TWO 2MASS-SELECTED YOUNG STELLAR CLUSTERS: PHOTOMETRY, SPECTROSCOPY, AND THE INITIAL MASS FUNCTION

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Received 2005 January 12; accepted 2005 June 12

ABSTRACT

We present near-IR (NIR) J, H, and Ks images and K-band spectroscopy of two newly discovered stellar clusters at different stages of evolution. Our spectra suggest the presence of massive young stellar objects in the heavily embedded cluster in the star-forming region near radio source G353.4−0.4 and an O5−O6 V star in the cluster near radio source G305+00.2. We determine a K-band luminosity function (KLF) for both clusters and an initial mass function (IMF) for the cluster near G305+00.2. The derived IMF slope is \( \Gamma = -1.5 \) if the KLF is used to derive the IMF and is \( \Gamma = -0.98 \) if the color-magnitude diagram (CMD) and spectra are used. The more reliable CMD-based slope is flatter than the Salpeter value usually found for stellar clusters. We find that using the KLF alone to derive an IMF is likely to produce an overly steep slope in stellar clusters subject to variable extinction.

Key words: open clusters and associations: general — stars: formation —
stars: luminosity function, mass function

Online material: color figure, machine-readable table

1. INTRODUCTION

Despite their intrinsic rarity and short lifetimes, massive stars are extremely important in the evolution of galaxies. They play an important role in determining the course of the formation of less massive stars, although the nature of this role is still uncertain, and their stellar winds and eventual supernovae shape the interstellar medium. They produce most of the heavy elements in the universe, as well as much of the UV radiation in galaxies. Their rarity, combined with the effects of large Galactic extinction, often prompts more comprehensive studies of massive stars in external galaxies, where the entire stellar population can be observed at once, rather than within our own where massive stars must be studied individually and the census of massive stars is still very incomplete. High optical extinction within the Galactic plane (\( A_V > 20 \)) has limited optical studies of massive stars to relatively nearby regions (\( R_{\text{Solar}} \lesssim 3.0 \text{ kpc} \); Massey 2003). Even within that radius, optically selected catalogs of O stars have been found to be incomplete, especially in star-forming regions and young clusters (e.g., Hanson & Conti 1995). This incompleteness necessitates the use of infrared, radio, and X-ray observations, particularly in the inner regions of the Galaxy and in star formation regions. The near-IR (NIR; 1−5 \( \mu \text{m} \)) is an especially useful regime for the study of massive stars; the stellar atmosphere is still observed directly, but since, for example, \( A_K \approx 0.11 A_V \), we can observe these stars in regions where dust, either along the line of sight or local to the star-forming region, makes them inaccessible at optical wavelengths. The discovery and characterization of stellar clusters observable only in the infrared can significantly enhance our understanding of obscured Galactic regions that harbor embedded massive stars or massive protostars.

Recent studies indicate that clusters may account for 70%–90% of star formation and that embedded clusters (those still partially or fully enshrouded in their natal molecular cloud) may exceed the number of more traditional open clusters by a factor of \( \sim 20 \) (Elmegreen et al. 2000; Lada & Lada 2003). In the last decade, advancements in NIR observational capabilities resulted in the discovery and classification of some of the most massive young stellar clusters in the Galaxy, each containing dozens of O and Wolf-Rayet stars (e.g., Nagata et al. 1995; Cotera et al. 1996; Figer et al. 1996). Recent studies (Figer et al. 1999) have suggested that within these clusters, the initial mass function (IMF) does not follow the canonical Salpeter form with a slope \( \Gamma = -1.35 \) but instead is more heavily weighted toward massive stars; mass segregation has been proposed as a solution (Stolte et al. 2002). In the last several years a number of studies of well-known star formation regions have also been carried out in the NIR (e.g., Okumura et al. 2000; Blum et al. 2001; Conti & Blum 2002; Figueredo et al. 2002). These studies have in most cases found an IMF consistent with the Salpeter value and have uncovered candidate massive young stellar objects (YSOs). In addition, within the past 10 years, massive YSOs within molecular clouds have been studied in the NIR (e.g., Chakraborty et al. 2000; Ishii et al. 2001) and in young stellar clusters (e.g., Hanson et al. 1997). Massive YSOs, however, remain significantly less studied and are poorly understood in comparison with their lower mass counterparts; many more must be identified and studied before we can adequately address how the formation of massive stars differs from that of low-mass stars.

The final release of the Two Micron All Sky Survey (2MASS) has fostered studies that can probe the entire Galaxy for previously unknown stellar clusters. Initial attempts were made that searched for stellar density enhancements, (e.g., Dutra & Bica 2000, 2001; Dutra et al. 2003b), but the identification of previously unknown clusters has met with limited success. For example, Dutra & Bica (2000) identified 52 candidate clusters, which subsequent observations (Dutra et al. 2003b) indicated were in fact 10 “confirmed” clusters, 3 “probable” clusters, and 11 “dissolving cluster candidates;” the remainder were not clusters. Our observations of at least one of the Dutra et al. (2003b)
“confirmed” clusters, however, indicates that the “cluster” is most likely a region of low extinction rather than a true cluster (A. S. Cotera & A. L. Leistra 2005, in preparation). We have performed an independent search of the 2MASS archive, using color criteria in addition to stellar density enhancements. We have searched in the vicinity of regions identified as likely sites of star formation based on radio and IRAS far-IR flux ratios and are currently conducting a search of the entire 2MASS Point Source Catalog. We search the Point Source Catalog for regions of stellar density higher than the background (determined locally within a 5′ radius), which are redder in $H - K$ than the local field. This selects embedded clusters, with the color criteria helping to eliminate chance superpositions and regions of low extinction. In contrast, Dutra & Bica (2000, 2001) use only stellar density to select clusters. Our method has been relatively successful to date, correctly selecting seven clusters out of nine potential targets, including four candidates toward the inner Galaxy. We present NIR imaging and spectroscopy of the two confirmed clusters in the inner Galaxy in this paper and discuss the two unconfirmed targets in detail in A. S. Cotera & A. L. Leistra (2005, in preparation). The cluster near G305.3+0.2 was independently discovered by Dutra et al. (2003a). The additional five outer Galaxy targets are described in Paper II.

NIR imaging and spectroscopy of both young stellar clusters and nascent stellar clusters enables us to expand the study of the IMF in objects where there has been little to no stellar evolution off the main sequence or cluster evaporation, and where the cluster age can be constrained to within ~2 Myr. Spectral typing of the most massive stars in the cluster allows their masses to be determined relatively precisely, and when combined with photometry it facilitates a reliable determination of the masses of stars throughout the entire cluster (Massey et al. 1995; Massey 2002), allowing the IMF of the cluster to be determined more accurately than photometry alone would permit. In this paper we present the results of NIR observations of two clusters found toward the inner Galaxy, which we designate by the Galactic coordinates of their centers, G353.4−0.36 (R.A. = 17h30m28s, decl. = −34°41′36″ [J2000.0]) and G305.3+0.2 (R.A. = 13h11m39s6, decl. = −62°33′13″ [J2000.0]). In Paper II we will present the results of similar observations of five clusters in

![Color composite image](image-url)
the outer Galaxy. In § 2 we present the observations and data reduction, in § 3 we present the spectra and classifications of the spectroscopically observed cluster members, as well as the color-magnitude diagrams (CMDs), and in § 4 we describe the luminosity function and the IMF.

