DISKS AROUND BROWN DWARFS IN THE σ ORIONIS CLUSTER

K. L. LUHMAN,2 J. HERNÁNDEZ,3,4 J. J. DOWNES,4,5 L. HARTMANN,3 and C. BRICEÑO4

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ABSTRACT

We have performed a census of circumstellar disks around brown dwarfs in the σ Ori cluster using all available images from the Infrared Array Camera on board the Spitzer Space Telescope. To search for new low-mass cluster members with disks, we have measured photometry for all sources in the Spitzer images and have identified the ones that have red colors that are indicative of disks. We present five promising candidates, which may consist of two brown dwarfs, two stars with edge-on disks, and a low-mass protostar if they are bona fide members. Spectroscopy is needed to verify the nature of these sources. We have also used the Spitzer data to determine which of the previously known probable members of σ Ori are likely to have disks. By doing so, we measure disk fractions of ~40% and ~60% for low-mass stars and brown dwarfs, respectively. These results are similar to previous estimates of disk fractions in IC 348 and Chamaeleon I, which have roughly the same median ages as σ Ori (τ ~ 3 Myr). Finally, we note that our photometric measurements and the sources that we identify as having disks differ significantly from those of other recent studies that analyzed the same Spitzer images. For instance, previous work has suggested that the T dwarf S Ori 70 is redder than typical field dwarfs, which has been cited as possible evidence of youth and cluster membership. However, we find that this object is only slightly redder than the reddest field dwarfs in [3.6] – [4.5] (1.56 ± 0.07 vs. 0.93–1.46). We measure a larger excess in [3.6] – [5.8] (1.75 ± 0.21 vs. 0.87–1.19), but the flux at 5.8 μm may be overestimated because of the low signal-to-noise ratio of the detection. Thus, the Spitzer data do not offer strong evidence of youth and membership for this object, which is the faintest and coolest candidate member of σ Ori that has been identified to date.

Subject headings: accretion, accretion disks — planetary systems: protoplanetary disks — stars: formation — stars: low-mass, brown dwarfs — stars: pre–main-sequence

Online material: machine-readable table

1. INTRODUCTION

The lifetime of an accretion disk around a young star represents a fundamental constraint on the amount of time available for the formation of giant planets. The typical lifetimes of disks are estimated by comparing the prevalence of disks among clusters that span a range of ages (τ ~ 1–10 Myr). By measuring disk fractions as a function of stellar mass and star-forming environment as well as age, the influence of these two factors on disk lifetimes can be characterized.

Disk fractions are usually measured through infrared (IR) photometry of young clusters (λ > 3 μm) and the identification of the stars that exhibit excess emission from cool dust. Observations of this kind were first performed with the Infrared Astronomical Satellite and ground-based near-IR cameras (Kenyon & Hartmann 1995; Haisch et al. 2001) and have made rapid progress in recent years with the Spitzer Space Telescope (Werner et al. 2004). Because Spitzer is exceptionally well suited for detecting disks around members of young clusters (Allen et al. 2004; Gütermuth et al. 2004; Megeath et al. 2004; Muzerolle et al. 2004), it has been used extensively for measuring the disk fractions of stars (Megeath et al. 2005; Lada et al. 2006; Carpenter et al. 2006; Sicilia-Aguilar et al. 2006; Hernández et al. 2007a; Hernández et al. 2007b, 2008; Muench et al. 2007; Dahm & Hillenbrand 2007; Barrado y Navascués et al. 2007; Damjanov et al. 2007; Luhman et al. 2008). Spitzer’s unique sensitivity to faint IR sources has enabled measurements of disk fractions well into the substellar regime in nearby star-forming regions (d = 150–300 pc; Luhman et al. 2005, 2006, 2008; Guieu et al. 2007).

The cluster of young stars associated with the O star σ Ori A has been thoroughly searched for low-mass stars and brown dwarfs (e.g., Béjar et al. 2001; Barrado y Navascués et al. 2002; Martín et al. 2001; Zapatero Osorio et al. 2002a, 2002b). As a result, it is an attractive target for measuring the disk fraction among low-mass objects. Several recent studies have sought to do this with Spitzer. Hernández et al. (2007a) performed Spitzer imaging of most of the σ Ori cluster and measured the disk fraction as a function of mass down to ~0.1 M⊙ for a sample of ~300 probable members (see also Caballero 2006). Caballero et al. (2007) identified a sample of brown dwarf candidates from optical and near-IR data and used the Spitzer images from Hernández et al. (2007a) to estimate a disk fraction for those sources, arriving at a value of ~50%. Through further analysis of those Spitzer data, Zapatero Osorio et al. (2007) found that 6 of 12 brown dwarf candidates exhibited excess emission at 8 μm. Scholz & Jayawardhana (2008) obtained deeper Spitzer images of 18 of the faintest candidate members and reported a disk fraction of 29%. In addition to measuring disk fractions, the Spitzer data have been used to assess the youth and membership of the coolest candidate member of the cluster, the T dwarf S Ori 70 (Zapatero Osorio et al. 2002a). Zapatero Osorio et al. (2008) found that it is redder than typical field dwarfs in [3.6] – [4.5] in the images from Hernández et al. (2007a). Similarly, Scholz & Jayawardhana (2008) suggested that S Ori 70 could be anomalously red in [3.6] – [4.5] and [3.6] – [5.8] based on their deeper images, which they attributed to a disk or low surface gravity. In either case, the apparent color excesses
would comprise evidence of youth for this object, whose membership in the \( \sigma \) Ori cluster has been questioned (Martín & Zapatero Osorio 2003; Burgasser et al. 2004).

