THE STELLAR CONTENT OF OBSCURED GALACTIC GIANT H II REGIONS. V. G333.1–0.4

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ABSTRACT

We present high angular resolution, near-infrared images of the obscured Galactic giant H II region G333.1–0.4, in which we detect an OB star cluster. For G333.1–0.4 we find OB stars and other massive objects in very early evolutionary stages, possibly still accreting. We obtained K-band spectra of three stars; two show O-type photospheric features, while the third has no photospheric features but does show CO 2.3 μm band-head emission. This object is at least as hot as an early B-type star, based on its intrinsic luminosity, and is surrounded by a circumstellar disk or envelope that produces near-infrared excess emission. A number of other relatively bright cluster members also display excess emission in the K band, indicative of disks or envelopes around young massive stars. Based on the O star photometry and spectroscopy, the distance to the cluster is 2.6 ± 0.4 kpc, similar to a recently derived kinematic (near side) value. The slope of the K-band luminosity function is similar to those found in other young clusters. The mass function slope is more uncertain, and we find −1.3 ± 0.2 < Γ < −1.1 ± 0.2 for stars with M > 5 M☉, where the upper and lower limits are calculated independently for different assumptions regarding the excess emission of the individual massive stars. The number of Lyman continuum photons derived from the contribution of all massive stars in the cluster is 0.2 × 10⁵⁰ s⁻¹ < N_{Lyc} < 1.9 × 10⁵⁰ s⁻¹. The integrated cluster mass is 1.0 × 10³ M☉ < M_{cluster} < 1.3 × 10³ M☉.

Key words: H II regions — infrared: stars — stars: early-type — stars: fundamental parameters — stars: formation

1. INTRODUCTION

Massive stars have a strong impact on the evolution of galaxies. O-type stars and their descendants, the Wolf-Rayet stars, are the main source of UV photons, mass, energy, and momentum for the interstellar medium. They play the main role in the ionization of the interstellar medium and dust heating. The Milky Way is the nearest place to study, simultaneously, massive stellar populations and their impact on the surrounding gas and dust. The Sun’s position in the Galactic plane, however, produces a heavy obscuration in the visual window (ΔV ≈ 20–40 mag) toward the inner Galaxy, where massive-star formation activity is the greatest. At longer wavelengths, such as in the near-infrared, the effect of interstellar extinction is lessened (ΔK ≈ 2–4 mag), yet the wavelengths are still short enough to probe the stellar photospheric features of massive stars (Hanson et al. 1996).

The study of giant H II (GHII) regions (emitting at least 10⁵⁰ Lyman continuum photons per second, or ≈10 times Orion) in the near-infrared can address important astrophysical issues such as (1) characterizing the stellar content by deriving the initial mass function (IMF), star formation rate, and age; (2) determining the physical processes involved in the formation of massive stars, through the identification of OB stars in very early evolutionary stages, such as embedded young stellar objects (YSOs) and ultracompact H II regions; and (3) tracing the spiral arms of the Galaxy by measuring spectroscopic parallaxes for main-sequence OB stars. The exploration of the stellar content of obscured Galactic GHII regions has been undertaken recently by several groups (Hanson et al. 1997; Blum et al. 1999, 2000, 2001; Figueredo et al. 2002; Okumura et al. 2000). These observations have revealed clusters of massive stars at the center of H II regions that had been previously discovered and studied only at much longer radio wavelengths.

In this work, we present results for G333.1–0.4 (R.A. = 16h21m03s, decl. = −50°36′19″; J2000), located at a kinematic distance of 2.8 kpc (near side) or 11.3 kpc (far side), which we adopt from Vilas-Boas & Abraham (2000) with R₀ = 7.9 kpc. Inward of the solar circle, the Galactic kinematic rotation models give two values for the distance. A difficulty with such models comes from the classical twofold distance ambiguity for lines of sight close to the Galactic center (Watson et al. 2003). Furthermore, noncircular velocity components can lead to erroneous distances. We show below that a spectroscopic parallax...
method leads to a distance of 2.6 ± 0.4 kpc. G333.1–0.4 does not appear in visual-passband images, but in the infrared, one sees a spectacular star formation region.

In this paper, we present an investigation of the stellar content of G333.1–0.4 through JHK imaging and K-band spectroscopy (described in § 2). In § 3, we consider the photometry, and in § 4 we analyze the spectra. We determine the distance in § 5 and discuss the results in § 6.

2. OBSERVATIONS AND DATA REDUCTION

\[ J(\lambda \approx 1.3 \mu m, \Delta J \approx 0.3 \mu m), H(\lambda \approx 1.6 \mu m, \Delta H \approx 0.3 \mu m), \text{ and } K(\lambda \approx 2.1 \mu m, \Delta K \approx 0.4 \mu m) \]

images of G333.1–0.4 were obtained on the night of 1999 May 1, and a new set of images 65'' east of the cluster was obtained on the night of 2001 July 10. Both sets utilized the f/14 tip-tilt system on the Cerro Tololo Inter-American Observatory (CTIO) 4 m Blanco Telescope using the facility imager OSIRIS.\(^2\) Spectroscopic data were acquired with the Blanco Telescope on 2000 May 19, 21, and 22 and 2001 July 11. OSIRIS delivers a plate scale of 0'.16 pixel\(^{-1}\). All basic data reduction was accomplished using IRAF.\(^3\) Each image was flat-fielded using dome flats and then sky-subtracted using a median-combined image of five to six dithered frames. Independent sky frames were obtained 5'–10' south of the G333.1–0.4 cluster for direct imaging and 1'–2' west for spectroscopy.