2. OBSERVATIONS AND DATA REDUCTION

We observed candidate young stellar clusters with the facility instrument IRIS2 on the 3.9 m Anglo-Australian Telescope (AAT) on 2003 July 12–15. IRIS2 is an imaging spectrometer that uses a 1024 × 1024 Rockwell HAWAII-1 HgCdTe array with a plate scale of 0.45 pixel⁻¹, resulting in a 7.7 × 7.7 field of view. Images were obtained in the J (1.25 μm), H (1.63 μm), and Ks (2.14 μm) filters, and R ∼ 2300 spectra of selected stars were obtained in K for each cluster candidate.

We selected a total of four cluster candidates in the southern hemisphere using the 2MASS Point Source Catalog based on color and density criteria. Two of the candidates observed appear to be regions of low extinction and are discussed elsewhere (A. S. Cotera & A. L. Leistra 2005, in preparation). The two confirmed clusters are near radio H II regions designated G305.3+00.2 and G353.4–0.4. We present three-color composites of the 8′ × 8′ images of the G305.3+00.2 and G353.4–0.36 clusters in Figures 1 and 2, respectively. G305.3+00.2 is an H II region that has been previously observed using radio recombination lines (Wilson & Mezger 1970) and submillimeter C i emission (Huang et al. 1999), and in the mid-IR (MIR) by the Midcourse Space Experiment (MSX). The kinematic distance of 3.5 ± 1.1 kpc obtained for this H II region (Wilson & Mezger 1970) agrees well with the distance of 3.3 kpc for masers several arcminutes away (Caswell et al. 1995), suggesting they may be part of a single star formation complex. A distance of 4 kpc is adopted as an upper limit to the radio kinematic distance by Clark & Porter (2004) in a study of the star clusters Danks 1 and 2 in this region. The situation is more complex for the G353.4–0.36 cluster, which is in a region known to be a site of massive star formation. There are numerous radio sources located within 1′ of the NIR cluster, which we discuss in detail in § 3.2.2.
All photometric observations were done in excellent seeing conditions: 0.07–0.09. The images were reduced and combined automatically at the telescope using the ORAC-DR pipeline. ORAC-DR is a generic data reduction pipeline created at the Joint Astronomy Centre in Hawaii, originally for use with various UKIRT and James Clerk Maxwell Telescope instruments. Subsequent reprocessing did not noticeably improve the images; therefore, the pipeline-processed data have been used throughout. Source detection, point-spread function (PSF) fitting, and photometry were carried out using IRAF DAOPHOT and are discussed in detail in § 3.2.

All spectra were obtained with a 1" x 7.7 slit. The long-slit format combined with the high stellar density within the field of view resulted in the simultaneous observation of multiple stars. Total integration times ranged from 10 to 30 minutes and were chosen to provide an adequate signal-to-noise ratio for NIR spectral classification as described in Hanson et al. (1996). After the data were flat-fielded, grism curvature was removed using the FIGARO tasks cdist and sdist. Wavelength calibration was performed using the OH− night sky lines and the FIGARO task arc.

The uncertainty in the wavelength calibration fit was determined to be 2.18 Å. The FIGARO task irflux was used to both flux-calibrate the spectra and remove the telluric absorption using the G2 V standards HD 157017 and HD 115496. Both of the standards had intrinsic Brγ in absorption, with equivalent widths of 5.7 Å for HD 157017 and of 5.6 Å for HD 115496; in each case, the absorption line was removed by fitting a line to the continuum in the region of the line in the standard star spectrum prior to flux calibration. The individual spectra were obtained by extracting apertures 4–5 pixels wide from the full spectral array and then performing background subtraction using apertures of the same width on either side of the source, separated by 2 pixels (0.09). We also extracted off-source spectra in each cluster to characterize any nebular emission.

3. ANALYSIS

3.1. Spectroscopy

The development of NIR spectral atlases of nearby massive stars of known spectral type (Hanson et al. 1996; Morris & Serabyn 1996; Blum et al. 1997) provides a valuable classification scheme for stars too heavily obscured by dust to permit optical spectroscopy. In the K band, in addition to the Brγ (2.165 μm) line, massive O stars have helium (He i 2.058 μm, He II 2.112 μm, He II 2.189 μm), carbon (C IV 2.078 μm), and nitrogen (N II 2.166 μm) lines in their spectra, which allow for the determination of the spectral type to within a subtype if there is adequate (~70 Å) line signal-to-noise ratio. Table 6 of Hanson et al. (1996) indicates that in many cases the mere presence of these lines in emission or absorption (without considering equivalent width) is sufficient to determine spectral type to within two subtypes for O stars. The situation is more complicated for B stars, which have fewer features in this part of the spectrum; however, they are still classifiable using only K-band spectra.

We obtained K-band spectra of five stars in the G305.3+0.2 cluster field and three stars in the G353.4–0.36 cluster. In order to reduce the level of foreground contamination, we imposed a color cut of $H - K > 0.5$ based on the 2MASS magnitudes and selected the brightest stars meeting this requirement. Despite this cutoff, two of the five stars observed in the G305.3+0.2 cluster proved to be foreground contaminants with sufficient line-of-sight extinction to push them over our threshold. The cluster sequence was much narrower and more well separated from the foreground in the G353.4–0.36 cluster, and no obvious foreground contaminants were present in our spectroscopic sample. The G353.4–0.36 cluster was sufficiently red ($H - K_{\text{cluster}} > 1.3$) that the time required to obtain a useful signal-to-noise ratio in H-band spectra would have been prohibitively large, so only K-band spectra were obtained.

3.1.1. G305.3+0.2 Cluster

We present spectra for the three cluster members, which we label A1–A3, in Figure 3. In Figure 4 we present a 106′′ x 120′′ image of the cluster and label the positions of sources A1–A3. The measured magnitudes (see § 3.2) and observed spectral lines for A1–A3 are presented in Table 1. The other two stars for which we obtained a high signal-to-noise ratio have late-type spectra, as indicated by strong CO absorption at 2.29 and 2.32 μm, suggesting they are either foreground objects or YSOs. The lack of nebular emission in the cluster and the presence of weak (nearly the same as in the G2 V spectral standard) Brγ absorption in one of the spectra suggest that these are foreground objects rather than YSOs. In addition, the $K$ magnitudes of these objects ($K = 9.43$ and 10.114) make them too bright to be low-mass YSOs at the cluster distance, and the presence of main-sequence O and B stars argues against identifying these objects as massive YSOs. We thus conclude that these two stars are most likely late-type foreground stars and exclude them from further analysis.

Although nebular emission can be seen in the full image (Fig. 1), it is significantly removed (~1′) from the cluster. Nevertheless, in order to ensure that any measured Brγ (2.166 μm) is stellar in origin and not contaminated by nebular emission within the cluster, we extract a local background spectrum for the cluster. There are no features apparent in the resulting spectrum, so we conclude that nebular emission within the cluster is negligible. This conclusion is supported by an apparent bubble of MIR emission seen in the MSX-band A image (see Fig. 5); the MIR emission avoids the cluster itself.

