NEW LOW-MASS STARS AND BROWN DWARFS WITH DISKS IN LUPUS

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ABSTRACT

Using the Infrared Array Camera and the Multiband Imaging Photometer aboard the Spitzer Space Telescope, we have obtained images of the Lupus 3 star-forming cloud at 3.6, 4.5, 5.8, 8.0, and 24 μm. We present photometry in these bands for the 41 previously known members that are in our images. In addition, we have identified 19 possible new members of the cloud based on red 3.6–8.0 μm colors that are indicative of circumstellar disks. We have performed optical spectroscopy on six of these candidates, all of which are confirmed as young low-mass members of Lupus 3. The spectral types of these new members range from M4.75 to M8, corresponding to masses of 0.2–0.03 M☉ for ages of ~1 Myr according to theoretical evolutionary models. We also present optical spectroscopy of a candidate disk-bearing object in the vicinity of the Lupus 1 cloud, 2M 1541–3345, which Jayawardhana & Ivanov recently classified as a young brown dwarf (M ~ 0.03 M☉) with a spectral type of M8. In contrast to their results, we measure an earlier spectral type of M5.75 ± 0.25 for this object, indicating that it is probably a low-mass star (M ~ 0.1 M☉). In fact, according to its gravity-sensitive absorption lines and its luminosity, 2M 1541–3345 is older than members of the Lupus clouds (τ ~ 1 Myr) and instead is probably a more evolved pre–main-sequence star that is not directly related to the current generation of star formation in Lupus.

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

1. INTRODUCTION

Young embedded clusters are the primary laboratories for studies of the formation of stars and brown dwarfs. The dark clouds in the constellation of Lupus are potentially attractive sites for such studies because of their proximity to the Sun (d = 140–200 pc; F. Comerón 2007, in preparation). Molecular and extinction maps have shown that the clouds extend across ~20° of the sky (Cambrésy 1999; Tachihara et al. 2001) and the richest cloud in the complex in terms of ongoing star formation is Lupus 3. It has a fairly high surface density of young stars, with a peak value of ~200 stars pc−2. The stellar population within Lupus 3 is a good example of a nearby, well-defined small system embedded in a filamentary dark cloud (Nakajima et al. 2003; Teixeira et al. 2005; Tachihara et al. 2007).

Recent efforts have been made at extending the census of the stellar population in Lupus 3 to low-mass stars and brown dwarfs (Comerón et al. 2003; López Martí et al. 2005). Like their more massive counterparts, low-mass disk-bearing members of embedded clusters can be identified by the presence of mid-infrared (IR) emission above that expected from a photosphere alone (Comerón et al. 1998). However, conducting a wide-field mid-IR survey for faint, low-mass objects is technologically challenging. For instance, the Infrared Astronomical Satellite was capable of mapping large fields, but it lacked the sensitivity for reliably reaching substellar members of nearby star-forming regions. With its combination of wide field of view and excellent sensitivity, the Spitzer Space Telescope (Werner et al. 2004) has made it possible to search for low-mass stars and brown dwarfs in young embedded clusters such as Lupus based on the presence of circumstellar disks (Allen et al. 2004; Megeath et al. 2004).

In this paper we present the results of a search for low-mass disk-bearing members of the most heavily populated cloud in the Lupus complex, Lupus 3, using Spitzer’s Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). We begin by describing the mid-IR images of Lupus 3 obtained with these instruments (§ 2) and the identification of candidate low-mass disk-bearing objects with these data (§ 3). We then use optical spectroscopy to measure spectral types for a sample of these candidates and to determine if they are young members of Lupus (§ 4). In addition to the Lupus 3 targets, we include in our spectroscopic sample a candidate brown dwarf near Lupus 1 from Allers et al. (2006). We conclude by summarizing the properties of the new low-mass stars and brown dwarfs found in this work (§ 5).

