line accretion tracers in the spectrum of SR 12 c, confirming this disk.

The 4.5 $\mu$m photometry we measure for the companion is the most discrepant from previous studies. No WISE photometry has been reported for SR 12 c either, likely due to its crowded environment. Since our photometry of SR 12 AB agrees with previously reported values, any uncertainties would likely come from PSF subtraction. We again consider the rms of flux values measured using apertures with a radius equal to 1 FWHM at the radial separation of the companion around SR 12 AB when calculating the detection limit in the PSF-subtracted images. At 4.5 $\mu$m, we find the rms to be 1.75 DN s$^{-1}$, which is 6.4% of the flux measured for SR 12 c. Similarly, at 5.8 $\mu$m, we find the rms of the flux values to be 4.63 DN s$^{-1}$, or 14.2% of the measured flux of the companion. We conclude here that any large-scale deviation from an M9 photosphere may be outlining the SED of the disk harbored by SR 12 c.

As we mentioned in Section 3, SR 12 is 25″ away from YLW 13B, a bright and saturated young stellar object. The discrepancies between the c2d companion photometry and ours could be a result of the c2d pipeline’s handling of bright neighbors, especially in channel 1. Conversely, if there is a disk excess in the IRAC bands, then it seems likely that we either...
overestimate the brightness at 4.5 $\mu$m or underestimate it at 5.8 $\mu$m.

5. Discussion

Free-floating young brown dwarfs are observed to follow color–magnitude sequences that are distinct from those of older brown dwarfs (e.g., Allers et al. 2010; Faherty et al. 2016; Liu et al. 2016). In the near-infrared, young brown dwarfs are redder in $J - K$ colors, suggesting enhanced dust abundances (e.g., Woitke & Helling 2004; Barman et al. 2011) or lower surface gravities (e.g., Burrows et al. 1997; Kirkpatrick et al. 2006; Looper et al. 2008). Determining whether wide-orbit PMCs also follow the trends previously established for free-floating brown dwarfs into the mid-infrared could point to formation pathway commonalities. Deviations would imply differing formation processes, and redder colors could indicate the presence of circum(sub)stellar disks.

5.1. Absolute Magnitude Trends with Spectral Type

A star forms with a large radius that subsequently contracts in its pre-main-sequence phase, which might result in an observable difference between the luminosities of young stars or substellar objects, and those of the field. These objects would also appear brighter in the Spitzer/IRAC bands, especially the later spectral types and objects that harbor disks.

Figure 8 shows absolute magnitude–spectral type diagrams plotting $M_{[3.6]}$ through $M_{[8.0]}$ versus spectral type for the detected wide-orbit companions in our sample (filled circles), as well as others from Paper I (FU Tau B, FW Tau C, SCH J0359 B, and USco 1610 B), ROXs 12 B, GQ Lup B, and GSC 6214 B (purple upside-down triangles). We complement these data with late M to early L brown dwarfs from the Taurus and Upper Sco star-forming regions (Esplin & Luhman 2017; Luhman & Esplin 2020). The absolute magnitudes for the individual PMCs were calculated from either the Gaia EDR3 or DR2 parallactic measurements (Bailer-Jones et al. 2021, 2018).
brown dwarfs, depicted as in Figures 4, 8 and 9. We also for our PMC sample and the young Taurus and Upper Sco and AMES-Dusty isochrones as a theoretical comparison. We themselves in the young regions (τ ~ 1–3 Myr; Taurus, Chameleon, Ophiuchus). The only PMC in our sample that is consistently below the YMG sequence is AB Pic b. The high scatter within these sequences suggests that magnitudes alone do not provide a sensitive view of which objects are outliers.

5.2. Color Trends of Wide-orbit Companions in the Mid-infrared

The colors of wide-orbit PMCs provide a more nuanced view of their nonphotospheric behavior. The colors of our sample are expected to be close to zero, given their range in spectral types; thus, objects with nonzero colors are potentially interesting.

In Figure 9, we show [3.6]–[8.0] color as a function of spectral type for the same systems as described above for Figure 8. We again indicate the Taurus (triangles) and Upper Sco (squares) members as disk-bearing (red) or disk-free (orange) and include the field and YMG member polynomial sequences of Dupuy & Liu (2012; solid line, dark gray) and Faherty et al. (2016; dashed line, light gray).