4 FIGARO is part of the Starlink software package available at http://star-www.rl.ac.uk.
nondetection. If real, the absence of the He II/C2 line in a O star; by estimating the strength of possible features dominates the spectral type to O6 or earlier. A He II (2.112 μm) lines used in the classification system presented in Hanson et al. (1996) and, if real, significantly constrains the stellar type. Helium lines are often observed in both emission and absorption. The presence of Br β/C13 and the “cluster” area is marked. [See the electronic edition of the Journal for a color version of this figure.]

Figure 3 shows that source A1 has emission lines with equivalent widths stronger than –2 Å at 2.116 and 2.166 μm (see Table 1). The line at 2.166 μm is immediately identifiable as Brγ. We identify the line at 2.116 μm as N iii, which is consistent with the lines used in the classification system presented in Hanson et al. (1996); the broad nature of this line is due to the multiplet nature of the transition responsible rather than broadening by stellar winds. The presence of Brγ and N iii 2.116 μm in emission, without further information and without equivalent widths, is sufficient to identify the star as being an early to middle O supergiant; the broad Brγ, produced in the stellar winds, is not observed in main-sequence O stars (Hanson et al. 1996). There is a possible weak detection (~2σ) of C iv in emission at 2.078 μm. This line only appears in O stars ranging from O5 to O6.5 (Hanson et al. 1996) and, if real, significantly constrains the stellar type. Helium lines are often observed in both emission and absorption in the spectra of massive stars: He I (2.058 μm), He I (2.112 μm), and He II (2.189 μm) are all absent from the spectrum of A1. Poor removal of the telluric features near the 2.058 μm feature prevents us from drawing any conclusions based on our nondetection. If real, the absence of the He I (2.112 μm) line restricts the spectral type to O6 or earlier. A He II line is expected in an O star; by estimating the strength of possible features dominated by the noise (as described in detail in § 3.1.2), we can place an upper limit of 0.5 Å on the equivalent width of any potential He II (2.188 μm) feature. This is consistent with the width of the feature in the stars observed by Hanson et al. (1996), so the nondetection does not rule out an O star identification for this source.

Taken together, these spectral characteristics suggest a spectral type of O5 Ib–O6 Ib for source A1. If the weak detection of C iv is discounted, the presence of the N iii line and the limit on a He II line at 2.188 μm allows an O7–O8 identification as well. Even when present, however, the C iv line is weak, with an equivalent width weaker than –2 Å; thus, while a positive detection of this line would allow for definitive classification of this source as an O5 Ib–O6 Ib star, a nondetection at the given signal-to-noise ratio does not preclude the same classification.

The intrinsic NIR colors of O and B stars range from –0.08 to –0.01 (Wegner 1994); this small range allows an extinction to be derived even without knowing the precise spectral type of a massive star. For source A1, the extinction thus derived based on the observed H – K color is A_v = 12 assuming the extinction law of Rieke & Lebofsky (1985). However, the large range in absolute MK for O supergiants prevents us from making a distance determination based on source A1. We can only say the distance is greater than ~3.3 kpc, which would be the distance for a main-sequence O5–O6 star. Clark & Porter (2004) adopt a distance of 4 kpc to the Danks 1 and 2 clusters in the same star formation complex, calling it an upper limit to the values allowed by the radio and Hα observations, and we follow suit, acknowledging that the uncertainties in this value are ~0.5 kpc.

Source A2 shows a strong Brγ (2.166 μm) line in absorption with an equivalent width of 6.2 ± 1.2 Å and a probable weak He I (2.112 μm) line in absorption with EW = 0.7 ± 0.2 Å. This combination of features occurs only in B stars; a comparison of the equivalent width of the lines with the B stars of Hanson et al. (1996) suggests a spectral type in the range of B2–B4. If the Brγ line is considered only as an upper limit, the classification becomes more problematic, and the star could range from B2 to A2. The star has H – K = 0.68, which for any star in this range of spectral type excludes a foreground object. Unlike for A1, the luminosity class of these sources cannot be determined from these spectral features; as Hanson et al. (1996) point out, the K-band spectra of early-B supergiants are indistinguishable from those of early-B main-sequence stars about half the time, and those of late-B supergiants cannot be distinguished from early-B dwarfs.

If we assume that A2 is a cluster star, we can constrain the absolute magnitude, and thus the spectral type, by requiring the distance to be the same as for the O star. Since the intrinsic NIR colors vary by less than 0.1 mag for stars in the range of spectral type.

| MAGNITUDES AND SPECTRAL LINE IDENTIFICATIONS OF SOURCES IN G305.3+0.2 FOR WHICH WE OBTAINED SPECTRA |
|---------------------------------------------------------------|
| **STAR** | **R.A.** | **DECL.** | **PHOTOMETRY** | **SPECTRAL PROPERTIES** |
| | (13h11m) | (−62°) | **J** | **H** | **K** | **Species** | **λ** | **EW** | **SPECTRAL TYPE** |
| A1......... | 41.04 | 32 56.8 | 11.75 ± 0.01 | 10.39 ± 0.03* | 9.58 ± 0.03* | Brγ | 2.166 | −5.7 ± 0.6 | O5 V–O6 V |
| | | | | | | N iii | 2.116 | −2.7 ± 0.7 |
| | | | | | | C iv | 2.078 | ≥ −0.8 |
| | | | | | | Brγ | 2.166 | 6.2 ± 1.2 | B0 V–B1 V |
| | | | | | | He I | 2.112 | 0.7 ± 0.2 |
| | | | | | | Brγ | 2.166 | 5.9 ± 1.3 | B2 V–B3 V |

**Notes.**—Units in the right ascension column are seconds, and units in the declination column are arcminutes and arcseconds.

* 2MASS magnitude.
types allowed by the spectrum (Wegner 1994), we can derive an extinction for this source rather than use that derived from the O star, thus reducing the effects of differential extinction. This gives an extinction to source A2 of $A_T = 11.6$, or $A_K = 1.3$ using the reddening law of Rieke & Lebofsky (1985). At the distance of $4$ kpc, we obtain an absolute magnitude for source A2 of $M_K = -4.0$, roughly that expected for an O8 V star. This identification is not consistent with the spectral features of A2; a smaller distance, or an identification of A2 as an early-B supergiant, could explain the spectrum of A2. If the radio distance of $3.3 \pm 0.3$ kpc is used instead, we obtain an absolute magnitude of $M_K = -3.3$ for source A2, making it a B0 V–B1 V.

Source A3 shows only Br$\gamma$ in absorption, with an EW of $5.9 \pm 1.3$ Å. We place an upper limit on a He $i$ absorption line at $2.112 \mu$m of 0.6 Å. As discussed above, this width for Br$\gamma$ only constrains the classification of the star as main-sequence B or early A. The observed $K$ magnitude is 11.96, which corresponds to an absolute $M_K \simeq -2.6$ assuming the extinction and distance of an O5 Ib–O6 Ib star for source A1; this is consistent with an identification of A3 as a main-sequence B1 V star. The radio distance would imply a B2 V identification, also consistent with the spectral features of A3. Source A3 is not among the brightest stars in the cluster region; it happened to fall in the same long slit as one of the foreground contaminants we had targeted for observation. This suggests that the other cluster members brighter than A3 are also late-O or early-B stars.