2. INFRARED IMAGES

2.1. Observations

As a part of the Guaranteed Time Observations (GTO) of the IRAC instrument team, we obtained images of the Lupus 3 cloud at 3.6, 4.5, 5.8, and 8.0 μm with IRAC and at 24 μm with MIPS on the Spitzer Space Telescope. The IRAC observations were performed on 2004 March 7 (UT) and consisted of a mosaic of 6 × 7 pointings, with each pointing separated by 298″ and aligned with the array axes. The mosaic was centered on α = 16°08′56″, δ = −39°08′33″ (J2000.0). Images were obtained in the high dynamic range (HDR) mode, which consisted of one 0.4 s exposure and one 10.4 s exposure. This mosaic was observed twice consecutively. The MIPS observations were performed on 2004 February 23 (UT) and were centered on the same position as the IRAC mosaic. We operated MIPS in the scan mode with the medium scan rate and individual exposure times of 3.67 s. We performed six scans, each with a length of 55′.

We also make use of an IRAC map that was obtained by the Cores 2 Disks (c2d) Spitzer Legacy Team (Evans et al. 2003) on 2004 September 4 (UT), which has the same location and dimensions as the GTO mosaic. Because the dates of these two maps are

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separated by 6 months, the roll angle of the telescope differed by 180° between them. As a result, the combination of the two maps provides full coverage in all four IRAC bands for the area imaged. Unlike the GTO mosaic, the c2d data were not taken in HDR mode. Instead, they consisted of two 10.4 s exposures at each pointing in a map that was performed once.

2.2. Data Reduction

Fig. 1.—False-color image of the Lupus 3 star-forming region consisting of Spitzer data at 3.6, 8.0, and 24 μm. Previously known members (circles) and new members found in this work (crosses) are indicated. The unmarked red source to the east of the central cluster is IRAS 16059–3857. The size of the image is 40′ × 28′.

The IRAC data were processed with the Spitzer Science Center (SSC) S13.2.0 pipeline, the MOPEX software from the SSC, and the IRACproc software (Schuster et al. 2006). For each of the four IRAC bands, we produced one 40′ × 28′ mosaic consisting...
of a combination of the GTO and c2d data at 10.4 s and one 35′ × 28′ mosaic consisting of the GTO 0.4 s data. The MIPS data at 24 μm were reduced with MOPEX. The resulting mosaic had dimensions of 55′ × 30′.5 and a total exposure time of 50 s at a given position. A false-color image composed of the mosiacs at 3.6, 8.0, and 24 μm is shown in Figure 1.

We used standard IRAF photometry routines in the apphot package to identify all point sources in the IRAC and MIPS mosaics and to measure photometry for them. For the IRAC data, we adopted zero-point magnitudes (ZPs) of 19.670, 18.921, 16.855, 17.394 in the 3.6, 4.5, 5.8 and 8 μm bands, where \( M = -2.5 \log \text{(DN s}^{-1}) + ZP \) (Reach et al. 2005). For most IRAC sources, we measured photometry using a radius of 4 pixels for the aperture and inner and outer radii of 4 and 5 pixels, respectively, for the sky annulus. We used a smaller aperture radius of 2.5 pixels for Sz 108 A and B. The plate scale of the reduced IRAC mosaic was 0.86′′ pixel \(^{-1}\). To adjust these measurements to the apertures used by Reach et al. (2005) we applied aperture corrections of 0.18, 0.16, 0.22, and 0.48 mag for 3.6, 4.5, 5.8 and 8 μm, respectively, which we measured from bright stars in these data. For MIPS sources, we measured photometry with a radius of 3 pixels for the aperture and inner and outer radii of 3 and 4 pixels, respectively, for the sky annulus. The plate scale of the reduced MIPS mosaic was 2.45′′ pixel \(^{-1}\). For the MIPS 24 μm data we applied a flux calibration of 0.0067 mJY (DN s\(^{-1}\)) and an aperture correction of 0.6 mag, which were provided by the MIPS GTO team (D. Trilling 2006, private communication).