The substellar population of the \( \sigma \) Ori cluster extends down to and below the detection limits of the images that have been obtained by \textit{Spitzer}. Thus, determining whether these objects have disks is a challenging task. For instance, Zapatero Osorio et al. (2007) and Scholz & Jayawardhana (2008) disagree on whether the \textit{Spitzer} data show evidence of disks for half of the sources considered by both studies. In this paper we seek to accurately characterize the disk population among low-mass stars and brown dwarfs in \( \sigma \) Ori through an analysis of all \textit{Spitzer} images of this cluster that includes careful treatment of errors and biases. We begin by summarizing the \textit{Spitzer} observations and our data reduction methods (§2). We then use these data to search for new low-mass members of \( \sigma \) Ori that have disks (§3) and to estimate the disk fraction for the substellar members of the cluster (§4).

2. OBSERVATIONS

For our study of disks around brown dwarfs in the \( \sigma \) Ori cluster, we use images at 3.6, 4.5, 5.8, and 8.0 \( \mu \)m obtained with \textit{Spitzer}'s Infrared Array Camera (IRAC; Fazio et al. 2004). We consider all IRAC observations that have been performed in this region, which consist of images analyzed by Hernández et al. (2007a) and Scholz & Jayawardhana (2008). Henceforth in this paper we refer to these sets of data as the \textquoteleft shallow\textquoteright\ and \textquoteleft deep\textquoteright\ images, respectively. The boundaries of these images are indicated on images of \( \sigma \) Ori from the Digitized Sky Survey (DSS) in Figure 1.

The shallow IRAC images were collected on 2004 October 9 as a part of G. Fazio's IRAC Guaranteed Time Observations in \textit{Spitzer} program 37 (Hernández et al. 2007a). Each IRAC mosaic for a given filter covered an area of 0.56 deg\(^2\) (0.7'' \( \times \) 0.8''). The overlapping area between the four filters was 0.5 deg\(^2\) (0.7'' \( \times \) 0.7''). At each cell in the mosaic and in each filter, IRAC obtained three 1 s exposures and three 26.8 s exposures.

The deep IRAC imaging was executed on 2006 September 28, 2007 March 30–31, and 2007 April 3–4 through \textit{Spitzer} program 30395 (Scholz & Jayawardhana 2008). Instead of mosaics, 13 individual pointings were selected to encompass 18 candidate substellar members of \( \sigma \) Ori. Some of the images from these separate observations overlapped with each other, as shown in Figure 1. For each filter, a total area of 0.20 deg\(^2\) was imaged. An area of 0.12 deg\(^2\) was covered by all four bands. At each of the 13 pointings and in each of the 3.6, 4.5, and 5.8 \( \mu \)m filters, 12 images were obtained with exposure times of 96.8 s. For 8.0 \( \mu \)m, the number of images was doubled and the exposure times were 46.8 s.

The shallow images were processed with the \textit{Spitzer} Science Center (SSC) S14.0.0 pipeline and the deep data were processed with the S14.4.0 and S15.3.0 pipelines. We combined the images produced by the SSC pipelines into mosaics and measured photometry for all point sources appearing in them using the methods described by Luhman et al. (2008). We selected a plate scale of 0.86'' pixel\(^{-1}\) for the reduced IRAC mosaics, which is the native scale divided by \( \sqrt{2} \). We used an aperture radius of 4 pixels when measuring photometry for most sources. Smaller apertures with radii of 2 or 3 pixels were applied to sources that were near other stars, which included the candidate brown dwarfs S Ori 25, S Ori 45, S Ori 47, S Ori 54, S Ori 65, S Ori 68, S Ori J053932.4–025220, S Ori J053949.5–023130, and S Ori J053929.4–024636. We also used a small aperture of 2 pixels for the new candidate member IRAC J05384729–0235194 (see §3.2). The inner radius of the sky annulus was the same as the aperture radius in all cases. For the 4 pixel apertures at 5.8 and 8.0 \( \mu \)m, we selected relatively large widths of 6 pixels for the sky annuli to better measure the bright background emission at those wavelengths. In all other cases, the width of the annulus was 1 pixel. As noted above, some of the deep images overlapped with each other. For stars that were observed more than once during the spring observations, which spanned only a few days, we have adopted the average of the multiple measurements. Data obtained in both the fall and spring...
for a given star are presented separately. The completeness limits of the shallow images are 17.25, 17, 14.75, and 14 at 3.6, 4.5, 5.8, and 8.0 μm, respectively. The limits for the deep images are fainter by 0.75–1.25 mag. The quoted photometric errors include the Poisson errors in the source and background emission and the 2% uncertainty in the calibration of IRAC (Reach et al. 2005).