2.1. Imaging

All images were obtained under photometric conditions. Total exposure times during the 1999 run were 270, 135, and 81 s at \(J\), \(H\), and \(K\), respectively. The individual \(J\), \(H\), and \(K\) frames from 1999 were shifted and combined. These combined frames have point sources with FWHM of approximately 0'.63, 0'.54, and 0'.56 at \(J\), \(H\), and \(K\), respectively. DoPHOT (Schechter et al. 1993) photometry was performed on the combined images. All reduction procedures and photometry were performed for each set of images (1999 and 2001) separately, and the resulting combined magnitudes were included in a single list. The 1999 images are deeper than the 2001 images, so we performed photometric completeness tests and applied corrections to each set of images independently (see below).

The flux calibration was accomplished with the standard star GSPC S875-C (also known as [PMK98] 9170) from Persson et al. (1998), which is on the Las Campanas Observatory (LCO) photometric system. The LCO standards are essentially on the CIT/CTIO photometric system (Elias et al. 1982), though color corrections exist between the two systems for the reddest stars. No transformation has been derived for OSIRIS and either the CIT/CTIO or LCO system. Figure 1 shows a finding chart using the \(K\)-band image made from a combination of the 1999 and 2001 observations. The area used to measure the sky counts is shown at lower left.

The standard-star observations were taken just after the G333.1–0.4 data acquisition and within 0.17 air masses of the target. The color correction and this remaining air mass will add uncertainties on the order of 2% in the worst case (\(J\) band). No corrections were applied for this small difference in air mass between target and standard.

Aperture corrections for 16 pixel radius circles were used to put the instrumental magnitudes on a flux scale. Ten uncrowded stars on the G333.1–0.4 images were used for this purpose. In order to determine the zero point for the 2001 images, we used stars in common with the 1999 images.
Uncertainties for the $J$, $H$, and $K$ magnitudes in the 1999 images include the formal DoPHOT error added in quadrature to the error in the mean of the photometric standard and to the uncertainty of the aperture correction used in transforming from the DoPHOT photometry to OSIRIS magnitudes. The sums in quadrature of the aperture correction and standard-star uncertainties are $\pm 0.010$, $\pm 0.017$, and $\pm 0.044$ mag in $J$, $H$, and $K$, respectively. The scatter in the instrumental magnitudes in the 2001 images includes all objects detected are $\pm 0.04$, $\pm 0.07$, and $\pm 0.06$ mag in $J$, $H$, and $K$, respectively. Thus, the errors in the bright star magnitudes in the 2001 images are dominated by this scatter. The means of the final magnitude errors including all objects detected are $\pm 0.047$, $\pm 0.049$, and $\pm 0.078$ mag in $J$, $H$, and $K$, respectively. We adopted an arbitrary cutoff of 0.2 mag (stars with larger errors were excluded from further analysis).

The completeness of the DoPHOT detections was determined through artificial-star experiments. This was accomplished by inserting fake stars in random positions on the original frame and then checking how many times DoPHOT retrieved them. The point-spread function (PSF) of the fake star was determined from an average of real stars found in isolation. Adding a large number of stars to the real images could affect the crowding; instead, we chose to add a small number and repeat the test many times. We inserted a total of 24,000 stars in the magnitude interval $8 \leq K \leq 20$, corresponding to 27 times the number of real stars recovered in the original DoPHOT run. For every $\Delta K = 0.5$, we simultaneously inserted 10 stars in the $K$-band image (240 stars total) and then reran DoPHOT to see how many were recovered. This was repeated 100 times. The completeness of the sample is defined as the percentage of stars recovered in these tests. In Figure 2, we present the result of these experiments—the photometric completeness. The performance of the photometry is better than 92% for a 16th magnitude star in the $K$ band. The procedure above was repeated for the $J$ and $H$ bands, and in both cases the performance of the photometry is better than 92% for $J < 16.5$ and $H < 16.75$. The right panel of Figure 2 shows the differences between the input magnitudes of the artificial stars and the output magnitudes of the artificial stars detected by DoPHOT. Using the magnitude limit (16.0), the difference between the input and output magnitudes of the false stars is 0.044. This difference is similar to the instrumental uncertainties given by DoPHOT. Although we show in Figure 2 only the results for the 1999 data set completeness test, the same experiment was performed for the offset images, which have different depth. All data sets were corrected for completeness separately before constructing the combined luminosity function.

2.2. Spectroscopy

$K$-band spectra of three of the brightest stars in the G333.1–0.4 cluster, Nos. 1, 2, and 4, were obtained with OSIRIS. One-dimensional spectra were obtained by extracting and summing the flux in $\pm 2$ pixel apertures. The extractions include local background subtraction from apertures $\approx 1''$ on either side of the object. Moreover, we used background apertures in order to subtract the uniform nebular component of emission from the target spectra.

Wavelength calibration was accomplished by measuring the position of bright OH lines from the $K$-band sky spectrum (Oliva & Origlia 1992). The spectra were divided by the average continuum of several B9 V stars to remove telluric absorption. The air-mass differences between the objects and the B9 V stars are less than 0.05, and no corrections were applied for these small differences.

The Br$\gamma$ photospheric feature was removed from the average B9 V spectrum by eye, by drawing a line between two continuum points. Since Br$\gamma$ is free from strong telluric features, it is sufficient to cut off this line by eye by drawing a line between two continuum points, to obtain the template for telluric lines. Br$\gamma$ does play a key role in classification of the cluster stars. The $K$-band classification scheme for OB stars is based on faint lines of C iv, He i, N iii, and He ii. The spectra of young stars in H ii regions are in fact often contaminated by the 2.058 $\mu$m He i and Br$\gamma$ nebular lines, but this is not important, since these lines are not necessary for classifying O-type stars (Hanson et al. 1996).

The spectral resolution at $2.2\mu$m is $R \approx 3000$ for OSIRIS, and the linear dispersion is $\lambda \approx 3.6$ $\AA$ pixel$^{-1}$.