DH Tau B, 2M0441 B, AB Pic b, CHXR 73 b, SR 12 c, and ROXs 42B b are significantly redder than the field polynomial sequence. The young (τ ~ 2–10 Myr) Taurus and Upper Sco disk-hosting and disk-free members also readily differentiate themselves in the [3.6]–[8.0] color space.

Interestingly, the disk-bearing members fall right in line with the continuation of the YMG (~20–120 Myr) dwarf sequence. The detected PMCs of this sample also are consistent with the YMG sequence, except for DH Tau B, which is already known to show active accretion. Objects 2M0441 B, SR 12 c, and ROXs 42B b are above the average YMG polynomial sequence color for their spectral type, which could be due to the youth of the systems or the presence of circum(sub)stellar disks. There also is the possibility that some YMG members may also harbor circum(sub)stellar disks.

5.3. Identifying Disk-hosting PMCs in Color–Color Space

Identifying disk hosts in color–color space removes the reliance on spectral type measurements that can be highly uncertain. In Figure 10, we show Ks–[8.0] versus Ks–[3.6] color (left panel) and [3.6]–[8.0] versus Ks–[3.6] color (right panel) for our PMC sample and the young Taurus and Upper Sco brown dwarfs, depicted as in Figures 4, 8 and 9. We also include the expected color–color sequence of 5 Myr BT-Settl and AMES-Dusty isochrones as a theoretical comparison. We show both of these color spaces to take advantage of better-

| Parameter | Primary | Companion |
|-----------|---------|-----------|
| T_eff (K) | 2600 ± 100 | 1800 ± 50 |
| E(B − V) (mag) | 1.27 ± 0.06 | 0.00 ± 0.03 |
| χ^2 | 0.65 | 6.03 |
| [8.0]_mod − [8.0]_lam (mag) | 0.41 | 1.94 |

or, if not available, the adopted distance to the star-forming region. Individual association members are color-coded red if they are thought to harbor a disk from measured mid-infrared excess or orange if they are thought to be disk-free. We also indicate the expected field polynomial sequence as determined by Dupuy & Liu (2012; solid line, dark gray), as well as the young (τ < 1 Gyr, τ ~ 5–150 Myr; Faherty et al. 2016; Liu et al. 2016) ultracool dwarf polynomial sequence from Faherty et al. (2016; dashed line, light gray).

In general, brown dwarfs with spectral types <M8 are 1–2 mag brighter than the YMG polynomial sequence, while substantial overlap begins between the YMG sequence and brown dwarfs with spectral types >M8. This overluminosity above the field sequence is expected, as the young objects have not yet contracted to their final radii. Objects DH Tau B, 2M0441 B, CHXR 73 b, and ROXs 42B b are consistently above the YMG polynomial sequence, as is FU Tau B. These wide companions orbit host stars that are among the very young regions (τ ~ 1–3 Myr; Taurus, Chameleon, Ophiuchus). The only PMC in our sample that is consistently below the YMG sequence is AB Pic b. The high scatter within these sequences suggests that magnitudes alone do not provide a sensitive view of which objects are outliers.

| Table 8: SED-fitting Results for Sample Systems |
|----------|---------|---------|
| Parameter | Primary | Companion |
| T_eff (K) | 3200 ± 100 | 2800 ± 50 |
| E(B − V) (mag) | 0.00 ± 0.02 | 0.46 ± 0.04 |
| χ^2 | 0.36 | 3.11 |
| [8.0]_mod − [8.0]_lam (mag) | 0.22 | 1.50 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 6000 ± 100 | 2100 ± 100 |
| E(B − V) (mag) | 0.30 ± 0.02 | 1.70 ± 0.19 |
| χ^2 | 4.12 | 0.84 |
| [8.0]_mod − [8.0]_lam (mag) | 0.08 | 0.21 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 3700 ± 50 | 1700 ± 50 |
| E(B − V) (mag) | 2.12 ± 0.03 | 1.77 ± 0.11 |
| χ^2 | 1.69 | 0.45 |
| [8.0]_mod − [8.0]_lam (mag) | −0.07 | 0.01 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 6900 ± 200 | 800 ± 100 |
| E(B − V) (mag) | 0.16 ± 0.04 | 0.00 ± 0.18 |
| χ^2 | 2.78 | 12.17 |
| [8.0]_mod − [8.0]_lam (mag) | 0.06 | <8.46 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 3700 ± 50 | 2000 ± 100 |
| E(B − V) (mag) | 0.00 ± 0.01 | 2.30 ± 0.13 |
| χ^2 | 0.60 | 3.92 |
| [8.0]_mod − [8.0]_lam (mag) | 0.02 | <0.24 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 3600 ± 50 | 2200 ± 50 |
| E(B − V) (mag) | 0.22 ± 0.01 | 0.14 ± 0.03 |
| χ^2 | 1.14 | 4.24 |
| [8.0]_mod − [8.0]_lam (mag) | 0.04 | 1.35 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 3600 ± 50 | 1700 ± 50 |
| E(B − V) (mag) | 0.50 ± 0.02 | 0.49 ± 0.18 |
| χ^2 | 4.29 | 4.20 |
| [8.0]_mod − [8.0]_lam (mag) | 0.01 | 0.46 |