3.1.2. G353.4–0.36 Cluster

Spectra for the three sources observed in this cluster are presented in Figure 6. An enlarged version of the relevant portion of Figure 2 is presented in Figure 7, with the positions of the spectroscopic targets indicated with arrows and labels. The only nonnebular feature that we detect is CO absorption in source B1; the Br$\gamma$ emission observed in all three spectra is contaminated by nebular emission to such a degree that we cannot disentangle any stellar component that may be present. While this line is much stronger in B1 than in the other two sources, the nebular emission is highly spatially variable in the cluster region, and this does not
demonstrate a stellar origin for the line. In addition, the line width is significantly narrower than that of source A1 and is similar to that observed in the off-source nebular spectrum (Fig. 8). The CO absorption in source B1 in combination with the red colors (Table 2) is similar to that associated with solar-mass YSOs (Greene & Lada 1996) or a cool giant or supergiant. If B1 is a YSO, the CO absorption is from the circumstellar material; otherwise, it is photospheric in nature. Using the radio kinematic distance (Forster & Caswell 2000) of 3.6 kpc to the cluster, we derive an $M_K$ for source B1 of $-0.8$ without correcting for extinction. Correcting for extinction is difficult to do accurately in this region of highly variable extinction, especially when the intrinsic colors are not known, since the nature of the object is uncertain. Nevertheless, limits can be placed on the amount of extinction present and thus on the absolute magnitude of source B1. The lower limit is given by the uncorrected value of $M_K = -0.8$, which assumes the color observed is the intrinsic color, while the bright limit can be derived assuming an intrinsic $H-K = 0.3$, characteristic of late-type stars; this gives an extinction to source B1 of $A_V = 16.6$ mag and an extinction-corrected absolute $M_K$ of $-2.6$. This is several magnitudes brighter than the expected magnitude of YSOs of approximately a solar mass at the distance and extinction of this cluster, $M_K = -1$–$-3$ (Oasa et al. 1999), and somewhat lower than the $M_K$ for massive YSOs, $M_K = -1$ to $-5$ (Ishii et al. 2001). Finally, we note that this $M_K$ is consistent with that for a 7 $M_{\odot}$ YSO (Chakraborty et al. 2000). We conclude that if source B1 is a YSO, it has a mass greater than a few solar masses based on its absolute magnitude in $K$, but observations of more massive YSOs are still sufficiently few that a more accurate mass determination based solely on the absolute magnitude is not possible. Given the nebular emission, seen as He $i$ 2.058 $\mu$m, H$_2$ 2.12 $\mu$m, and Br$\gamma$ 2.166 $\mu$m emission off the stellar sources (see Fig. 8), G353.4$-$0.36 is obviously a region of current star formation; therefore, the identification as a massive YSO is more probable than a late-type cool giant or supergiant located in the cluster itself.

Since source B1 was not detected in $J$, it cannot be placed on a color-color diagram to determine whether an NIR excess is present, which could help to discriminate between the YSO and cool field star possibilities. For B1 to be a cool giant, it would need to be a foreground star with the appropriate color and magnitude, which falls by chance in the cluster region. Rather than use the entire 8$^\prime$ $\times$ 8$^\prime$ field to determine the field star density, as we did for the G305.3+0.2 cluster ($\frac{1}{2}$ 3.2), we used only the heavily extincted region surrounding the cluster. This is because the molecular cloud in which the cluster is embedded extinguishes the background stars to such a degree that using the entire field would significantly overestimate the level of field star contamination in the immediate region of the cluster. We estimate the probability of a field source as bright as or brighter than source B1 and red enough to satisfy the color cut falling within

![Fig. 6.—Spectra for sources in the G353.4$-$0.36 cluster. All three are identified as massive YSO candidates. The Br$\gamma$ emission line seen in B1 is contaminated by nebular emission (see Fig. 8).](image)

![Fig. 7.—Maser positions from the literature (Caswell et al. 2000; Argon et al. 2000; Val’tts et al. 2000) overlaid on the G353.4$-$0.36 cluster K-band image. Note that they appear in regions that are dark in the NIR, suggesting a more deeply embedded origin. Sources B1–B3 are indicated, and all cluster sources detected in $H$ and $K$ are marked with crosses.](image)

![Fig. 8.—Nebular spectrum from the G353.4$-$0.36 cluster region. The emission lines present are He $i$ 2.058 $\mu$m, H$_2$ 2.12 $\mu$m, and Br$\gamma$ 2.166 $\mu$m.](image)
the cluster region to be approximately 18%. This is a conservative estimate, since at the edges of the cloud reddened sources become visible and increase the field star density, especially of red objects, over what it would be at the location of the cluster. Nevertheless, we cannot rule out either a foreground giant or a YSO explanation for source B1.

As with source B1, the nondetection of sources B2 and B3 in $J$ prevents us from using a color–color diagram to measure NIR excess. No photospheric features are detected in the spectra of either source B2 or B3; source B2 shows a rising spectrum in $K$, suggesting a strong NIR excess, while the spectrum of B3 is essentially flat in this region. In order to determine whether the spectra were truly featureless or merely had a signal-to-noise ratio too low to see expected features, we fitted a continuum to the spectra and examined all excursions above and below the fit. We found that 90% of these deviations had an equivalent width less than 1.7 Å. For comparison, the detected absorption lines tabulated by Greene & Lada (1996) for low-mass YSOs range in equivalent width from 0.3 to 5.6 Å for Na i and Ca i, with CO usually exceeding 2 Å when present. Ishii et al. (2001) conducted a similar survey of massive YSOs; the only emission lines other than Brγ detected in a significant number of sources were CO (with an equivalent width exceeding 4 Å) and H2 (with EW $> 3$ Å in all cases and $>5$ Å in most cases). We thus conclude that source B2 is genuinely featureless but cannot classify it. The final source, B3, has no reliably detected features, but the signal-to-noise ratio is low enough that we cannot reliably call it featureless.

The observed K magnitudes are consistent within a B star identification for sources B2 and B3; however, the extincted but distance-corrected $M_K$ magnitudes of $\sim -0.2$ to $-0.6$ are also similar to those observed for the massive YSO ($M \sim 7 M_\odot$) 05361+3539 (Chakraborty et al. 2000). Thus, although these sources are massive, we cannot distinguish based on their NIR spectra or magnitudes between shrouded B stars and less-evolved YSOs. NIR measurements with sufficient resolution to resolve the individual sources (separated by $>/= 5''$) would aid in this determination; deeper $J$-band photometry, detecting more of the cluster stars, would also be useful. We note that although we see ionized gas, suggesting the presence of O stars, we have not detected any O stars that would be the source of the ionizing radiation in this cluster.

Due to the young age of the sources observed in this cluster and the lack of photospheric features, their spectra were unsuitable for determining a reliable distance. Thus, the kinematic distance to the associated maser and ultracompact H ii region (UCHII; Forster & Caswell 2000) was used instead, adjusted to a distance to the Galactic center of 8 kpc from the original 10 kpc. This gave a distance to the cluster of 3.6 kpc. Assuming an intrinsic $H - K = 0$, we estimated the reddening to the cluster to be $A_J = 22$ based on the narrow cluster sequence at $H - K \sim 1.3$ and assuming the extinction law of Rieke & Lebofsky (1985). This estimate is highly uncertain due to the young age of the sources; many are likely to have an NIR excess leading to an overestimate of the line-of-sight extinction to the cluster.