3. RESULTS: IMAGING

The OSIRIS $J$-, $H$-, and $K$-band images reveal a rich embedded star cluster, readily seen on the right side of Figure 1, where the stellar density is higher than the area to the left. We detected a total of 866 stars in the $K$-band image of the cluster and the field located 65$''$ east. Of those 866 stars, 757 were also detected in the $H$-band and 343 in all three filters. We did not detect objects in $J$ or $H$ that were not picked up in $K$ with magnitude errors below the cutoff limit. The image measures 1.69 $\times$ 2.87, amounting to an area of $\approx 4.75$ arcmin$^2$ (ignoring the two blank strips at top and bottom right). A false-color image is presented in Figure 3, made by combining the three near-infrared images and adopting the colors blue, green, and yellow.
red for $J$, $H$, and $K$, respectively. The bluest stars are likely foreground objects, and the reddest stars are probably $K$-band excess objects, indicating the presence of hot dust for objects recently formed in the cluster (background objects seen through a high column of interstellar dust would also appear red). The bright ridge of emission that can be seen in the figure crossing the central region of the cluster in the north-south direction is most likely due to $\text{Br}\gamma$ emission arising from the ionized face of the molecular cloud from which the cluster was born. Darker regions are seen to the west of the emission ridge in Figure 3. This geometry suggests a young cluster containing massive stars, now in the process of destroying the local molecular cloud.

The $K$ versus $H-K$ color-magnitude diagram (CMD) is displayed in Figure 4. The labels in this and subsequent plots refer to the same stars as in Figure 1. We can see two concentrations of objects in the CMD. The first appears around $H-K \approx 0.3$, which corresponds to an extinction of $A_K = 0.42$ mag ($A_V \approx 4.2$ mag) using the interstellar reddening curve of Mathis (1990; see below). This sequence represents foreground stars; the expected extinction for this position along the Galactic plane is $A_V \approx 1.8$ mag kpc$^{-1}$, or $A_K \approx 0.18$ mag kpc$^{-1}$ (Jønch-Sørensen & Knude 1994). The second concentration of objects appears around $H-K = 0.8$, or $A_K = 1.22$ mag, probably
indicating the average color of cluster members. A number of stars display much redder colors, especially the brightest ones in the $K$ band. These objects are located at $H-K > 2.0$, or $A_K = 3.2$. The dashed vertical line indicates the position of the theoretical zero-age main sequence (ZAMS; see Table 1 of Blum et al. 2000) shifted to 2.6 kpc distance (derived in § 5) and with interstellar reddening $A_K = 0.42$ mag. An additional local reddening of $A_K = 0.80$ mag results in the ZAMS position indicated by the vertical solid line.

The $J-H$ versus $H-K$ color-color plot is displayed in Figure 5. In this diagram the diagonal lines, from top to bottom, indicate interstellar reddening for main-sequence M-type (Frogel et al. 1978), O-type (Koornneef 1983), and T Tauri (Meyer et al. 1997) stars (dashed line). The solid vertical line between the main-sequence M-type and O-type lines indicates the position of the theoretical zero-age main sequence (ZAMS; see Table 1 of Blum et al. 2000) shifted to 2.6 kpc distance (derived in § 5) and with interstellar reddening $A_K = 0.42$ mag. An additional local reddening of $A_K = 0.80$ mag results in the ZAMS position indicated by the vertical solid line.

3.1. Cluster Members

So far, we have assumed that our sample of stars is composed only of cluster members (not contaminated by foreground or background stars). In fact, it is not an easy task to identify these two populations except through statistical procedures. All details of our procedure used to separate the cluster members from projected stars in the cluster direction can be seen in Figure 6. The left panel shows the CMD (Fig. 4) binned in intervals of $\Delta K = 1.0$ and $\Delta (H-K) = 1.0$ and containing all stars (clusters members plus projected stars). We used the stars in the region indicated by the square at lower left in Figure 1 to define a field population. In this case, we supposed that there were only foreground or background stars and no cluster members in this small area. The star counts inside this square were normalized by the relative areas projected on the sky and then binned in the same intervals cited above (Fig. 6, middle). The stellar density in the field (middle) was then subtracted from the CMD with all stars (left) in bins of magnitude and color interval, resulting in a CMD without contamination by projected stars (statistically; see Fig. 6, right). In the case of negative counts, which occur when the field values are larger than the cluster as a result of statistical fluctuations, the counts are added to an adjacent bin that has a larger number of objects.

The procedure works well for foreground stars, since there are relatively few stars in the direction of the cluster. For the background stars the situation is more complex. However, we believe the excess of field stars that might contaminate the cluster sample is relatively small, because of the high obscuration toward the cluster itself and the large density of cluster stars expected. Unfortunately, we cannot use this procedure to cut off projected stars from our CMD or color-color diagram. However, we can use this result to correct the luminosity function from contamination by non–cluster members, taking into account not only the magnitudes of the stars but also their colors.

3.2. Reddening and Excess Emission

We estimate the reddening toward the cluster from the extinction law $A_K \sim 1.6E_{H-K}$ (Cardelli et al. 1989; Mathis 1990), using an average intrinsic color $H-K = -0.04$ from Koornneef (1983) for OB stars. The Cardelli et al. extinction law assumes $R_V = 3.1$. This extinction law is not truly independent of environment for $\lambda > 0.9 \mu m$, as pointed out by Whitney et al.
(2004). However, for the J, H, and K bands, differences in the extinction law are small enough to be neglected in the present case (see Fig. 3 of Whitney et al. 2004). The stars brighter than $K = 14$ have an average observed color of $H - K = 0.8$, corresponding to $A_K = 1.22$ mag ($A_J = 12.2$). The interstellar component of the reddening can be separated from that local to the cluster stars by using the foreground sequence of stars seen in the CMD (Fig. 5) at $H - K \approx 0.3$, as mentioned in § 3. For G333.1−0.4, the foreground component is then $A_K \approx 0.42$, leaving a local component of $A_K \approx 0.8$ mag. Regarding the foreground component, as mentioned in § 3, the value that we have found ($A_K \approx 0.42$) agrees very well with the value estimated from Joch-Sørenson & Knude (1994) for the distance of 2.6 kpc ($A_K \approx 0.47$).