| Parameter | Primary | Companion |
|----------|---------|---------|
| T_eff (K) | 5600 ± 50 | 1700 ± 50 |
| E(B − V) (mag) | 0.01 ± 0.02 | 2.61 ± 0.30 |
| χ^2 | 8.79 | 0.68 |
| [8.0]_mod − [8.0]_lam (mag) | 0.13 | 0.56 |
constrained ground-based $K$-band contrasts for some companions that were marginally detected by our pipeline at $[3.6]$. Five of the wide-orbit PMCs in this work (DH Tau B, 2M0441 B, ROXs 42B b, SR 12 c, and HD 203030 b), along with two from Paper I (FU Tau B and SCH J0359 B), have colors consistent with young disk-bearing brown dwarfs. However, HD 203030 b is the latest spectral type of our sample (L7.5); thus, its position in this parameter space is likely explained by differences in late L atmospheric characteristics, rather than the presence of a circum(sub)stellar disk. Only one object in this combined sample, the more massive USco 1609 B ($M \sim 70 \, M_{\text{Jup}}$), falls among the disk-free young brown dwarfs. Objects AB Pic b and CHXR 73 b fall outside of the disk-free locus, along with a few late-type disk-free members, but their locations are consistent with predictions from the AMES-Dusty models (Chabrier et al. 2000; Allard et al. 2001). FW Tau C sits furthest from the disk-hosting and disk-free objects, but given the ongoing debate over whether it is a more massive object hosting an edge-on disk (Wu & Sheehan 2017), it might be expected to have anomalous colors.

Figure 7. Stacked images of HD 203030 across all four IRAC channels (rows) after its first-epoch images have gone through the PSF-fitting pipeline. The images were generated in the same fashion as AB Pic in Figure 2. The first and second columns show the original IRAC data of HD 203030 and the median two-source PSF model, respectively, displayed with a logarithmic color scale (leftmost color bar). The third column shows the residuals left behind after only the primary PSF model is subtracted from the data. The fourth column shows the residuals left behind after the two-source PSF model is subtracted from the data. The standard deviation of the pixel values outside an $\sim 6''$ radius from the primary centroid is displayed in the lower left corner of the fourth column in units of DN s$^{-1}$. Both the third and fourth columns are displayed in a linear color scale (rightmost color bar) with the area within $\sim 6''$ of the primary centroid masked and 3σ and 5σ contours overlaid with solid and dotted lines, respectively. After subtracting the primary star PSF, a statistically significant positive residual is seen at the expected position of HD 203030 b. This residual disappears after subtracting the best-fit system PSFs, and no significant structure is left behind at the location of the companion.
5.4. Disk Fraction of Wide-orbit PMCs

Determining the presence of circumstellar disks around young star-forming region members has been a useful tool to infer the dominant formation pathway of substellar objects, as well as their planet-forming capabilities. Similarly, identifying and characterizing the disks harbored by PMCs offers a direct avenue to study planet assembly and evolution, as well as potential satellite formation.

Mass-dependent disk evolution has been observed for stars and brown dwarfs in young star-forming regions or associations through the measurement of disk fractions. Luhman et al. (2010) found the disk fraction for solar-type stars in Taurus ($\tau \sim 2$ Myr) to be $\sim 75\%$ and the disk fraction for lower-mass stars ($0.01 \sim 0.3 \, M_\odot$) to be $\sim 45\%$. For the older Upper Sco OB association ($\tau \sim 10$ Myr), Carpenter et al. (2006) found that $<1\%$ of stars more massive than K0 have circumstellar disks, while the disk fraction for K0–M5 stars is 19%. Substantial disk fractions persisting for stars $<1 \, M_\odot$ and substellar objects indicate that disk dispersal is less efficient and that planet formation timescales are longer. We can now begin to quantify whether these disk frequency trends continue for wide-orbit PMCs. For instance, Bowler et al. (2017) found that...
46% ± 14% of young (<15 Myr) substellar (<20 M_{Jup}) companions have detectable Paβ emission, indicating that accretion disks are very common around wide-orbit PMCs. Here we incorporate our findings into previous disk fraction determinations and explore their global frequency.