3.2. Photometry

We obtained images in $J$, $H$, and $K_s$ of both clusters to limiting magnitudes of approximately $J = 16$, $H = 18$, $K_s = 18.5$, with total integration times of 12 minutes in each band. The limiting magnitudes were brighter than expected due to confusion, which is most noticeable in $J$ due to the slightly larger PSF and the greater sensitivity of the instrument at shorter wavelengths. Seeing was $0''.7 - 0''.8$, which, since the IRIS2 plate scale is $0''.45$ pixel$^{-1}$,

resulted in a slight undersampling of the PSF, thus making PSF fitting more uncertain. Our individual images were taken using a random dither pattern, with subpixel dithers employed to improve the PSF. In an effort to better understand our errors, we performed both PSF fitting and aperture photometry for each source. There was no systematic offset between the two methods, but the errors were $\sim 2$ times larger for the aperture photometry due to the crowded fields.

Photometric calibration was performed using the 2MASS magnitudes of field stars, after correcting from the IRIS2 filter system to the 2MASS filter system as described by J. Carpenter. The calibrated magnitudes for the stars in the cluster area are presented in Table 3. The large field of view and location in the Galactic plane provided over 100 stars in each pointing that were bright enough to have good photometry with 2MASS but faint enough to be unsaturated in our IRIS2 images ($11.5 < K_s < 14$). Those stars that were relatively isolated in the IRIS2 images were used as the photometric calibration set. We chose to use a relatively large number of calibration stars rather than selecting the few most isolated stars to reduce the effects of potential variability and photometric outliers among the calibration stars. The scatter in the photometric calibration derived from comparison with 2MASS is the dominant source of photometric error, contributing 2–3 times the measurement errors as reported by DAOPHOT. DAOPHOT errors were $\sim 0.03$ mag, while the calibration uncertainties were $\Delta J = \pm 0.05$, $\Delta H = \pm 0.06$, and $\Delta K = \pm 0.06$ mag. Quoted errors in the 2MASS photometry were negligible, with most stars having an error of $\pm 0.003$ mag or less in all bands. Thus, the quoted error should be considered an overestimate when considering the relative photometry of stars within either cluster; the calibration errors from comparison with the 2MASS photometry shift all our measurements by the same amount. No trend in the photometric errors, either internally or relative to the 2MASS data, was observed with location. Finally, the positions of the stars were also adjusted to agree with 2MASS by minimizing the offsets between the 2MASS and IRIS2 positions, allowing for pointing offset and rotation.

3.2.1. G305.3+0.2

The color composite of the full $J$, $H$, and $K_s$ images is presented in Figure 1; the cluster alone is shown in Figure 4, with the spectroscopic targets marked. The cluster is clearly visible in the full-size image, with a concentration of nebular emission to the northwest. In order to help determine whether the nebular emission is physically associated with the cluster, we overplotted the contours at 8 μm from the MSX mission (Fig. 5). The ridge of NIR nebulosity corresponds to the brightest portion of a roughly circular structure of MIR emission, with the cluster located in the interior where there is no MIR emission present. The general appearance is that of a windblown bubble, and the 8 μm emission wraps entirely around the cluster at a lower level. The cluster is located off-center in this structure, near the brightest portion of the MIR emission, but there is no MIR emission and no MIR nebulosity present in the area of the cluster itself. The cluster is dense and well defined, with stellar density much higher than in the field.

The $K$ versus $H - K$ CMD of the cluster region is shown in Figure 9. At radii of approximately 30″ in the east-west direction and 20″ in the north-south direction from the cluster center the
stellar density has fallen to that of the field, which we use to define the cluster region. Foreground stars are apparent in the CMD at \( H - K \sim 0.3 \); in this cluster there is no clear separation in color between cluster and field stars, just an overdensity of redder stars in the cluster. As a result, we cannot impose a firm color cut to separate field stars from cluster stars. A CMD of a randomly selected control field with the same area as the cluster region, we determined the average number of stars per square arcminute in the image outside the cluster region in color-magnitude bins of \( \Delta K = 0.5 \), \( \Delta (H - K) = 0.5 \) and randomly selected the appropriate number of stars from the cluster field for removal. This is similar to the procedure employed by, among others, Blum et al. (2000) and Figuerêdo et al. (2002). In cases in which less than one star was expected in the cluster field in a particular color-magnitude bin, the number expected was used as a probability for removing the star. A total of 24 “field” stars were removed, leaving 115. The main concentration of cluster stars is at about \( H - K \sim 8 \), with a gradually declining number of cluster stars as the color gap, we consider it more probable that the field stars statistically removed is shown in Figure 11. Given the spectroscopically confirmed presence of OB stars in the cluster, as well as the lack of an obvious color gap, we consider it more

| R.A. (J2000.0) | Decl. (J2000.0) | \( J \) | \( \Delta J \) | \( H \) | \( \Delta H \) | \( K \) | \( \Delta K \) |
|---------------|---------------|--------|-------------|--------|-------------|--------|-------------|
| 13 11 41.040 | -62 32 56.77 | 11.751 | 0.010 | 10.394 | 0.027 | 9.575 | 0.029 |
| 13 11 33.877 | -62 33 27.12 | 12.310 | 0.001 | 11.020 | 0.027 | 10.342 | 0.023 |
| 13 11 39.503 | -62 33 28.17 | 14.063 | 0.004 | 12.646 | 0.004 | 11.969 | 0.018 |
| 13 11 37.680 | -62 33 09.60 | 11.949 | 0.041 | 10.776 | 0.047 | 10.185 | 0.037 |
| 13 11 36.286 | -62 33 13.30 | 12.488 | 0.010 | 11.519 | 0.001 | 10.655 | 0.037 |
| 13 11 41.620 | -62 33 17.40 | 12.936 | 0.029 | 11.650 | 0.038 | 10.953 | 0.034 |
| 13 11 41.111 | -62 33 18.39 | 16.309 | 0.036 | 14.514 | 0.018 | 11.142 | 0.002 |
| 13 11 39.268 | -62 33 24.85 | 13.467 | 0.003 | 12.095 | 0.003 | 11.494 | 0.018 |
| 13 11 39.439 | -62 33 03.63 | 13.218 | 0.003 | 12.018 | 0.002 | 11.524 | 0.018 |
| 13 11 43.767 | -62 33 26.39 | 16.065 | 0.104 | 13.312 | 0.003 | 11.594 | 0.018 |
| 13 11 40.045 | -62 33 18.89 | 13.549 | 0.006 | 12.236 | 0.006 | 11.596 | 0.018 |
| 13 11 38.141 | -62 33 13.66 | 13.428 | 0.003 | 12.270 | 0.003 | 11.745 | 0.018 |
| 13 11 39.493 | -62 33 10.25 | 16.021 | 0.129 | 14.851 | 0.116 | 11.860 | 0.004 |
| 13 11 40.458 | -62 33 03.65 | 15.989 | 0.019 | 14.766 | 0.029 | 11.920 | 0.003 |
| 13 11 40.021 | -62 33 07.26 | 13.884 | 0.004 | 12.591 | 0.003 | 11.970 | 0.018 |
| 13 11 40.992 | -62 33 07.86 | 14.258 | 0.005 | 12.845 | 0.005 | 12.123 | 0.018 |
| 13 11 36.748 | -62 33 11.14 | 14.115 | 0.010 | 12.898 | 0.005 | 12.153 | 0.053 |
| 13 11 37.474 | -62 33 24.02 | 14.067 | 0.010 | 12.742 | 0.002 | 12.311 | 0.029 |
| 13 11 34.525 | -62 33 11.13 | 14.362 | 0.010 | 12.969 | 0.004 | 12.334 | 0.044 |
| 13 11 40.031 | -62 33 11.38 | 14.315 | 0.010 | 13.098 | 0.014 | 12.518 | 0.018 |
| 13 11 40.433 | -62 33 23.29 | 16.065 | 0.108 | 15.615 | 0.049 | 12.698 | 0.005 |
| 13 11 39.217 | -62 33 08.44 | 14.799 | 0.010 | 13.578 | 0.007 | 12.789 | 0.164 |
| 13 11 38.080 | -62 32 59.21 | 16.267 | 0.017 | 13.972 | 0.005 | 12.872 | 0.018 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Magnitudes less than 11.5 are taken from the 2MASS Point Source Catalog, since the IRIS2 images are saturated. Sources A1, A2, and A3 are listed first, followed by the remaining sources. Field stars that were removed before deriving the luminosity and mass functions are included. Table 3 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
likely that these very red sources are either background sources or sources with an NIR excess due to local dust than that they represent a separate cluster giant branch. The red sources are not concentrated toward any part of the cluster, although they may occur more frequently on the outskirts (as would be expected if they were background objects). Sources redder than $H - K = 1.5$ were excluded from analysis of the cluster $K$-band luminosity function (KLF) and IMF; they are unlikely to be main-sequence cluster members. If they are included and assumed to be on the main sequence, the resulting extinction correction gives very large values for the masses and an overly flat slope to the IMF. If these sources are cluster members, they are pre-main-sequence objects, and their masses are difficult to determine from $H$ and $K$ photometry alone. Thus, including them in the IMF determination would give an inaccurate result whether or not they were cluster members, and they have been excluded. Finally, the crowded nature of the cluster region means that these very red sources may suffer from poor photometry.