In order to place the ZAMS in the CMD, we used the $H - K$ colors from Koornneef (1983) and absolute K magnitudes from Blum et al. (2000). The ZAMS is represented by a vertical solid line in Figure 4, shifted to $D = 2.6$ kpc and reddened by $A_K = 0.42$ due to the interstellar component. When adding the average local reddening ($A_K = 0.8$), the ZAMS line is displaced to the right and downward, as indicated by the dotted lines. We cannot fix the position of the ZAMS, since there is a scatter in the reddening. The small group of relatively bright stars ($K \sim 12$) between these two lines suggests that some of them, the bluer ones, could mark the position of the ZAMS.

Objects found to the right of the O star reddening line in the CMD of Figure 5, shown as a solid diagonal line, have colors that deviate from pure interstellar reddening. This is frequently seen in young star clusters and is explained by hot dust in the immediate circumstellar environment. We can estimate a lower limit to the excess emission in the K band by supposing that the excesses at J and H are negligible, and that the intrinsic colors of the embedded stars are those of OB stars. Indeed, assuming that our sample of stars is composed of young objects (not contaminated by foreground or background stars), any OB star would have an intrinsic color in the range $(H - K)_0 = 0.0 \pm 0.06$ mag (Koornneef 1983). Let us adopt for all objects in our sample the intrinsic colors of a B2 V star: $(J - H)_0 = -0.09$ and $(H - K)_0 = -0.04$ (Koornneef 1983). The error in the color index would be smaller than the uncertainty in the extinction law we are using for the interstellar extinction. From the difference between the observed $J - H$ and the adopted B2 V intrinsic $J - H$ color, we obtain the J-band extinction by using the extinction law. In other words, in order to estimate a lower limit to the excess emission, we have assumed the intrinsic colors of all stars that were detected in $J$, $H$, and $K$ bands to be that of a B2 V star. Assuming the $J - H$ color is not strongly affected by circumstellar excess emission, we determine the line-of-sight extinction to each star using the extinction law. We derive the intrinsic apparent magnitudes based on $A_J$ and the intrinsic $B$ V colors. The K-band excess emission is then derived as $K_{\text{exc}} = K_0 - (K - A_K)$, or simply as the difference between the observed $A_K$ and the $A_K$ estimated from the $J - H$ excess alone.

Our results are displayed in Figure 7. In this plot we have only included objects with measured $J$, $H$, and $K$ magnitudes. The solid line indicates $K_{\text{exc}} = 0$. Connected diamonds refer to the average value of the K excess in 1 mag bins. Dashed lines indicate 1, 2, and 3 $\sigma$ from the average. Bright objects with very large excesses in the upper right of Figure 7 cannot be explained by errors in the dereddening procedure, because they have measured $J$, $H$, and $K$. They could represent the emission from accretion disks around the less massive objects in the cluster. Objects such as Nos. 488, 472, and 416 are well above the 3 $\sigma$ scatter for otherwise normal stars.

Most of the stars in Figure 7 have a modest negative excess, about $-0.2$ mag. This negative excess is a consequence of our assumption that all stars have the intrinsic color of a B2 V star and thus is not physical. With reference to Figure 5, one can see that any star that lies above the reddening line for a B2 V star must, by definition, have a negative excess under the assumption that the excess emission is in the K band and the intrinsic photospheric colors are those for a B2 V star. Our goal is to identify stars with a significant excess that would cause them to lie to the right of the reddening line in Figure 5, so this modest negative excess for “normal” stars, or stars with a small excess, is not important for our purposes.

In Figure 7 the magnitude of the largest excess (almost 2 mag, for object 6) is in agreement with the values found by Hillenbrand & Carpenter (2000) for young stars in the Orion cluster. In the following sections we have only corrected the K excess for stars with positive excess as determined here; for all others we impose zero excess emission. Low-mass YSOs have a typical excess of several tenths of a magnitude (Hillenbrand & Carpenter 2000), depending on the age of the cluster.

### 3.3. The KLF and the IMF

Having correcting for non–cluster members, interstellar reddening, excess emission (a lower limit), and photometric completeness, we present the resulting K-band luminosity function (KLF) in Figure 8. A linear fit (solid line) excluding measures more deviant than 3 $\sigma$ has a slope $\alpha = 0.24 \pm 0.02$. A considerably steeper KLF slope was obtained for W42 ($\alpha = 0.40$) in Blum et al. (2000) and for NGC 3576 ($\alpha = 0.41$) in Figuerêdo et al. (2002). A linear fit using only stars measured in all three filters (Fig. 8, dashed line) results in a slope ($\alpha = 0.26 \pm 0.04$) very close to that found when all stars are included. The coincidence is not surprising, since the fitting in both cases is dominated by the objects detected in the three filters.

We can evaluate the stellar masses by using Schaller et al. (1992) models, assuming that the stars are on the ZAMS instead of the pre–main sequence. This is a reasonable approximation for massive members of such a young cluster. Stars more
massive than about $M = 5 M_\odot$ should be on the ZAMS according to the pre–main-sequence evolutionary tracks presented by Siess et al. (2000). The main errors in the stellar masses, given this restriction, will be due to the effects of circumstellar emission and stellar multiplicity. Our correction to the excess emission is only a lower limit, since we assumed the excess was primarily in the $K$ band (but according to Fig. 7, there are not many stars with large excesses at higher masses). Hillenbrand et al. (1992) have computed disk reprocessing models that show the excess in $J$ and $H$ can also be large for disks that reprocess the central star radiation. An underestimate of the excess emission will result in an overestimate of the mass for any given star and for the cluster as a whole. The slope of the mass function should be less affected. It is difficult to quantify the effect of binarity on the IMF. If a given source is binary, for example, its combined mass would be larger than inferred from the luminosity of a “single” star, and its combined ionizing flux would be smaller. The cluster total mass would be underestimated, and the number of massive stars and the ionizing flux would be overestimated. The derived IMF slope would be flatter than the actual one.