3. SEARCHING FOR NEW MEMBERS WITH DISKS

3.1. Compilation of Probable Members

In the first stage of our analysis of the disk population in σ Ori, we use our catalog of all sources detected by IRAC to search for new disk-bearing members of the cluster. We can use the IRAC data for known probable members of σ Ori to illustrate the typical colors of young stars with disks. To create a list of probable members, we begin with the sources that were considered by the other recent studies of disks in σ Ori (Hernández et al. 2007a; Caballero et al. 2007; Zapatero Osorio et al. 2007; Scholz & Jayawardhana 2008). We exclude sources from Hernández et al. (2007a) that are resolved as galaxies in images from the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007) or that have been spectroscopically classified as nonmembers by Kenyon et al. (2005) and Sacco et al. (2008). We also exclude stars that appear in the compilation of nonmembers from Caballero (2008) as well as source 668 from Hernández et al. (2007a) which is a galaxy according to spectroscopy from Caballero et al. (2008). S Ori 47 has been classified as a field dwarf rather than a cluster member based on gravity-sensitive absorption lines (McCormick et al. 2004), but we retain it in our compilation for the purposes of comparing our IRAC measurements to those from Caballero et al. (2007) and Scholz & Jayawardhana (2008).

We add stars that have been spectroscopically confirmed as members by Scholz & Eisloffel (2004), Kenyon et al. (2005), Caballero (2006), and Sacco et al. (2008), and the young stars associated with HH 446, Haro 5-22, and Haro 5-35, and σ Ori C and D. We also treat as members S Ori J053946.5–022423 and S Ori J053912.8–022453, which were identified as candidate members by Béjar et al. (2001) and exhibit evidence of disks in their IRAC colors. We present our IRAC measurements for this compilation of probable members in Table 1, which includes the source identifications from the 2MASS Point Source Catalog, Hernández et al. 2007a, Béjar et al. (1999, 2001), and the Henry Draper (HD) Catalog. We note that the evidence of membership varies significantly among the sources in Table 1, and that some of them are better characterized as possible members rather than probable members (e.g., S Ori 70; Burgasser et al. 2004).

3.2. Candidate Members with IRAC Excesses

A color-color diagram constructed from IRAC data is a convenient tool for efficiently identifying stars that exhibit IR excess emission indicative of disks. In Figure 2 we plot diagrams of [3.6] – [4.5] versus [5.8] – [8.0] for the probable members of σ Ori that are not saturated and that have photometric uncertainties less than 0.1 mag in all of the IRAC bands. The data from the shallow and deep images are shown separately. The stars in these diagrams reside near the origin or have significantly redder colors. These distinct populations are typical of young stellar populations (Hartmann et al. 2005) and represent stellar photospheres and stars with disks, respectively. In previous IRAC surveys of Taurus, Lupus, and Chamaeleon (Luhman et al. 2006, 2008; Allen et al. 2007), we have used color criteria of [3.6] – [4.5] > 0.15 and [5.8] – [8.0] > 0.3 to identify stars that might be new disk-bearing members. As shown in Figure 2, these colors also encompass most of the red population of probable members of σ Ori. Therefore, we have applied these criteria to the data in the bottom panels of Figure 2 to search for new members with disks. To further refine the sample of candidates, we have adopted an additional criterion of [4.5] – [5.8] > 0.15, which is satisfied by most stars with disks in σ Ori and in other clusters. The resulting candidates are plotted in the IRAC color-magnitude diagrams in Figure 3. Most of these sources are redder and fainter than the probable members of σ Ori, and thus are likely to be galaxies.

Seven of the candidates are in the list of uncertain members from Hernández et al. 2007(a) consisting of sources 336, 361, 395, 614, 633, 916, and 950 from that study. Based on their faint magnitudes and red colors, sources 336, 361, 916, and 950 are either low-mass protostars or galaxies. Indeed, 950 is extended in K-band images from UKIDSS, indicating that it is probably a galaxy. Among the remaining candidates that are not in Hernández et al. 2007(a) we have searched for sources that have colors similar to those of the probable members ([3.6] – [8.0] < 2), that are point sources in IRAC and UKIDSS images, and that are detected in the Z and K bands by UKIDSS. The five most promising candidate members are presented in Table 2. In addition to our IRAC data, we include photometry for these candidates measured from the 24 μm images from Hernández et al. 2007(a). Two of the candidates, 2MASS J05383446–0253514 and 2MASS J05375398–0249545, are below the cluster sequence in the diagram of V versus V – J from Hernández et al. 2007(a), which may indicate that they are seen in scattered light (e.g., edge-on disks) if they are bona fide members. The latter candidate also appears near the lower edge of the cluster sequence in V versus V – I (Sherry et al. 2004). Although it is underluminous in V versus V – J, 2MASS J05383446–0253514 does appear within the cluster sequence in I versus I – K (Caballero 2008), probably because of K-band excess emission. 2MASS J05375398–0249545 was detected in an Hα objective prism survey (Weaver & Babcock 2004), providing additional evidence that it could be a young star. Based on their IRAC magnitudes, these two candidates should have masses of ~0.5 M⊙ if they are cluster members. The candidates IRAC J05391066–0229238 and IRAC J05384459–0225433 have much fainter magnitudes that are indicative of brown dwarfs. The former underwent significant variability in all IRAC bands between the shallow and deep images. The final candidate, IRAC J05384729–0235194, exhibits very red IRAC colors that are consistent with either a protostar or a galaxy. This object is only 6″ from source 726 from Hernández et al. 2007(a) and is 1′ from σ Ori. Its close proximity to the center of the cluster and its relatively bright magnitude compared to most galaxies (see Fig. 3) tend to favor membership.