Combining the nine PMC systems from this work with three from Paper I, 10 belong to star-forming regions or associations with τ < 15 Myr: DH Tau, SCH J0359, FU Tau, FW Tau, 2M0441, AB Pic, CHXR 73, ROXs 42B, 1RXS J1609, and SR 12. Since 2M0441 is an interesting quadruple system comprised of close binary pairs, they should be considered separately and not incorporated into our disk fraction calculation. Thus, six of these companions have dislikable mid-infrared excesses determined from this work, suggesting a disk frequency of 67% ± 16% for PMCs with τ < 15 Myr. The two older PMC systems in our sample, GJ 504 and HD 203030, host companions that do not have dislikable mid-infrared excesses.

Previous PMC disk fraction determinations from Bowler et al. (2017) and Bryan et al. (2020) required emission line accretion signatures or UV continuum excess detections to designate a companion as a disk host, potentially underestimating their occurrence rate measurement because of the variability of these signatures or the overall faintness of the disk. Here we combine our PMC sample disk determinations with their findings, updating ROXs 42B b and SR 12 c as disk-bearing, giving a disk fraction of 56% ± 12%. This confirms that PMCs harboring circum(sub)stellar disks is very common at young ages. Even within our <15 Myr age bin, hints of PMC disk evolution may be emerging, since two of the three companions with no mid-infrared excess from this work had system ages above 5 Myr. Increasing the sample of >5 Myr PMC systems with and without circum(sub)stellar disks will ultimately confirm whether the rate at which they host disks follows that observed for star-forming region members.

6. Summary
We have used our MCMC-based PSF formalism to reanalyze Spitzer/IRAC images of nine stars known to host faint PMCs, examining higher-contrast systems and closer-in separations than our previous work to measure the mid-infrared photometry of the companions. We report new IRAC photometry for all nine primaries in our sample and eight of the companions, five of which have not been resolved in IRAC images before. We also include the expected color–color sequence of 5 Myr BT-Settl and AMES-Dusty isochrones. The disk-bearing objects are clear outliers in these particular color–color spaces, providing a criterion to say that DH Tau B, 2M0441 B, ROXs 42B b, and SR 12 c appear to host disks.

Figure 10. $K_s$–[8.0] vs. $K_s$–[3.6] color (left panel) and [3.6]–[8.0] vs. $K_s$–[3.6] color (right panel) for our sample companions, the Paper I wide-orbit PMC sample, and the young Taurus and Upper Sco brown dwarfs, depicted as in Figures 4, 8, and 9. We show both of these color spaces to take advantage of better-constrained ground-based $K$-band contrasts for some companions that were marginally detected by our pipeline at [3.6]. We also include the expected color–color sequence of 5 Myr BT-Settl and AMES-Dusty isochrones. The disk-bearing objects are clear outliers in these particular color–color spaces, providing a criterion to say that DH Tau B, 2M0441 B, ROXs 42B b, and SR 12 c appear to host disks.
wide-orbit PMCs, we optically thick, and thus easier to study in the mid-infrared.

The disks surrounding wide-orbit PMCs are compact and optically thick, and thus easier to study in the mid-infrared (Wu et al. 2017), highlights the importance of leveraging Spitzer to motivate future observations of PMC systems in the JWST era.