The $J - H$ versus $H - K$ color-color diagram (Fig. 12) is of limited utility in identifying cluster members or determining whether some cluster members are pre-main-sequence objects. Since many sources were undetected in $J$, it does not represent all cluster members, and faint red sources (where we expect to find relatively low mass, pre-main-sequence objects) would be most commonly missed in the color-color diagram. A cut based solely on $H - K$ must still be applied to exclude background sources. Figure 12 shows few sources in the area occupied by pre-main-sequence objects. Of those sources separated from reddened main-sequence stars by more than $3 \sigma$, three are relatively faint sources adjacent to bright sources and one is in a particularly crowded region. The remaining three could potentially be pre-main-sequence objects. However, due to the lack of observed gaseous emission from the cluster, we consider it unlikely that these are truly pre-main-sequence stars and exclude them from the analysis along with the objects in the unphysical blue region of the color-color diagram as likely suffering from blending or a mismatch between sources in the different bandpasses. There are few enough sources in this region that we do not expect their inclusion or exclusion to greatly affect the IMF determination.

**3.2.2. G353.4$-$0.36**

The $J, H,$ and $K$ color composite of G353.4$-$0.36 is presented in Figure 2. The youth of this cluster is immediately apparent from its heavily embedded nature and the dense molecular cloud that surrounds it. This region has long been known to be a site of massive star formation, and it has been studied extensively in the radio and submillimeter, including continuum observations at 1.5 and 5 GHz (Becker et al. 1994) and 850 $\mu$m (Carey et al. 2000), as well as molecular line observations in CS (Gardner & Whiteoak 1978), CO (Whiteoak et al. 1982), H$_2$CO (Gardner & Whiteoak 1984), HNCO (identified as a dense molecular core; Zinchenko et al. 2000), and SiO (Harju et al. 1998). These signatures of ongoing star formation, combined with the strong nebular emission still present around the sources observed spectroscopically, suggest that the cluster is quite young, without main-sequence stars. Many of the continuum and molecular line observations quote slightly different positions for the source peak, and sources separated by several tens of arcseconds are all identified with the IRAS point source 17271$-$3439. Since the beam sizes in many instances are comparable to the size of the NIR-bright nebulosity and to the separation between sources, it is likely that the extended source measurements are observing the same complex, which may peak at different locations in different wavelengths. Many of the radio data are tabulated by Chan et al. (1996), who identify a massive YSO in the region based on the IRAS colors. It is obvious from the NIR imaging that this source is not a single point source; in addition to the NIR sources, there are at least four separate sets of masers (e.g., Caswell et al. 2000; Argon et al. 2000; Val’tts et al. 2000), one of which is associated with an UCHII (Forster & Caswell 2000). Positions of the masers are indicated in Figure 7. We note that the masers occur in regions that are heavily extincted in the NIR. OH, H$_2$O, and CH$_3$OH masers are all known in the region; the latter in particular are indicative of ongoing massive star formation. Clearly, the sources visible in the NIR are only the tip of the iceberg, with other massive stars still in the process of formation. Higher resolution maps at radio and submillimeter wavelengths are necessary to obtain a full understanding of this region.

In the region of the large dark molecular cloud, only foreground stars are visible. This implies $A_V > 50$ in order to completely obscure the stars even in $K$, assuming a $K$-band detection limit of 17 and a distribution of $K$ magnitudes similar to the rest of the field. The less heavily extincted region in which the cluster is visible in the NIR must have been partially cleared out by stellar winds and ionization from massive stars. The relative position of the NIR stars and the methanol masers (which lie in regions of higher extinction) suggest that we are observing stars nearer the main sequence that are emerging from the dust, while...
objects at an earlier evolutionary state are offset from this region, indicating ongoing star formation.

The CMD of the G353.4−0.36 cluster is presented in Figure 13. The cluster sequence is much narrower and more well separated than in the G305.3+0.2 cluster, allowing for reliable separation of foreground objects based solely on $H - K$. Thus, we do not carry out a statistical removal of foreground objects for this cluster, instead considering only the objects well separated from the foreground sequence. Due to the high extinction toward this cluster, a large number of objects in the cluster area were detected only in $K$ (shown as limits in Fig. 13). The KLF is thus likely to be more reliable than the color-magnitude and color-color diagrams in determining cluster characteristics.

4. THE K-BAND LUMINOSITY FUNCTION AND THE INITIAL MASS FUNCTION

Once field stars have been rejected as described in § 3.2.1, we can compute the KLF for both clusters. For the G305.3+0.2 cluster, which has more than 100 stars remaining, we also compute the IMF using two different techniques, the first using the KLF and the second using the CMD and the spectroscopy of the massive stars. The KLF is commonly used to determine the IMF even when multicolor photometry is available; we take this opportunity to test the robustness of this method and compare the results between this simple and commonly used method and the more involved method using the CMD. This will help to understand the uncertainties and systematic errors that may be a factor when only the KLF method can be used to derive an IMF. There were too few stars to robustly compute the IMF for the G353−0.4 cluster, so we computed only the KLF in this case.