4. DISK POPULATION

4.1. Identifying the Members that have Disks

To characterize the disk population among low-mass members of the σ Ori cluster, we begin by using the IRAC data to identify the probable members that are likely to have disks. Because a disk produces greater excess emission above a stellar photosphere at longer wavelengths, we select the 5.8 and 8.0 μm bands of IRAC for measuring disk emission. To construct colors with these data that can be used for measuring excess emission, we combine them
with the IRAC data at 3.6 μm, which are available for nearly all of the probable members that are measured at 5.8 and 8.0 μm. Measuring excess emission from [3.6] – [5.8] and [3.6] – [8.0] requires estimates of the intrinsic colors for stellar photospheres and their dependence on spectral type. We can obtain these estimates by plotting the colors as a function of magnitude, which is a reasonable proxy for spectral type in a sample of stars that are roughly coeval and have low reddening ($A_V < 5$). In Figure 4 we show color-magnitude diagrams of this kind for the probable members of σ Ori. The stars that lack disk emission in the IRAC bands form a well-defined sequence near colors of zero. In both [3.6] – [5.8] and [3.6] – [8.0], the sequence becomes slightly redder with fainter magnitudes, which reflects the dependence on spectral type. For comparison, we include in Figure 4 a fit to the sequence of diskless members of the Chamaeleon I star-forming region (Luhman et al. 2008). The averages of [3.6] – [5.8] and [3.6] – [8.0] for all stars detected by IRAC toward Chamaeleon I, which are mostly background stars, are 0.05 mag greater than the average values in σ Ori, which is consistent with the difference in average extinction for the two regions. Therefore, we have reddened the sequence for Chamaeleon I accordingly in each color in Figure 4. We have also corrected for differences in ages and distances by adding 1.6 mag to the Chamaeleon I fits, which is the average difference between the two cluster sequences in [3.6] versus spectral type. After applying these color and magnitude offsets, the sequence for Chamaeleon I agrees well that of σ Ori.

To identify members that exhibit significant excess emission in [3.6] – [5.8] and [3.6] – [8.0] and thus are likely to have disks, we must properly account for errors and biases in the photometric measurements, particularly near the detection limits of the data. As mentioned in §2, our reported errors include Poisson errors and a 2% uncertainty in the calibration of IRAC. However, additional systematic errors are also present, such as location-dependent variations in the calibration. The precision with which we can measure excess emission is also limited by the intrinsic scatter of photospheric colors among cluster members at a given magnitude. Fortunately, in a well-populated sample of stars, the sum of these uncertainties is reflected in the spread in colors at a given magnitude among diskless cluster members. Therefore, we can use the widths of the sequences in Figure 4 to define color thresholds for identifying sources that have significant color excesses. For the shallow data, we have computed the standard deviation of colors in each sequence as a function of magnitude for the range of magnitudes in which the sequences are sufficiently