### 3. SELECTION OF CANDIDATE MEMBERS OF LUPUS

We can identify possible new disk-bearing members of Lupus 3 by examining the colors of sources detected in the IRAC and MIPS images (Allan et al. 2004; Megaeath et al. 2004; Hartmann et al. 2005b; Luhan et al. 2006). To do this, we first consider the colors of previously known members of Lupus 3. From Comerón et al. (2003), F. Comerón (2007, in preparation), and Krautter et al. (1997) we have compiled a list of 41 previously known members. Our
IRAC and MIPS measurements for these objects are given in Table 1. In a diagram of $\text{[3.6]} - \text{[4.5]}$ versus $\text{[5.8]} - \text{[8.0]}$ in Figure 2, we plot the 35 previously known members that are not saturated and that have photometric uncertainties less than 0.1 mag in all of the IRAC bands. The IRAC colors of the known members exhibit either neutral colors consistent with stellar photospheres or significantly redder colors that indicate the presence of a circumstellar disk, which is the same behavior that has been observed in IRAC data for young stars in other star-forming regions like Taurus (Hartmann et al. 2005b). As in the survey for new members of Taurus by Luhman et al. (2006), we adopt color criteria of $\text{[3.6]} - \text{[4.5]} > 0.15$ and $\text{[5.8]} - \text{[8.0]} > 0.3$ for selecting candidate objects with disks in Lupus 3. We use these criteria because they encompass nearly all class I and II members of Taurus (Hartmann et al. 2005b). We applied these criteria to the $\sim 1300$ sources with photometric errors less than 0.1 mag in all four IRAC bands, which are shown in Figure 2. This process produced 19 candidates. Most of these candidates are fainter than the previously known members of Lupus 3, as illustrated in the diagram of $\text{[3.6]} - \text{[3.6]}$ versus $\text{[3.6]} - \text{[8.0]}$ in Figure 3. Six candidates are classified spectroscopically in Table 2. The IRAC and MIPS data for the six spectroscopic targets and the remaining 13 candidates that lack spectroscopy are listed in Tables 2 and 3, respectively. Five of the 19 candidates were also identified as possible members by López Martí et al. (2005) through optical and near-IR photometry, and seven of the candidates were detected in X-rays by Gondoin (2006), as noted in Tables 2 and 3.

4. INFRARED SPECTROSCOPY OF CANDIDATES

4.1. Observations

We performed optical spectroscopy on six of the 19 candidate members of Lupus 3 that were identified in the previous section using the Low Dispersion Survey Spectrograph (LDSS-3) on the Magellan II Telescope during the nights of 2006 February 9 and 11. We observed 2MASS 16081497$-3857145$, 16085953$-3856275$, and 16073773$-3921388$ during the first night and 2MASS 16080017$-3902595$, 16083733$-3923109$, and 16085373$-3914367$ during the second night. On the first night, we also observed an additional target, source 18 from Allers et al. (2006), which is also known as 2MASS J15414081$-3345188$ (hereafter 2M 1541$-3345$). This object was identified as a candidate low-mass disk-bearing member of Lupus 1 in a similar manner as our candidates (Allers et al. 2006). The procedures for the collection and reduction of the optical spectra were similar.
to those described by Luhman (2004b). The spectra obtained on the first and second nights exhibit wavelength coverages of 0.68–1.1 and 0.58–1 μm and resolutions of 6 and 4 Å, respectively. The spectra of the six candidates in Lupus 3 are shown in Figures 4 and the spectrum of 2M 1541—3345 is shown in Figures 5 and 6.