With these limitations in mind, we have transformed the KLF into an IMF. Since other authors also do not typically correct for multiplicity, our results can be compared, as long as this parameter does not change from cluster to cluster. The IMF slope derived for G333.1–0.4 is $\Gamma = -1.1 \pm 0.2$, which is flatter than Salpeter’s slope (1.5 $\sigma$ from his value; Salpeter 1955). Figure 9 shows the binned magnitudes from Figure 8 transformed into masses (triangles) and the fit to these points considering all objects more massive than 5.0 $M_\odot$ (solid line). The dashed line in the figure indicates a fit for the case of only those objects more massive than 5.0 $M_\odot$ that have $JHK$ magnitudes measured. The fit ($\Gamma = -1.0 \pm 0.2$) is very close to that derived for all the stars. Our result depends on the calculation of the excess emission, which is uncertain. In the following subsection, we show that different assumptions about the excess emission lead to an IMF slope that is consistent with Salpeter’s slope.

Massey et al. (1995) made a comparison between the IMFs of Galactic and LMC OB associations and clusters, and no significant deviation was found from Salpeter’s value. A steeper IMF slope was obtained for the Trapezium cluster ($\Gamma = -1.43 \pm 0.10$) by Hillenbrand & Carpenter (2000) and for NGC 3576 ($\Gamma = -1.62 \pm 0.12$) by Figer et al. (2002). Flatter slopes have been reported only for a few clusters, most notably the Arches and Quintuplet clusters (Figer et al. 1999), both near the Galactic center. Flatter slopes may indicate that in the inner Galactict star-forming regions the number of high-mass stars relative to low-mass stars is higher than elsewhere in Galaxy. It is also possible that dynamical effects may be more important in the inner Galaxy. Portegies Zwart et al. (2002) have modeled the Arches cluster data with a normal IMF but include the effects of dynamical evolution in the presence of the Galactic center’s gravitational potential. They find the observed counts to be consistent with an initial Salpeter-like IMF.

We can determine an approximate lower limit to the total mass of the cluster by integrating the IMF between 5 and 90 $M_\odot$. The upper integration limit corresponds to the mass of a O3-type star as given by Blum et al. (2000). The integrated cluster mass is $M_{\text{cluster}} = (1.3 \pm 0.5) \times 10^5 M_\odot$. To the extent that excess emission is underestimated for these stars, this lower limit to the cluster mass is overestimated.

The number of Lyman continuum photons derived from the IMF (Fig. 9) was calculated from the contribution of all massive stars in the cluster. The Lyman continuum flux comes from the brightest stars, which are well above our completeness limit. The intervals of masses in the IMF have been transformed into $K$-band luminosity (see below) and that recently derived from radio observations (see § 3) put G333.4–0.1 on the near side of the Galactic center; Smith et al. (1978) estimated $N_{\text{LyC}}$ based on the far-side distance.

### 3.4. Embedded Young Stellar Objects

As can be seen from Figures 4, 5, and 7, some objects in G333.1–0.4 are very bright, exhibit colors much redder than average, and have excess emission. This is the case for objects such as Nos. 4, 6, 9, 13, 14, and 598. In NGC 3576 (Figerédo...
was for two stars in NGC 3576 (Figueiredo et al. 2002). Barbosa et al. (2003) inferred similar spectral types from mid-infrared photometric data of the CMD. In Table 1, we summarize the properties of these YSOs with excess emission and extinction.

Given such evidence for circumstellar disks, we attempt to estimate the excess emission using Hillenbrand et al.’s (1992) models for reprocessing disks to get a sense of how much greater the excess might be compared with that derived by assuming all the excess is in the $K$ band. By starting with the maximum excess emission, $\Delta K = 4.05$, valid for an O7-type star (Table 4 of Hillenbrand et al. 1992; all excess-emission values are for face-on line of sight), we derive the corresponding $M_{\star}$. Using the ZAMS properties from Table 1 of Blum et al. (2000), we obtain the corresponding stellar spectral type and mass. This is generally much smaller than the O7 type with which we started; the excess is obviously overestimated and the new luminosity and mass are underestimated. From this smaller mass, we use the corresponding excess emission and find a higher mass and luminosity. We iterate this procedure until convergence. This was done for all the stars listed in Table 1, and the results are given in Table 2. The resultant reddening was determined in the same way as for Table 1, except that now we have included the excess in the $H-K$ color due to the Hillenbrand et al. (1992) reprocessing disks (nearly constant and equal to 0.5 mag).

The values in Tables 1 and 2 give a rough indication of the range of excesses that might be present, though neither is fully correct. The values in Table 2 do not account for accretion luminosity or for the inclination of the disk, while those derived only with photometric data assume a negligible excess at $J$ and $H$. We adopted a similar procedure using $JHK$ photometry for two stars in NGC 3576 (Figuereido et al. 2002). Barbosa et al. (2003) inferred similar spectral types from mid-infrared imaging techniques.

Although the Table 2 values are not true upper limits, since they do not account for accretion and may be too extreme if the disk we see is highly inclined, we can use them as a plausible "large excess" case. We used these assumptions about the excess, adopting the masses of the objects shown in Table 2, to compare with those from the previous IMF estimate (Fig. 9). The slope in the case of the "large excess" is $\Gamma = -1.3 \pm 0.2$, which is similar to Salpeter’s slope (0.25 $\sigma$ from his value; Salpeter 1955).

New masses, derived from the "large excess" correction, lead to an $N_{\text{LyC}} = 0.2 \times 10^{50}$ s$^{-1}$. This is smaller than the number of Lyman continuum photons detected from radio observations ($0.6 \times 10^{50}$ s$^{-1}$ at our derived distance). However, the $N_{\text{LyC}}$ observed by radio techniques is only a lower limit on that emitted by the stars, since some of the photons are absorbed by dust grains or leaked through directions of low optical depth. In this way, we can define a lower limit to the IMF slope of $\Gamma < -1.3$. The integrated cluster mass in this case is $M_{\text{cluster}} > 1.0 \times 10^5 M_\odot$.