| IDb | Nameb | [3.6] | [4.5] | [5.8] | [8.0] | Date       |
|-----|--------|------|------|------|------|-----------|
| 2MASS J05371537–0230534............. | ... | Sat  | Sat  | 10.69 ± 0.03 | 10.79 ± 0.03 | 2006 Sep 28 |
| 2MASS J05371869–0240218............. | SO 9 | 11.01 ± 0.02 | 10.98 ± 0.02 | 10.81 ± 0.03 | 10.94 ± 0.03 | 2004 Oct 9 |
| 2MASS J05372036–0232465............. | SO 27 | 13.02 ± 0.02 | 12.95 ± 0.02 | 12.90 ± 0.04 | 13.03 ± 0.04 | 2004 Oct 9 |
| IRAC J05372470–0231523............. | S Ori 66 | 17.43 ± 0.06 | 16.82 ± 0.08 | ... | ... | 2004 Oct 9 |
| IRAC J05372587–0234320............. | S Ori 55 | 16.49 ± 0.04 | 16.23 ± 0.05 | ... | ... | 2004 Oct 9 |
| 2MASS J05372761–0257100............. | ... | Out  | 16.44 ± 0.02 | 16.14 ± 0.02 | 15.93 ± 0.07 | 15.51 ± 0.11 | 2006 Sep 28 |
| 2MASS J05372806–0236065............. | SO 59 | 12.66 ± 0.02 | 12.58 ± 0.02 | 12.51 ± 0.03 | 12.60 ± 0.04 | 2004 Oct 9 |
| 2MASS J05372831–0224182............. | SO 60 | 12.72 ± 0.02 | 12.53 ± 0.02 | 12.63 ± 0.03 | 12.59 ± 0.03 | 2006 Sep 28 |
| 2MASS J05373094–0223427............. | SO 73 | 12.88 ± 0.02 | 12.81 ± 0.02 | 12.79 ± 0.03 | 12.83 ± 0.04 | 2004 Oct 9 |
| 2MASS J05373153–0224269............. | SO 77 | 10.99 ± 0.02 | 10.96 ± 0.02 | 10.93 ± 0.03 | 10.95 ± 0.03 | 2006 Sep 28 |
populated ($m_{\text{J}} < 14.25$). Stars that are redder than the $2\sigma$ thresholds are classified as having disks. Because the sequences in the deep images contain fewer stars, we adopt for those data the thresholds from the shallow images after shifting them to fainter magnitudes by 0.75 mag, which is the difference in completeness limits between the shallow and deep $m_{[8.0]}$ data. The classifications produced by $m_{[3.6]} - m_{[5.8]}$ and $m_{[3.6]} - m_{[8.0]}$ agree for 99.5% of the sources. For the remaining 0.5% of the sample, we adopt the classifications from $m_{[3.6]} - m_{[8.0]}$ since this color is more sensitive to disk emission. Our classifications apply only to inner disks that are capable of producing emission at 8 $\mu$m. A few of the stars that exhibit photospheric colors in the IRAC bands may have disks with inner holes that produce excess emission only at longer wavelengths.

At the faintest magnitudes in Figure 4, the photospheric sequences are too sparsely populated for reliable measurements of...
Based on our classifications in Table 3, S Ori 60 is the faintest object in σ Ori that exhibits significant evidence of a disk. If we adopt a distance modulus of 7.65 (± 0.2) and photometry from UKIDSS,7 then S Ori 60 has $M_J = 11.3$, $M_H = 10.5$, and $M_K = 9.9$. In comparison, the least luminous disk-bearing brown dwarf found in other young clusters is Cha J11070768−7626326, which has slightly fainter magnitudes of $M_J = 11.56$, $M_H = 10.75$, and $M_K = 9.86$ (Luhman et al. 2008). The faintest σ Ori source that has marginal excess emission is S Ori 66. It is ~0.8 mag fainter than S Ori 60 according to UKIDSS.

### 4.2. Disk Fraction

We now use the IRAC classifications derived in the previous section to compute the disk fraction among the probable members of σ Ori. We wish to measure the dependence of this disk fraction on stellar mass. Ideally, the masses would be estimated by combining spectral types and luminosities with theoretical evolutionary models. However, spectral classifications are unavailable for many of the probable members of σ Ori. Therefore, we adopt $M_J$ as a proxy for stellar mass, as done by Hernández et al. (2007a). We adopt the $J$ measurements from 2MASS and UKIDSS when possible. For the few sources that do not have photometric errors less than 0.2 mag in these surveys, we use the $J$ data from Bejar et al. (2001), Martin et al. (2001), Caballero et al. (2007), and Zapatero Osorio et al. (2008). We assume that the probable members of σ Ori have negligible extinctions at $J$. For comparison to σ Ori, we also consider other clusters in which disk fractions have been measured for both stars and brown dwarfs using IRAC data. Therefore, we have recomputed the disk fractions for IC 348 and

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7 We adopt the UKIDSS magnitudes measured with an aperture radius of 1″ (Dye et al. 2006).
Chamaeleon I from Muench et al. (2007) and Luhman et al. (2008) as a function of $M_J$ using the $J$-band data from 2MASS and Luhman et al. (2003, 2007) and extinction estimates from Muench et al. (2007) and Luhman (2007). We adopt distance moduli of 7.5 and 6.05 for IC 348 and Chamaeleon I, respectively (Herbig 1998; Luhman 2008). To enable a meaningful comparison of the disk fractions of these clusters, $M_J$ must be corrected for differences in age so that a given value of $M_J$ corresponds to the same mass in each cluster. For the adopted distances, IC 348 and Chamaeleon I do have similar ages (Luhman 2007). In order to compare the disk fraction in $\sigma$ Ori to those of the other two clusters in a manner that is as age-independent as possible, we adopt a distance modulus that is the sum of the distance modulus for Chamaeleon I and the difference of the apparent magnitudes as a function of spectral type between Chamaeleon I and $\sigma$ Ori ($\S$ 4.1), corresponding to a value of 7.65 (340 pc). In other words, we are adopting a distance for $\sigma$ Ori that gives it the same age as IC 348 and Chamaeleon I. Similar distances have been adopted in some previous studies of $\sigma$ Ori (Béjar et al. 2001; Oliveira et al. 2002) while values near 440 pc have been used elsewhere (Sherry et al. 2004; Hernández et al. 2007a). The larger distances would imply that $\sigma$ Ori is younger than IC 348 and Chamaeleon I.