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References

Adame, L., Calvet, N., Luhman, K. L., et al. 2011, ApJL, 726, L3
Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357
Allard, F., Homeier, D., & Freytag, B. 2012, RSPTA, 370, 2765
Allers, K. N., Liu, M. C., Dupuy, T. J., & Cushing, M. C. 2010, ApJ, 715, 561
Alves de Oliveira, C., Moraux, E., Bouvier, J., et al. 2010, A&A, 515, A75
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, AJ, 161, 147
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, AJ, 156, 58
Bailey, V., Meshkat, T., Reiter, M., et al. 2014, ApJL, 780, L4
Barnes, T. S., Macintosh, B., Konopacky, Q. M., & Marois, C. 2011, ApJ, 733, 65
Baron, F., Artigau, É., Rameau, J., et al. 2018, AJ, 156, 137
Bell, C. P. M., Mamajek, E. E., & Nayler, T. 2015, MNRAS, 454, 593
Bonnefoy, M., Chauvin, G., Lagrange, A. M., et al. 2014, A&A, 562, A127
Bonnefoy, M., Chauvin, G., Rojo, P., et al. 2010, A&A, 512, A52
Booth, M., del Burgo, C., & Hamelryck, V. V. 2021, MNRAS, 500, 5552
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Bowler, B. P. 2016, PASP, 128, 102001
Bowler, B. P., & Bullen, L. A. 2015, ApJ, 811, L30
Bowler, B. P., Kraus, A. L., Bryan, M. L., et al. 2017, AJ, 154, 165
Bowler, B. P., Liu, M. C., Kraus, A. L., & Mann, A. W. 2014, ApJ, 784, 65
Bryan, M. L., Ginzburg, S., Chiang, E., et al. 2020, ApJ, 905, 37
Bulger, J., Patience, J., Ward-Duong, K., et al. 2014, A&A, 570, A29
Burrows, A., Marley, M., Hubbard, W. B., et al. 1997, ApJ, 491, 856
Camper, J. M., Mamajek, E. E., Hillenbrand, L. A., & Meyer, M. R. 2006, ApJL, 651, L49
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Chauvin, G., Lagrange, A. M., Zuckerman, B., et al. 2005, A&A, 438, L29
Chinchilla, P., Béjar, V. J. S., Lodieu, N., et al. 2020, A&A, 633, A152
Cieza, L., Padgett, D. L., Stapelfeldt, K. R., et al. 2007, ApJ, 657, 308
Cieza, L. A., Padgett, D. L., Allen, L. E., et al. 2009, ApJ, 696, L84
Currie, T., Duemgen, S., Debes, J., et al. 2014, ApJL, 780, L30
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, yCat, II, 246
Cutri, R. M., Wright, E. L. N., Conrow, T., et al. 2021, yCat, II, 328
Deming, D., Wilkins, A., McCullough, P., et al. 2013, ApJ, 774, 95
Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19
Durkan, S., Janson, M., & Carson, J. C. 2016, ApJ, 824, 58
Epchtein, N., de Batz, B., Capoani, L., et al. 1997, Msngr, 87, 27
Esplin, T. L., & Luhman, K. L. 2017, AJ, 154, 134
Esplin, T. L., & Luhman, K. L. 2020, AJ, 159, 282
Esplin, T. L., Luhman, K. L., & Mamajek, E. E. 2014, ApJ, 784, 126
Evans, N. J., II, Dunham, M. D., Jorgensen, J. K., et al. 2009, ApJS, 181, 321
Faherty, J. K., Riedel, A. R., Cruz, K. L., et al. 2016, ApJS, 225, 10
Fazio, G. G.,Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Filippazzo, J. C., Rice, E. L., Faherty, J., et al. 2015, ApJ, 810, 158
Fitzpatrick, E. L. 1999, PASP, 111, 63
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A11
Günnther, H. M., Cody, A. M., Covey, K. R., et al. 2014, AJ, 148, 122
Gutermuth, R. A., Megeath, S. T., Myers, P. C., et al. 2009, ApJS, 184, 18
Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, NatAs, 3, 749
Herbig, G. H. 1977, ApJ, 214, 747
Hoffman, W. F. 2005, 25 Position Model Pixel Response Functions (PRF), Simfit Report 52 Final IRAC/TM05-014, https://irsa.ipac.caltech.edu/data/SPITZER/docs/files/spitzer/simfitreport52_final.pdf
Howe, R. W., Fabivcici, C., Karavov, V. V., et al. 2000, A&A, 555, L27
Ireland, M. J., Kraus, A., Martinache, F., Law, N., & Hillenbrand, L. A. 2011, ApJ, 726, 113
Itoh, Y., Hayashi, M., Tamura, M., et al. 2005, ApJ, 620, 984
Janson, M., Quanz, S. P., Carson, J. C., et al. 2015, A&A, 574, A120
Kirkpatrick, J. D., Barman, T. S., Burgasser, A. J., et al. 2006, ApJS, 639, 1120
Kraus, A., Shkolnik, E., Liu, M. C., et al. 2014b, ApJL, 780, L4
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2008, ApJL, 689, L153