**Table 1**

| ID  | $J-H$  | $H-K$  | $K$   | $K$ Excess$^a$ | $A^K_b$ | Spectral Type$^c$ | Mass$^a$ $(M_\odot)$ |
|-----|--------|--------|------|--------------|--------|------------------|---------------------|
| 4   | 1.80 ± 0.02 | 1.44 ± 0.04 | 10.92 ± 0.04 | 0.35 | 2.37 | O7.5 | 29 |
| 6   | 2.69 ± 0.02 | 3.28 ± 0.04 | 11.20 ± 0.04 | 1.67 | 5.31 | O6 | 70 |
| 9   | 2.55 ± 0.02 | 1.80 ± 0.04 | 12.08 ± 0.04 | 0.26 | 2.94 | O9 | 22 |
| 10  | 2.26 ± 0.02 | 1.28 ± 0.05 | 11.49 ± 0.04 | -0.08 | 2.11 | O8.5 | 23 |
| 11  | 4.20 ± 0.05 | 2.46 ± 0.05 | 11.85 ± 0.04 | -0.05 | 4.00 | O4.5 | 50 |
| 13  | 3.43 ± 0.04 | 2.59 ± 0.04 | 12.28 ± 0.04 | 0.54 | 4.21 | O6.5 | 34 |
| 14  | 2.67 ± 0.02 | 2.51 ± 0.04 | 12.19 ± 0.04 | 0.91 | 4.08 | O8 | 27 |
| 416 | 1.10 ± 0.04 | 1.38 ± 0.05 | 15.72 ± 0.05 | 0.71 | 2.27 | A7 | 1.7 |
| 472 | 0.26 ± 0.03 | 1.26 ± 0.05 | 15.05 ± 0.05 | 1.09 | 2.08 | A5 | 1.7 |
| 488 | 1.77 ± 0.06 | 2.20 ± 0.07 | 14.86 ± 0.04 | 1.13 | 3.58 | B4 | 4 |
| 598 | 2.53 ± 0.07 | 1.89 ± 0.08 | 10.49 ± 0.06 | 0.38 | 3.09 | O4.5 | 59 |

$^a$ Assumed Koornneef’s (1983) color for normal stars and that all excess emission is in the $K$ band.

$^b$ Derived reddening after correcting for the excess in the $K$ band; see § 3.4.

$^c$ Derived from corrected $K$ magnitudes, assumed intrinsic colors, and properties of ZAMS or typical OB stars. We obtain the stellar spectral type and mass using the ZAMS properties from Blum et al. (2000); see text.

**Table 2**

| ID  | $K$ Excess$^a$ | $A^K_b$ | Spectral Type$^c$ | Mass$^a$ $(M_\odot)$ |
|-----|---------------|--------|------------------|---------------------|
| 4   | 2.9           | 1.57   | B4               | 4                   |
| 6   | 3.5           | 4.51   | B0.5             | 14                  |
| 9   | 2.8           | 2.14   | B6               | 3                   |
| 10  | 2.4           | 1.31   | B5               | 4                   |
| 11  | 3.0           | 3.2    | B2               | 5                   |
| 13  | 3.0           | 3.41   | B2               | 5                   |
| 14  | 3.0           | 3.28   | B2               | 5                   |
| 416 | 1.1           | 1.47   | G0               | 1                   |
| 472 | 1.3           | 1.28   | F5               | 1.2                 |
| 488 | 1.7           | 2.78   | A2               | 2                   |
| 598 | 3.2           | 2.29   | B1               | 7                   |

$^a$ Excess emission resulting from a face-on reprocessing disk with a central source corresponding to the spectral type listed in the fourth column (Hillenbrand et al. 1992).

$^b$ Resultant extinction after correcting for the excess $H-K$ using Hillenbrand et al. (1992) models for reprocessing disks. The $H-K$ excess is nearly constant and equal to =0.5 mag; see § 3.4.

$^c$ Obtained from the observed photometric data, extinction correction, excess-emission models of Hillenbrand et al. (1992), and ZAMS properties from Blum et al. (2000).
3.5. G333.1−0.4 No. 18

In Figure 7 we have only included objects with measured \( J \), \( H \), and \( K \) magnitudes, but object 18 was not detected in the \( J \) band and, for this reason, needs to be discussed separately. This object is bright and has the reddest color and largest excess in the cluster (\( K = 12.46 \) and \( H−K = 5.74 \)). Figure 10 shows this object in the \( J \), \( H \), and \( K \) bands. The \( K \)-band contours are overplotted on the \( J \) and \( H \) images for comparison. Figure 10 demonstrates that source 18 is extremely red and suggests that this object is a deeply buried YSO.

Object 18 probably is a YSO that is consistent with an O-type star. A similar object was located in W51 (IRS 3, from Goldader & Wynn-Williams 1994). This object has a \( K \) excess greater than 4.05 when using the model with a reprocessing disk (Hillenbrand et al. 1992). Certainly, this is an object that deserves further study at longer wavelengths and could aid in trying to understand the processes involved in the formation of massive stars.

4. RESULTS: ANALYSIS OF SPECTRA

The spectra of sources 1 and 2 are shown in Figure 11, and source 4 is presented in Figure 12. Sources 1 and 2 have been divided by a low-order fit to the continuum after correction for telluric absorption. The signal-to-noise ratio is \( S/N > 80 \) for each of these objects. These spectra have been background-subtracted...
with nearby ($\approx 1^\circ$) apertures, though nonuniform extended emission could affect the resulting He $\alpha$ and Br$\gamma$ seen in the stars themselves.