![Spitzer color-magnitude diagrams for probable members of $\sigma$ Ori in the shallow and deep images of the cluster (top and bottom). For comparison, we show a fit to the sequence of diskless members of Chamaeleon I after adjusting it to the distance of $\sigma$ Ori (left solid lines). This fit is connected to the typical colors of T6 dwarfs for the magnitude of the T dwarf S Ori 70 (dashed lines). The 2 $\sigma$ scatter of the $\sigma$ Ori sequence about this fit represents our adopted threshold for identifying sources that exhibit significant color excesses at brighter magnitudes ($[3.6] < 14.5$, right solid lines). At the fainter levels encompassing the brown dwarf candidates that were analyzed by Zapatero Osorio et al. (2007) and Scholz & Jayawardhana (2008) we have identified color excesses by considering the Poisson uncertainties in the colors (error bars), the size of the scatter in colors, and the general tendency to overestimate fluxes for sources with very low S/Ns ($\S$ 4.1). The brown dwarf candidates that we classify as "disk?" or "disk" in Table 3 are indicated (triangles and circles).]
As a result, a star with an edge-on disk can appear at a magnitude brighter than a given spectral type. In addition, the near-IR magnitude of stars with edge-on disks are typically much fainter than a given spectral type. In fact, in the faintest bin of the disk fraction for \( \sigma \) Ori (\( M_J = 10-12 \)), two objects have tentative detections of excesses and two others are too faint for classification. For the purposes of this work, we assume that disks are present in the former but not the latter.

The disk fractions versus \( M_J \) for \( \sigma \) Ori, IC 348, and Chamaeleon I are listed in Table 4 and are plotted in Figure 5. For \( M_J > 4 \) (\( M \leq 0.5 M_J \)), the three regions exhibit similar disk fractions. In each case, \( \sim 40\% \) of low-mass stars (\( 0.08-0.5 M_J \)) and \( \sim 50\% - 60\% \) of brown dwarfs (\( 0.01-0.08 M_J \)) have disks. Meanwhile, the disk fractions at \( M_J < 4 \) range from \( \sim 30\% \) in \( \sigma \) Ori to \( \sim 65\% \) in Chamaeleon I. Since these clusters have similar ages, these data suggest that the lifetimes of disks around solar-mass stars increase from \( \sigma \) Ori to IC 348 to Chamaeleon I.

We note a few caveats regarding the disk fractions in Figure 5. A given \( M_J \) magnitude corresponds to a larger range of stellar masses than a given spectral type. In addition, the near-IR magnitudes of stars with edge-on disks are typically much fainter than most other cluster members at the same spectral type and color. As a result, a star with an edge-on disk can appear at a magnitude bin corresponding to substellar masses in a plot of disk fraction versus \( M_J \). Meanwhile, stars with disks can have systematically brighter \( J \) magnitudes than diskless stars because of disk emission in this band, which would cause these sources to appear in magnitude bins that are too bright. Because of these effects, the disk fractions versus \( M_J \) in Figure 5 are smoothed versions of the disk fractions versus mass or spectral type. For instance, the difference between the disk fractions of Chamaeleon I and IC 348 at high masses is more pronounced when they are plotted as a function of spectral type or mass (Luhman et al. 2008). Finally, unlike the samples for IC 348 and Chamaeleon I, some of the sources included in the disk fraction for \( \sigma \) Ori lack definitive evidence of membership. Thus, our estimate of the disk fraction for \( \sigma \) Ori may be underestimated. Indeed, Sacco et al. (2008) obtained spectra of 23% of the probable members identified by Hernández et al. (2007a) and found a field star contamination rate of 20%. Because of the spectral classifications that are now available from Sacco et al. (2008) the contamination of our current sample of probable members should be lower.

4.3. Comparison to Previous Studies

As discussed in § 1, five previous studies have used IRAC data to investigate the disk population among brown dwarfs in the \( \sigma \) Ori

### Table 3

| Name          | IRAC Classifications | Candidate Brown Dwarfs in \( \sigma \) Ori |
|---------------|----------------------|--------------------------------------------------|
| S Ori 47\(^d\) | No disk              | Disk                                              |
| S Ori 50      | No disk              | Disk                                              |
| S Ori 51      | No disk              | Disk                                              |
| S Ori 53      | ? (too faint)        | Disk                                              |
| S Ori 54      | ...                  | Disk                                              |
| S Ori 55      | ...                  | Disk                                              |
| S Ori 56      | ...                  | Disk                                              |
| S Ori 58      | ...                  | Disk                                              |
| S Ori 60      | ? (too faint)        | Disk                                              |
| S Ori 62      | ...                  | Disk                                              |
| S Ori 63      | ...                  | Disk                                              |
| S Ori 65      | ...                  | Disk                                              |
| S Ori 66      | ...                  | Disk                                              |
| S Ori 67      | ...                  | Disk                                              |
| S Ori 68      | ...                  | Disk                                              |
| S Ori 69      | ...                  | Disk                                              |
| S Ori 70      | ...                  | Disk or low gravity?                              |
| S Ori 71      | Disk                 | Disk                                              |
| S Ori J053858.6–025228 | No disk     | Disk                                              |
| S Ori J053949.5–023130 | ? (too faint) | Disk or low gravity?                              |
| S Ori J053956.8–025315 | ? (too faint) | Disk or low gravity?                              |

\(^a\) Caballero et al. (2007).
\(^b\) Zapatero Osorio et al. (2007).
\(^c\) Scholz & Jayawardhana (2008).
\(^d\) Spectroscopically classified as a field dwarf rather than a cluster member (McGovern et al. 2004).