4.1. The G305.3+0.2 Cluster

To provide a robust determination of the KLF and the IMF, we had to determine the completeness of our data, which we established by performing artificial star tests. Five artificial stars at a time were inserted into the cluster region; a small number was chosen to avoid significantly changing the crowding characteristics. IRAF DAOPHOT was then run on the images to determine the number of artificial stars that were successfully recovered. The procedure was repeated 50 times for each magnitude bin ($\Delta m = 0.5$), for a total of 250 artificial stars added in each bin in $H$ and in $K$. Figure 14 shows the results; completeness falls sharply to about 25% at $H \sim 16.5, K \sim 15.5$. We can compare these magnitudes with the turnover in the "field luminosity function," which also probes incompleteness. The counts in the field turn over sharply at $K \simeq 16$, in reasonable agreement with the artificial star estimate of incompleteness.

4.1.1. The K Luminosity Function

Knowing our incompleteness, we can calculate the KLF for the cluster. Figure 15 shows the uncorrected data, with the field luminosity function normalized to the same total number of stars overplotted for comparison. Figure 16 shows the results after correcting for incompleteness by dividing the number of stars in each magnitude bin by the recovered fraction of artificial stars. As expected, there is an overabundance of bright stars ($K < 14.5$) in the cluster region relative to the field. This is not an artifact of incompleteness; the completeness fraction at this magnitude is $\sim 90\%$, and we expect incompleteness to be higher in the cluster than in the field due to the effects of crowding. Using the number counts corrected for field star contamination (as discussed in § 3.2.1) and incompleteness, we fit a slope to the number counts in bins of $\Delta K = 0.5$. We exclude sources fainter than $K = 15.5$ from the fit since errors in the incompleteness determination are likely to dominate the number counts. We derive a slope of $0.21 \pm 0.06$ for $\log N_*$. This slope is somewhat flatter than the KLFs derived for more massive embedded clusters (e.g., $0.41 \pm 0.02$ for NGC 3576 [Figuereído et al. 2002] and $0.40 \pm 0.03$ for W42 [Blum et al. 2000]). This suggests that this cluster is more weighted toward massive stars than the norm.

4.1.2. The Initial Mass Function

In order to better compare our results with the literature and to explore how much of a difference the use of multicolor photometry and spectra of the massive stars make in the determination
of the IMF, we used two methods to derive an IMF for the G305+00.2 cluster. For both methods we used a distance to the cluster of 4.0 kpc (as discussed in §3.1.1). The first IMF-determination method, which uses only the KLF, is commonly employed even when multicolor photometry and spectra are available (e.g., Figueredo et al. 2002; Blum et al. 2000). This method is simply a transformation from $K$ magnitude bins to mass bins. To make this transformation, we first correct the observed $K$ for distance and extinction as discussed in §3.1.1. Using the stellar evolutionary models of Meynet & Maeder (2003) for solar metallicity, we relate the mass for each track to an absolute $K$ magnitude for a star on the zero-age main sequence. We transform $L_{bol}$ to $K$ using the bolometric corrections from Vacca et al. (1996) for the early spectral types and from Malagnini et al. (1986) for later spectral types. We then use the intrinsic $V−K$ colors from Bessell & Brett (1988) for A–M stars and from Wegner (1994) for O and B stars. Finally, we interpolate linearly between the masses available on the evolutionary tracks to find the masses corresponding to our magnitude bins and fit a power law to the resulting mass function. Our resulting IMF slope is $Γ = −1.5 ± 0.3$, excluding the two lowest mass bins, in which incompleteness is significant.

Our second method of determining the IMF makes use of our multicolor photometry and spectra to estimate individual extinctions and masses for cluster members. Spectral typing of the brightest cluster stars allows their mass to be determined fairly accurately for a given stellar evolutionary model. For the models described above, the mass of an O6 V star is approximately $40 M_⊙$, that of a B0 V star is $15 M_⊙$, and that of a B2 V star is $8 M_⊙$. Although spectra are not available for most of the cluster stars, their masses, as well as extinctions to the individual stars, can be estimated from the accurate relative photometry. The presence of an O supergiant in the cluster suggests that, while the most massive stars have begun to evolve away from the main sequence, none have yet gone supernova, and less massive stars should still be on the ZAMS. Therefore, with the exception of the few most massive stars (for which we can estimate masses from their spectral types), the cluster stars should be scattered around the ZAMS primarily by differential extinction rather than by the effects of stellar evolution. We can then use the same models and conversions from theoretical to observed quantities described for the KLF method, with additional transformations from $T_{eff}$ to $H−K$ using intrinsic colors from Bessell & Brett (1988) and Wegner (1994) and from $T_{eff}$ to spectral type with colors from Repolust et al. (2004) or Johnson (1966).

This transformation from theoretical to observed quantities allows us to place the ZAMS on our CMD. If the cluster is sufficiently young that we can neglect the effects of stellar evolution, as discussed in the previous paragraph, we expect the ZAMS to lie in the middle of the distribution of cluster stars. The ZAMS derived from the evolutionary tracks of Meynet & Maeder (2003) is overplotted on the distance and extinction-corrected CMD in Figure 11. A significant number of stars are bluer than the ZAMS on this plot. We interpret these as stars that are less extincted than those used to determine the average cluster extinction and thus have been overcorrected by using the mean extinction. The scatter of stars around the ZAMS suggests that the extinction varies across the cluster region. To correct for this, we move the stars along the direction of the reddening vector until they lie on the ZAMS. If the resulting extinction differs from the mean cluster value by more than $A_V = 5$ for a given star, we exclude the star from the analysis, as it probably suffers from poor photometry. Examination of the color image of the cluster region (Fig. 1) suggests that the variation in internal extinction in this region is relatively small; no dust lanes or color variations across the cluster are visible to the eye. The exact value selected for the cutoff is somewhat arbitrary but does not greatly affect the results; most of the sources thus excluded have derived extinctions that differ from the median value by $A_V = 10$ or more.

Using the positions of the extinction-corrected photometry along the ZAMS, we are able to more accurately place stars in mass bins. The endpoints of the bins are determined by the masses for which theoretical tracks are present in the models we use. In order to have an adequate number of stars in each bin we construct bins using alternate tracks for the endpoints, rather than every track. The analysis is repeated for three different metallicities ($Z = 0.1$, 0.02, and 0.001) using the evolutionary tracks of Mowlavi et al. (1998) ($Z = 0.1$), Schaller et al. (1992) and Meynet & Maeder (2003) ($Z = 0.02$), and Schaller et al. (1992) ($Z = 0.001$). For the solar-metallicity case the high-mass points ($M > 9 M_⊙$) are from Meynet & Maeder (2003), while the lower mass points are from Schaller et al. (1992). The difference in $K$ for the two solar-metallicity tracks is always less than 0.1 mag for the masses for which the two sets of tracks overlap, and for most masses it is less than 0.03 mag. The high-metallicity model should be considered only as a limiting case, since such a high metallicity is not expected. The use of such a wide range of metallicities allows us to estimate the importance of this parameter in the final IMF determination.