### 4.1. O Star Spectra

The spectra of sources 1 and 2 may be compared with the $K$-band spectroscopic standards presented by Hanson et al. (1996). The features of greatest importance for classification are the C $\text{iv}$ triplet at (vacuum wavelengths) $2.0705, 2.0769,$ and $2.0842$ $\mu$m (emission), the N $\text{iii}$ complex at $2.116$ $\mu$m (emission), and He $\text{ii}$ at $2.1891$ $\mu$m (absorption). The $2.0842$ $\mu$m line of C $\text{iv}$ is typically weak and seen only in very high signal-to-noise spectra (Hanson et al. 1996). The present classification system laid out by Hanson et al. (1996) does not have strong luminosity-class indicators. Still, the He $\text{ii}$ ($2.0581$ $\mu$m) and Br$\gamma$ ($2.1661$ $\mu$m) features can be used to approximately distinguish between dwarfs and giants on the one hand, and supergiants on the other. Generally, strong absorption in Br$\gamma$ is expected for dwarfs and giant stars and weak absorption or emission for supergiants.

The presence of N $\text{iii}$ and He $\text{ii}$ in the spectrum of source 1 (see Fig. 11) leaves no doubt that this is an O-type star. The C $\text{iv}$ emission places source 1 in the kO5–O6 subclass. The apparent absorption features at the positions of Br$\gamma$ and He $\text{ii}$ suggest that source 1 probably is a dwarf or a giant star. The closest match in the Hanson et al. (1996) atlas is HD 93130, classified as O6 III(f). However, it is very difficult to be sure about the exact luminosity class. In our earlier work, we adopted a ZAMS classification because of the presence of massive YSOs in the cluster. Following the same reasoning, we classify object 1 as O6 V.

The spectrum of source 2 shows He $\text{ii}$ at $2.0581$ $\mu$m (emission), He $\text{ii}$ at $2.1137$ $\mu$m (weak absorption), N $\text{iii}$ at $2.116$ $\mu$m (emission), and Br$\gamma$ ($2.1661$ $\mu$m) in absorption. The presence of He $\text{ii}$ and the absence of the C $\text{iv}$ triplet indicate that this star is cooler than source 1, and a comparison with Hanson et al.’s standards gives an O8 V type star. In any event, as we stated in \S 2.2, the spectra of stars in H $\text{ii}$ region are often contaminated by the $2.058$ $\mu$m He $\text{ii}$ and Br$\gamma$ nebular lines. In source 1 it is not so critical, but in the case of source 2 it will require spectra with better S/N to definitively state its spectral type.

### 4.2. G333.1−0.4 No. 4

The spectrum of G333.1−0.4 No. 4 is shown in Figure 12. This object does not show photospheric lines, indicating that it is still (at least partially) enshrouded in its birth cocoon. This is corroborated by the excess emission derived from photometry (see Table 1 and Fig. 5).

The CO band head at $2.2935$ $\mu$m appears in emission, and it is usually attributed to warm (>1000 K), very dense ($\rho \approx 10^{10}$ cm$^{-3}$) circumstellar material near the star (Scoville et al. 1983; Carr 1989). However, a variety of mechanisms and models have been proposed to explain the origin of CO emission in YSOs. These include circumstellar disks, stellar or disk winds, magnetic accretion mechanisms such as funnel flows, and inner disk instabilities similar to those that have been observed in FU Orionis–like objects and T Tauri stars in a phase of disk accretion (Carr 1989; Carr et al. 1993; Chandler et al. 1993; Biscaya et al. 1997). Hanson et al. (1997) reported the presence of CO in emission in several massive stars in M17, and in Figuerêdo et al. (2002) we also found CO emission in a massive YSO in NGC 3576, as mentioned previously. A high-resolution spectrum of source 4 is presented in Blum et al. (2004), where it is shown that the emission is consistent with a disk origin.

### 5. DISTANCE DETERMINATION

In the previous section we classified the spectra of the two brightest stars in G333.1−0.4 as belonging to O-type stars (O6 and O8). We can now estimate the distance to G333.1−0.4 by using the spectroscopic and photometric results. We compute distances assuming the O stars shown in the Figure 11 are on the zero-age main sequence or in the dwarf luminosity class (i.e., hydrogen-burning). The spectral types in each case are assumed

| ID     | $K^*$  | $H−K^*$ | $A_K^b$ | $D_{\text{ZAMS}}^c$ | $D_N^c$ |
|--------|--------|---------|---------|---------------------|---------|
| 1      | 9.16 ± 0.06 | 0.54 ± 0.08 | 0.94     | 2.4                  | 3.0     |
| 2      | 10.22 ± 0.04 | 0.57 ± 0.04 | 0.98     | 2.7                  | 3.9     |
| Average | 0.96 ± 0.15 | 2.6 ± 0.04 | 3.5 ± 0.7 |

* Photometric uncertainties are the sum in quadrature of the photometric uncertainty and the PSF-fit uncertainty; see \S 2.

* The uncertainty in $A_K$ is dominated by the variation in the power-law exponent of the interstellar extinction law (±0.16; Cardelli et al. 1989); see \S 3.2. The uncertainty in the mean $A_K$ is the sum in quadrature of the standard deviation in the mean and the (0.15 mag) systematic uncertainty due to the extinction law.

* Distance estimates assuming mean ZAMS and dwarf (V) luminosities; see text. The uncertainty in the distance is taken as the sum in quadrature of the standard deviation in the mean of the individual estimates and a component (250–500 pc) due to the systematic uncertainty in $A_K$.  

![Graph showing normalized ratio vs. wavelength (Angstroms) for CO emission.](image-url)
to be O6 (star 1) and O8 (star 2). For the ZAMS case, the $M_K$ is taken from Blum et al. (2000). For the dwarf case, the distance is determined using the $M_V$ given by Vacca et al. (1996) and $V-K$ from Koornneef (1983). The distance estimates are shown in Table 3. For the derived spectral types, we obtain distances of $2.6 \pm 0.4$ and $3.5 \pm 0.7$ kpc for the ZAMS and dwarf cases, respectively. The former value is to be preferred, given the presence of massive YSOs in the cluster. The uncertainty quoted for the mean distance is the standard deviation in the mean of the individual distances, added in quadrature to the uncertainty in $A_K$ (250–500 pc).