### Table 4

| Disk Fractions |
|----------------|
| \( M_J \)     |
| Chamaeleon I   |
| IC 348         |
| \( \sigma \) Ori |

| \( 0-2 \)       | 7/11 = 0.64 – 0.12 | 7/19 = 0.37 – 0.12 | 4/14 = 0.29 – 0.14 |
| \( 2-4 \)       | 23/35 = 0.66 – 0.09 | 19/43 = 0.44 – 0.07 | 20/71 = 0.28 – 0.06 |
| \( 4-6 \)       | 43/91 = 0.47 – 0.05 | 57/139 = 0.41 – 0.04 | 62/164 = 0.38 – 0.04 |
| \( 6-8 \)       | 21/44 = 0.48 – 0.06 | 34/71 = 0.48 – 0.06 | 33/87 = 0.38 – 0.06 |
| \( 8-10 \)      | 8/12 = 0.67 – 0.10 | 11/19 = 0.58 – 0.11 | 7/11 = 0.64 – 0.15 |
| \( 10-12 \)     | 2/6 = 0.33 – 0.12 | ... | 5/10 = 0.50 – 0.14 |

Note.—The statistical errors in the disk fractions are computed in the manner described by Burgasser et al. (2003).
Most of the measurements from Caballero et al. (2007) and Zapatero Osorio et al. (2007) agree with our data within their quoted errors, but not within our errors. Roughly half of the measurements in common between this work and Scholz & Jayawardhana (2008) differ by an amount that is larger than the errors from either study. Our formal errors are much lower than the ones reported by Caballero et al. (2007), Zapatero Osorio et al. (2007), and Scholz & Jayawardhana (2008) but this in itself does not demonstrate that our measurements are truly more accurate. To test the relative accuracies of these sets of photometry, we compare them in color–color diagrams in Figure 8. For both the shallow and deep images, our colors are more tightly clustered into two groups (diskless and disk-bearing stars) than the colors in the other studies, which suggests that our colors indeed have lower errors. A similar result was found by Luhman et al. (2008) in a comparison of their IRAC data to measurements from Damjanov et al. (2007) in Chamaeleon I.

We now compare our classifications of the IRAC data in \( \sigma \) Ori to those derived in previous work. The classifications from Caballero et al. (2007) and our earlier survey of \( \sigma \) Ori (Hernández et al. 2007a) agreed for the 25 sources that were considered by both studies, which were predominantly low-mass stars. The samples from Zapatero Osorio et al. (2007) and Scholz & Jayawardhana (2008) consisted of fainter brown dwarf candidates. These sources are listed in Table 3, where we compare the classifications from Caballero et al. (2007), Zapatero Osorio et al. (2007), Scholz & Jayawardhana (2008), and this work. The four studies differ significantly in the sources that are found to exhibit excess emission from disks. Zapatero Osorio et al. (2007) reported excess emission at 5.8 or 8.0 \( \mu \)m in the shallow images for seven candidate brown dwarfs. However, we find that six of these sources have S/Ns in those data that are too low for useful photometry, as illustrated in Figure 9. Four of these six candidates are within the deep images from Scholz & Jayawardhana (2008) which provide much better detections. Using the deep data, we measure significant excess emission for \( \sigma \) Ori 56 and \( \sigma \) Ori 60 and marginal excesses for \( \sigma \) Ori 55 and \( \sigma \) Ori 58. Scholz & Jayawardhana (2008) derived the same classifications for \( \sigma \) Ori 58 and \( \sigma \) Ori 60, but concluded that the other two sources lack disks. The seventh object from Zapatero Osorio et al. (2007), \( \sigma \) Ori 54, is too close (\( 5^\circ \)) to a red galaxy for an accurate measurement at 8 \( \mu \)m using either the shallow or deep images. We do not find excess emission for this source at 5.8 \( \mu \)m, where the contrast relative to the galaxy is more favorable.