4.2. Spectral Classification

To assess the membership of the candidate members of Lupus in our spectroscopic sample and to measure their spectral types, we applied the optical classification methods developed in our previous studies of star-forming regions (Luhman 1999b; Luhman et al. 2003). The membership diagnostics included emission lines, IR excess emission, gravity-sensitive spectral features (Na i, K i, Fe H), and reddening. We also examined the Li absorption line at 6707 Å for the one spectrum that exhibited sufficient signal-to-noise ratio at this wavelength. Based on these diagnostics, we find that all of the candidates in our spectroscopic sample are members of the Lupus 3 cloud. The evidence of membership for each object is summarized in Table 2. For these young objects, spectral types were measured through comparison to the averages of spectra for standard dwarfs and giants, which is the method that has been employed for most previous optical spectral types of low-mass members of star-forming regions (Luhman 1999). During this process, reddening is applied to the dwarf/giant spectrum at each spectral type to optimize the match to the target spectrum. Thus, both spectral types and extinctions were produced. These reddening estimates were fine-tuned by comparing each spectrum to previously known young objects with negligible extinction (Luhman 2004a). The resulting spectral types for the six new members are listed in Table 2. The extinctions are indicated in Figure 4, where they are quantified by the color excess between 0.6 and 0.9 μm [E(0.6–0.9)], as done by Luhman (2004a). The positions of these new members and the previously known members of Lupus 3 are indicated in Figure 1.

As with the Lupus 3 candidates, we classified the spectrum of 2M 1541—3345 through comparison to the averages of spectra of dwarfs and giants, arriving at a spectral type of M5.75 ± 0.25 and an extinction of A_V = 0 with an upper limit of A_V < 0.5. Through analysis of its spectral energy distribution, Allers et al. (2006) also estimated A_V ~ 0 for 2M 1541—3345. The close agreement between its spectrum and the unreddened average of a dwarf and giant at M5.75 is demonstrated in Figure 5. In comparison, Jayawardhana & Ivanov (2006) reported a spectral type

| ID       | J - H   | H - K   | K   | [3.6]  | [4.5]  | [5.8]  | [8.0]  | [24]  |
|----------|---------|---------|-----|--------|--------|--------|--------|-------|
| 2MASS J16075475—3915446               | 1.09    | 1.66    | 14.45 | 12.54 ± 0.03 | 11.74 ± 0.03 | 11.14 ± 0.03 | 10.64 ± 0.04 | 7.23 ± 0.05 |
| 2MASS J16080175—3912316               | 1.34    | 0.81    | 14.25 | 13.43 ± 0.03 | 13.07 ± 0.04 | 12.62 ± 0.05 | 11.90 ± 0.08 | 8.39 ± 0.10 |
| 2MASS J16080618—3912225               | 1.50    | 0.86    | 7.67  | 6.81 ± 0.03  | 6.51 ± 0.03  | 6.28 ± 0.03  | 5.75 ± 0.03  | 4.06 ± 0.03 |
| IRAC J16082818—3913098               | ....    | ....    | 12.07 ± 0.03 | 11.90 ± 0.03 | 11.64 ± 0.03 | 10.78 ± 0.04 | 7.85 ± 0.06 |
| IRAC J16083010—3922592               | ....    | ....    | 15.18 ± 0.05 | 14.66 ± 0.04 | 13.88 ± 0.08 | 12.69 ± 0.09 | 8.79 ± 0.09 |
| IRAC J16083110—3956000               | ....    | ....    | 15.06 ± 0.05 | 14.26 ± 0.04 | 13.37 ± 0.06 | 12.79 ± 0.09 | 8.99 ± 0.12 |
| IRAC J16086799—39302074             | ....    | ....    | 14.69 ± 0.04 | 14.02 ± 0.04 | 13.29 ± 0.06 | 12.27 ± 0.08 | 8.43 ± 0.11 |
| 2MASS J16084747—3905087             | 1.08    | 0.54    | 14.83 | 12.86 ± 0.03 | 12.19 ± 0.03 | 11.54 ± 0.04 | 10.80 ± 0.09 | 7.21 ± 0.22 |
| 2MASS J16085324—3914401             | 1.04    | 0.48    | 9.80  | 9.15 ± 0.03  | 8.85 ± 0.03  | 8.59 ± 0.03  | 8.04 ± 0.04  | 5.27 ± 0.04 |
| 2MASS J16085529—3848481             | 0.59    | 0.38    | 12.02 | 11.41 ± 0.03 | 10.92 ± 0.03 | 10.70 ± 0.03 | 10.04 ± 0.04 | 7.73 ± 0.05 |
| IRAC J16093418—3915127             | 1.06    | 0.62    | 10.52 | 9.90 ± 0.03  | 9.61 ± 0.03  | 9.34 ± 0.03  | 8.92 ± 0.03  | 6.37 ± 0.04 |