Given these sets of mass bins, for each metallicity we determine the number of stars per unit logarithmic mass interval after correcting for completeness. We then fit a power law to the data. The two lowest mass bins ($M < 2 M_⊙$), in which incompleteness is significant, are excluded from the fit; uncertainty in the completeness correction applied could significantly influence the results in these mass bins. The resulting completeness-corrected IMF for the cluster is plotted in Figure 17. The solar-metallicity models yield an IMF slope $Γ = −0.98 ± 0.2$, where the quoted errors are only the formal fit errors and should be considered underestimates. The low-metallicity tracks yield $Γ = −1.01 ± 0.2$ for the same distance, suggesting that the cluster IMF determination is insensitive to metallicity for solar and subsolar values. The $Z = 0.1$ tracks give $Γ = −0.88 ± 0.15$.

4.1.3. Comparison of the IMF Methods

The IMF slopes we derive using these two methods are marginally consistent within the error bars: $Γ = −1.5 ± 0.3$ for the KLF method and $Γ = −0.98 ± 0.2$ for the CMD+spectroscopy method assuming solar metallicity. However, comparing these results individually with the Salpeter slope would lead to different conclusions. The KLF method produces a slope that is very close to the Salpeter value, while the slope from the CMD+spectroscopy method differs from the Salpeter by about 2 $σ$. While this difference in slopes could arise purely from statistical uncertainty, various systematic effects should cause the
KLF-derived slope to be steeper than the CMD-derived slope, as we observe. If the more massive stars are preferentially located toward the center of the cluster, as expected due to mass segregation, and if the extinction is higher in the center of the cluster, the mean extinction used in the KLF determination would be systematically low for the more massive stars. This method would then underestimate the masses of the highest mass stars, thus steepening the slope of the IMF. Evidence that this effect would then underestimate the masses of the highest mass stars, be systematically low for the more massive stars. This method ter, the mean extinction used in the KLF determination would segregation, and if the extinction is higher in the center of the clus-
toward the center of the cluster, as expected due to mass seg-
etation for the difference in the IMF slopes; the stars for which we observe only the massive objects.

An additional possible source of systematic error in the KLF method relative to the CMD method lies in field star rejection. In addition to the statistical field star rejection described in § 3.2.1, which was done before any further analysis and thus applies to both methods, the CMD method has color-based field star rejection. The CMD method can reject foreground objects, which due to lower extinction are bluer than cluster objects, as well as background objects that are redder than the cluster. The KLF method includes these objects, which tend to be fainter on average than the cluster stars (since they either are at a greater distance or are low-mass foreground stars), and thus finds an artificially high number of low-mass stars. We find that the use of K photometry alone to derive the IMF is likely to produce an overly steep IMF in regions with significant field contamination or variable extinction.

4.1.4. Comparison with Other Young Stellar Clusters

Most studies of young star clusters have found an IMF consistent with a Salpeter slope of $\Gamma = -1.35$, generally with uncertainties of 0.1–0.2 (e.g., Figuerêdo et al. 2002; Massey & Hunter 1998; Hillenbrand & Carpenter 2000; Okumura et al. 2000), including the extremely massive R136 cluster in the LMC (Massey & Hunter 1998). A review of the results is provided in Massey (2003). In the case of NGC 6611, reanalysis of the same data by different authors has produced dramatically different results; an IMF of $-1.1 \pm 0.1$ was found by Hillenbrand et al. (1993), while a reanalysis with different treatment of extinction produced $-0.7 \pm 0.2$ (Massey et al. 1995), suggesting that systematic effects are at work in IMF determinations that are at least as important as the statistical errors, as we see in this work. Slopes significantly flatter than Salpeter have been reported for the Arches cluster near the Galactic center (Figer et al. 1999), although later work suggests that this result is an artifact of mass segregation; Stolte et al. (2002) found a very flat IMF in the core of the Arches cluster with a steeper IMF at larger radii, with an overall slope consistent with a Salpeter value. The flatness we observe in both the KLF and the IMF for the G305+00.2 cluster using the CMD+spectroscopy method may similarly be due to mass segregation. In addition to the extinction effects mentioned previously, fainter stars in the outskirts of the cluster could be indistinguishable from the field star density (especially given the high field star density due to the location of the cluster in the Galactic plane) and not fall within the cluster boundaries we employ.

4.2. The KLF for the G353.4–0.36 Cluster

Completeness tests were performed for the G353.4–0.36 cluster using artificial stars as discussed above, and the completeness-corrected KLF is plotted in Figure 18. Since the cluster is significantly less crowded and faint cluster stars less common, our detections in this cluster are nearly complete in $K$, even though our detection limit is brighter than in the G305+00.2 cluster. The turnover at $K = 15.5$ appears to be genuine rather than an artifact of completeness. Perhaps lower mass stars in this cluster are still more deeply embedded in the gas and dust, and thus we observe only the massive objects.

Due to the small number of stars detected in this cluster ($N = 25$, only 7 of which were detected in $H$) and to the early evolutionary stage of the objects, we did not attempt to determine an IMF for this cluster or to place objects on the ZAMS. While the individual objects we observed in the G353.4–0.36 cluster are intriguing and worthy of further study, we cannot analyze the cluster as a whole because there are so few objects.

This cluster is a very promising target for study at other wavelengths more suited than the NIR to the study of YSOs and even earlier stages of star formation. The methanol masers and likely presence of massive YSOs suggest that several stages of massive star formation can be studied in this region.

5. SUMMARY

We present NIR images and spectroscopy of two young stellar clusters near radio sources G353.4–0.36 and G305+00.2. Our $K$-band spectrum of the brightest cluster star in G305+00.2 shows it to be an O5 Ib–O6 Ib star. Although the range of...
luminosities of supergiants prevents us from determining an exact distance; this identification suggests a larger distance than radio distance to the nearby methanol masers (Walsh et al. 1997) of 3.3 kpc. We also obtained spectra of two early-B stars in the cluster. There is no nebular emission present in the G305+00.2 cluster, although a ridge of nebular emission, coinciding with 8 μm emission and masers, is present ~1' away and may indicate sequential star formation, with the masers and gas indicating ongoing star formation and the cluster being the result of earlier star formation. We computed the KLF and IMF of this cluster and found them to be steeper than those reported for most young clusters (Γ ≈ −0.98 ± 0.2 for the more reliable CMD-based method) but generally consistent with the Salpeter value. We found that computing the IMF based only on a single color of photometry is prone to systematic errors when differential extinction and field-star contamination are significant.

Two of the three K-band spectra we observed in the G353.4–0.36 cluster were featureless, while the other showed CO absorption, which is consistent with either a cool foreground giant or a YSO. The absolute magnitudes derived from the distance to the radio sources are too bright for these objects to be solar-mass YSOs. None of the objects were detected in our J-band photometry, making identification as YSOs based on NIR excess impossible. They remain candidate massive YSOs, and observations at other wavelengths are needed to make a positive identification. The images of this cluster showed a region with intense nebular emission embedded in a very dark cloud where earlier stages of star formation are progressing.

We thank the AAT and Chris Tinney for assistance with the IRIS2 instrument. We thank Phil Massey, Margaret Hanson, and the anonymous referee for comments that improved this paper. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This publication made use of data products from 2MASS, which is a joint project of the University of Massachusetts and IPAC, funded by NASA and the NSF. A. C. was supported in part by NASA through the American Astronomical Society’s Small Research Grant Program.

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