The three remaining sources in Table 3 that have discrepant classifications are \( \sigma \) Ori 65, \( \sigma \) Ori 70, and \( \sigma \) Ori J053949.5–023130. Scholz & Jayawardhana (2008) found significant excess emission for \( \sigma \) Ori 65 and \( \sigma \) Ori J053949.5–023130 at 5.8 and 8.0 \( \mu \)m from their deep images. However, our measurements at 5.8 \( \mu \)m do not exhibit excesses and the detections at 8.0 \( \mu \)m are too weak to be useful (see Fig. 10). Although \( \sigma \) Ori 65 has \([3.6] – [8.0] \approx 1\) in our data, which implies an excess, the photometry at 8.0 \( \mu \)m has an error of 0.4 mag, corresponding to S/N \~ 3. As discussed in \S 4.1, measurements with such low values of S/N are subject to flux overestimation. To illustrate that color excesses with such large errors are not significant, we note that another source with comparable errors at 8.0 \( \mu \)m, \( \sigma \) Ori 50, has a nominal color that is unphysical for stellar sources (\([3.6] – [8.0] \approx 0.9\)). Finally, based on their deep images, Scholz & Jayawardhana (2008) suggested that \( \sigma \) Ori 70 may have excesses in [3.6] – [4.5] and [3.6] – [5.8] relative to typical colors of T6 dwarfs, which they attributed to either a disk or low surface gravity and cited as possible evidence of youth and membership in the \( \sigma \) Ori cluster. Zapatero Osorio et al. (2008) arrived at a similar
Fig. 6.— Comparison of the IRAC magnitudes from Caballero et al. (2007) and Zapatero Osorio et al. (2007) to our measurements of the same objects. Both sets of data were measured from the shallow images of the σ Ori cluster. The errors reported by Caballero et al. (2007) and Zapatero Osorio et al. (2007) are indicated. The formal errors for our measurements range between 0.02–0.12 mag.
Fig. 7.—Comparison of the IRAC magnitudes from Scholz & Jayawardhana (2008) to our measurements of the same objects. Both sets of data were measured from the deep images of the σ Ori cluster. The errors reported by Scholz & Jayawardhana (2008) are indicated. The formal errors for our measurements are smaller by factors of 2–3 in most cases.
Fig. 8.—Comparison of the IRAC colors from Caballero et al. (2007), Zapatero Osorio et al. (2007), and Scholz & Jayawardhana (2008) to our measurements of the same objects from the same images considered in those studies, which are the shallow and deep images of the σ Ori cluster (left and right).
Fig. 9.—IRAC images at 5.8 and 8.0 μm (odd and even columns) centered on the positions of six of the candidate brown dwarfs in σ Ori that were discussed by Zapatero Osorio et al. (2007). Based on the shallow images, Zapatero Osorio et al. (2007) reported detections of excess emission that indicated the presence of disks for all of these sources. However, we find that the S/Ns of these data are insufficient for reliably detecting excess emission. Deep images do show significant excesses for S Ori 56 and S Ori 60 and marginal excesses for S Ori 55 and S Ori 58 (Fig. 4). Each image has a size of 30″ × 30″ and is displayed linearly from $F - 2 \sigma$ to $F + 5 \sigma$, where $F$ and $\sigma$ are the median and standard deviation of the background emission, respectively.
5. CONCLUSIONS

We have investigated the disk population among stars and brown dwarfs in the σ Ori cluster using mid-IR images obtained with IRAC on board the Spitzer Space Telescope. For this study, we have employed all available IRAC data for σ Ori, which consist of shallow images (80.4 s) from Hernández et al. (2007a) and deep images (~1100 s) from Scholz & Jayawardhana (2008). We measured photometry for all sources detected in these images and searched the resulting data for new members of the cluster based on the red colors that are expected from stars with disks. The five most promising candidates have colors and magnitudes that are suggestive of edge-on disks, brown dwarfs, and a low-mass protostar. We then examined the IRAC colors for ~300 probable cluster members found in previous studies and identified the ones that are likely to have disks. In doing so, we have attempted to fully account for the errors and biases in the photometry of the brown dwarf candidates (e.g., flux overestimation at low S/N; Beichman et al. 2003), some of which are near the detection limits of the IRAC data. S Ori 60 is the faintest candidate member of σ Ori that exhibits significant IR excess emission. This object is comparable in luminosity to the faintest brown dwarf that shows evidence of a disk in other star-forming regions (Luhman et al. 2008). Using our classifications of the IRAC data, we computed the disk fraction as a function of $M_\star$, which acts as a proxy for stellar mass. The disk fractions for low-mass stars (0.08–0.5 $M_\odot$) and brown dwarfs (0.01–0.08 $M_\odot$) are ~40% and ~60%, respectively, which are similar to the disk fractions derived from IRAC surveys of two other clusters near the same age, IC 348 and Chamaeleon I (Muench et al. 2007; Luhman et al. 2008).

Although our disk fraction for brown dwarfs in σ Ori is similar to other estimates based on the IRAC data considered here (Caballero et al. 2007; Zapatero Osorio et al. 2007; Scholz & Jayawardhana 2008), our photometric measurements and our classifications of the IRAC colors (disk vs. no disk) differ significantly from those in previous studies. For instance, Zapatero Osorio et al. (2008) and Scholz & Jayawardhana (2008) suggested that the T dwarf S Ori 70 may exhibit color excesses in [3.6] – [4.5] and [3.6] – [5.8] relative to field dwarfs at the same spectral type. They cited these nonstandard colors as possible evidence of youth, which would indicate that S Ori 70 is a cluster member rather than a field dwarf. However, we have found that this object is not significantly redder in [3.6] – [4.5] than field dwarfs and that its S/N may be too low at 5.8 μm for a useful measurement of [3.6] – [5.8]. Therefore, we conclude that the IRAC data do not provide firm constraints on the membership of S Ori 70.

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