* 2MASS Point Source Catalog.
* X-ray source from Gondoin (2006).
* 2MASS Point Source Catalog.
* X-ray source from Gondoin (2006).
* X-ray source from Gondoin (2006).
* X-ray source from Gondoin (2006).

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Table 2

New Members of Lupus 3

Table 3

Candidate Members of Lupus 3

- **2MASS**
- **Spectral Type**
- **Membership Evidence**
- **J - H**
- **H - K**
- **K**
- **[3.6]**
- **[4.5]**
- **[5.8]**
- **[8.0]**
- **[24]**
of M8 for 2M 1541−3345, but the average of M8 V and M8 III is a poor match to its spectrum, as shown in Figure 5. Even if we classify our spectrum with dwarf standards as done by Jayawardhana & Ivanov (2006) rather than averages of dwarfs and giants, we still arrive at a spectral type of M5.75. As with the dwarf/giant average, M8 V is a poor match to the spectrum of 2M 1541−3345. To determine if 2M 1541−3345 is a member of the current generation of star formation in Lupus, we examined the gravity-sensitive lines appearing in its spectrum, namely, K i, Na i, and Fe H. We compared the strengths of these lines between 2M 1541−3345 and one of the new Lupus 3 members, 2MASS J16073773−3921388 (hereafter 2M 1607−3921). Although Jayawardhana & Ivanov (2006) reported a spectral type of M8 for 2M 1541−3345, its spectrum differs significantly from that of the average of standard M8 dwarfs and giants. The data are displayed at a resolution of 18 Å and are normalized at 7500 Å. 

Fig. 4.—Optical spectra of new members of the Lupus 3 star-forming region discovered in this work (solid lines) compared to best-fit averages of standard dwarfs and giants (dotted lines). The spectra have been corrected for extinction, which is quantified in parentheses by the magnitude difference of the reddening between 0.6 and 0.9 μm [E(0.6−0.9)]. The data are displayed at a resolution of 18 Å and are normalized at 7500 Å.

Fig. 5.—Optical spectrum of 2M 1541−3345 (solid lines) and three comparison spectra (dotted lines). The spectrum of 2M 1541−3345 agrees well with the average of a dwarf and giant at M5.75 and with the spectrum of the M5.75 Lupus member 2M 1607−3921. Although Jayawardhana & Ivanov (2006) reported a spectral type of M8 for 2M 1541−3345, its spectrum differs significantly from that of the average of standard M8 dwarfs and giants. The data are displayed at a resolution of 18 Å and are normalized at 7500 Å.

Fig. 6.—Comparison of the strengths of gravity-sensitive lines between 2M 1541−3345 and 2M 1607−3921. The lines are significantly stronger in 2M 1541−3345 than in 2M 1607−3921, indicating that the former has a higher surface gravity and hence greater age. Thus, we conclude that 2M 1541−3345 is not a member of the latest generation of ∼1 Myr old stars that are arising from the Lupus clouds. Instead, 2M 1541−3345 is an older object,
possibly a member of one of the older populations in the Sco-Cen complex (T. Preibisch & E. Mamajek 2007, in preparation).