Our distance estimates are in close agreement with the near distance given by Vilas-Boas & Abraham (2000), 2.8 kpc. Their distance was obtained from the radio recombination line velocity and Galactic rotation model. Smith et al. (1978) estimated the Lyman continuum luminosity of G333.1–0.4 to be $10.8 \times 10^{50}$ s$^{-1}$ assuming a far kinematic distance (10.7 kpc). Adopting our mean value of 2.6 kpc, as indicated by the spectroscopic parallax, considerably reduces the expected ionizing flux from the radio continuum measurements to $0.6 \times 10^{50}$ s$^{-1}$. This value is about 3 times smaller than the value of $1.9 \times 10^{50}$ s$^{-1}$ derived from counting the individual stars and using the mass function (see § 3.3).

6. DISCUSSION AND SUMMARY

We have presented deep $J$, $H$, and $K$ images of the stellar cluster in G333.1–0.4 (Fig. 3) and $K$-band spectra for three cluster members. Two of the latter have classic O star absorption lines. The spectrum of G333.1–0.4 No. 4 (Fig. 12) does not show photospheric lines but, rather, CO emission. These features indicate that it is still enshrouded in its birth cocoon and is perhaps surrounded by a circumstellar disk. The $K$-band excess emission displayed by objects 4, 6, 9, 13, 14, 18, 416, 472, 488, and 598 is similar to that of objects found in other GHII regions. These objects appear to be still heavily enshrouded by circumstellar envelopes or disks. Object 18 is an extremely buried YSO, and it deserves follow-up observations at longer wavelengths to further investigate its nature.

The $K$-band luminosity function and IMF were computed and compared with those of other massive-star clusters. The slope of the KLF ($\alpha = 0.24 \pm 0.02$) is similar to that found in other young clusters, and the IMF slope of the cluster, $-1.3 < \Gamma < -1.1$, is consistent with Salpeter’s value to within 1.25 $\sigma$.

The spectral types of the newly identified O stars and the photometry presented here constrain the distance to G333.1–0.4, which was uncertain from earlier radio observations. Our measurements break the ambiguity in the distance determinations from radio techniques. Our value, $2.6 \pm 0.4$ kpc, is consistent with the lower distance determined by Vilas-Boas & Abraham (2000) and implies an $N_{\text{luc}} = 0.6 \times 10^{50}$ s$^{-1}$, which is considerably lower than that adopted by Smith et al. (1978). The number of Lyman continuum photons derived from the contribution of all massive stars in the cluster is $0.2 \times 10^{50}$ s$^{-1} < N_{\text{luc}} < 1.9 \times 10^{50}$ s$^{-1}$. The integrated cluster mass is $1.0 \times 10^{4} M_{\odot} < M_{\text{cluster}} < 1.3 \times 10^{5} M_{\odot}$.

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REFERENCES

Barbosa, C. L., Damineli, A., Blum, R. D., & Conti, P. S. 2003, AJ, 126, 2411
Biscaya, A. M., Rieke, G. H., Narayan, G., Luhrman, K. L., & Young, E. T. 1997, ApJ, 491, 359
Blum, R. D., Barbosa, C. L., Damineli, A., Conti, P. S., & Ridgway, S. 2004, 617, 1167
Blum, R. D., Conti, P. S., & Damineli, A. 2000, AJ, 119, 1860
Blum, R. D., Damineli, A., & Conti, P. S. 1999, AJ, 117, 1392
--. 2001, AJ, 121, 3149
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Carr, J. S. 1989, ApJ, 345, 522
Carr, J. S., Tokunaga, A. T., Najita, J., Shu, F. H., & Glassgold, A. E. 1993, ApJ, 411, L37
Chandler, C. J., Carlstrom, J. E., Scoville, N. Z., Dent, W. R. F., & Geballe, T. R. 1993, ApJ, 412, L71
Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029 (erratum 87, 1893)
Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, ApJ, 525, 750
Figueiredo, E., Blum, R. D., Damineli, A., & Conti, P. S. 2002, AJ, 124, 2739
Frogel, J. A., Persson, S. E., Aaronson, M., & Matthews, K. 1978, ApJ, 220, 75
Goldader, J. D., & Wynn-Williams, C. G. 1994, ApJ, 433, 164
Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281
Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, ApJ, 489, 698
Hillenbrand, L. A., & Carpenter, J. M. 2000, ApJ, 540, 236
Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, ApJ, 397, 613
Joch-Sarenssen, H., & Knude, J. 1994, A&A, 288, 139
Koornneef, J. 1983, A&A, 128, 84
Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995, ApJ, 454, 151
Mathis, J. S. 1990, ARA&A, 28, 37
Meyer, M. R., Calvet, N., & Hillenbrand, L. A. 1997, AJ, 114, 288
Okumura, S., Mori, A., Nishihara, E., Watanabe, E., & Yamashita, T. 2000, ApJ, 543, 799
Oliva, E., & Origlia, L. 1992, A&A, 254, 466
Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, AJ, 116, 2475
Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., & Hut, P. 2002, ApJ, 565, 262
Salpeter, E. E. 1955, ApJ, 121, 161
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Scoville, N., Kleinmann, S. G., Hall, D. N. B., & Ridgway, S. T. 1983, ApJ, 275, 201
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Smith, L. F., Mezger, P. G., & Biermann, P. 1978, A&A, 66, 65
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
Vilas-Boas, J. W. S., & Abraham, Z. 2000, A&A, 355, 1115
Watson, C., Araya, E., Sewilo, M., Churchwell, E., Hofner, P., & Kurtz, S. 2003, ApJ, 587, 714
Whitney, B. A., et al. 2004, ApJS, 154, 315