5. DISCUSSION
We have presented images of the Lupus 3 star-forming cloud at 3.6, 4.5, 5.8, 8.0, and 24 μm obtained with IRAC and MIPS aboard the Spitzer Space Telescope. After measuring photometry for all point sources detected in these data, we searched the data for new disk-bearing members of the cloud through red colors at 3.6–8.0 μm. Among the 19 candidates identified in this way, 17 objects exhibit excess emission at 24 μm as well. Through optical spectroscopy of six of the candidates, we have confirmed that they are members of Lupus 3 and have measured spectral types of M4.75 to M8. These types correspond to masses of 0.2 M⊙ for the younger members of Lupus 3 and have measured spectral types of M4.75 to M8. These types correspond to masses of 0.2–0.3 M⊙ according to theoretical evolutionary models (Baraffe et al. 1998; Chabrier et al. 2000) and a compatible temperature scale (Luhman et al. 2003). Two of the new members, 2MASS J16083733–3923109 and J16085953–3856275, are likely to be substellar. We note that the candidate 2MASS J16085324–3914401 and the new member 2MASS J16085373–3914367 are separated by only 6″, and thus could comprise a wide binary system if the former is indeed a cluster member. Similarly, the candidate 2MASS J16095628–3859518 has a separation of only 10″ from the known member HBC 627. Most of the remaining 13 candidates that lack spectroscopy have IRAC magnitudes that are indicative of low-mass stars and brown dwarfs, as shown in Figure 3. The candidates with the reddest IRAC colors ([3.6] – [4.5] > 0.5, [5.8] – [8.0] > 1) are probably class I brown dwarfs or galaxies. Because of their youth and proximity, the new members that we have found and the remaining candidates (if confirmed) are attractive targets for detailed studies of circumstellar disks and multiplicity near and below the hydrogen burning limit (Burgasser et al. 2007; Luhman et al. 2007).

In addition to the candidates toward Lupus 3, we have performed spectral classification on 2M 1541–3345, which is a candidate 2MASS J16085324 that was identified in the vicinity of Lupus 1 by Allers et al. (2006). According to the same evolutionary models applied to the Lupus 3 members, the spectral type of M5.75 ± 0.25 that we have measured for this object implies a mass of ~0.1 M⊙. In comparison, Jayawardhana & Ivanov (2006) reported a significantly later spectral type of M8 for 2M 1541–3345 and thus derived a much lower mass (M ~ 0.03 M⊙). In addition, rather than being a member of Lupus 1 as assumed by Jayawardhana & Ivanov (2006) the gravity-sensitive lines in the spectrum of 2M 1541–3345 indicate that it is older than members of the current generation of star formation in Lupus 3 (τ ~ 1 Myr), and thus probably is not a member of the stellar population forming in the Lupus 1 cloud. This conclusion is supported by the fact that 2M 1541–3345 is much too faint to be a member of Lupus 1 given its spectral type of M5.75. For instance, the combination of this spectral type and the luminosity of 2M 1541–3345 from Allers et al. (2006), which assumes the distance of Lupus 1, implies an age of 30–100 Myr according to the evolutionary models of Baraffe et al. (1998). This age range is inconsistent with the ages of ~1 Myr that are typical of star-forming clouds like Lupus 1. Thus, 2M 1541–3345 is probably similar to St34, which is an evolved disk-bearing pre–main-sequence star that happens to be projected against a much younger star-forming region (White & Hillenbrand 2005; Hartmann et al. 2005a).

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Fig. 6.—Gravity-sensitive absorption lines for 2M 1541–3345 (solid lines) and the M5.75 Lupus 3 member 2M 1607–3921 (τ ~ 1 Myr; dotted lines). These data indicate that 2M 1541–3345 has a higher surface gravity than 2M 1607–3921. Thus, 2M 1541–3345 is older than ~1 Myr and is not a member of the current generation of star formation in Lupus. The data are displayed at a resolution of 6 Å.
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