A STRUCTURAL ANALYSIS OF STAR-FORMING REGION AFGL 490

L. C. Masiunas1, R. A. Gutermuth2,7, J. L. Pipher3,7, S. T. Megeath4, P. C. Myers5, L. E. Allen6, H. M. Kirk5, and G. G. Fazio5

1 Five College Astronomy Department, Smith College, Northampton, MA, USA
2 Department of Astronomy, University of Massachusetts, Amherst, MA, USA
3 Department of Physics & Astronomy, University of Rochester, Rochester, NY, USA
4 Department of Physics & Astronomy, University of Toledo, Toledo, OH, USA
5 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
6 National Optical Astronomy Observatory, Tucson, AZ, USA

Received 2011 September 30; accepted 2012 April 6; published 2012 June 5

ABSTRACT

We present Spitzer IRAC and MIPS observations of the star-forming region containing intermediate-mass young stellar object (YSO) AFGL 490. We supplement these data with near-IR Two Micron All Sky Survey photometry and with deep Simultaneous Quad Infrared Imaging Device observations off the central high-extinction region. We have more than doubled the known membership of this region to 57 Class I and 303 Class II YSOs via the combined 1–24 μm photometric catalog derived from these data. We construct and analyze the minimum spanning tree of their projected positions, isolating one locally overdense cluster core containing 219 YSOs (60.8% of the region’s members). We find this cluster core to be larger yet less dense than similarly analyzed clusters. Although the structure of this cluster core appears irregular, we demonstrate that the parsec-scale surface densities of both YSOs and gas are correlated with a power-law slope of 2.8, as found for other similarly analyzed nearby molecular clouds. We also explore the mass segregation implications of AFGL 490’s offset from the center of its core, finding that it has no apparent preferential central position relative to the low-mass members.

Key words: infrared: stars – stars: formation – stars: pre-main sequence

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Spitzer Space Telescope has provided a tremendous leap in sensitivity and spatial resolution over previous infrared telescopes, enabling numerous surveys of nearby star-forming regions (e.g., Megeath et al. 2004; Teixeira et al. 2006; Muench et al. 2007; Gutermuth et al. 2009) as well as unbiased surveys of entire star-forming molecular clouds (e.g., Jørgensen et al. 2006; Harvey et al. 2006; Evans et al. 2009; Rebull et al. 2010, 2011), revealing most of the members that have dusty circumstellar material in these regions. Such an unbiased view has demonstrated that despite the prevalence of the clustered formation environment (Lada & Lada 2003; Porras et al. 2003), less than a quarter of these stars are found in regions dense enough to experience close approaches with neighbors that would have notable effects on circumstellar disks (Bressert et al. 2010). The high frequency of clustered star formation gives insight into the physical processes that govern where and when molecular clouds form stars (Heiderman et al. 2010; Gutermuth et al. 2011). Therefore, in order to understand the process by which clouds give rise to young stars, we must compare the structure of star-forming regions to that of their natal clouds.

The many Spitzer surveys have brought an empirical basis against which we can compare any new data from an individual star-forming region. For example, Evans et al. (2009) found 1024 young stellar objects (YSOs) across five nearby star-forming clouds and improved the constraints on star formation rates and efficiencies at low and high densities. Rebull et al. (2011) studied the nearby North America Nebula, expanding the known population of the region by an order of magnitude. Gutermuth et al. (2009) found 2548 YSOs in 36 nearby star-forming regions, providing a comprehensive analysis of the clusters’ structures and forming a broad picture of star formation within the nearest kiloparsec.

Within this context, we have performed a focused investigation of the AFGL 490 star-forming region. The bright infrared source AFGL 490 (also known as GL 490), which lies at a distance of 900 pc (Snell et al. 1984) in the Cam OB1 association, has been well studied at many wavelengths from near-IR to millimeter. It resides ~5 pc away from the variable star CE Cam, an exposed A0I star whose UV emission is likely responsible for excitation of the strong 8.0 μm emission from polycyclic aromatic hydrocarbon (PAH) dust in the region. AFGL 490 is an 8–10 M⊙ protostar that is variable in the near-infrared (Jones et al. 1990); it has long been known to have a bipolar molecular jet (Snell et al. 1984), an extended envelope, and a rotating disk (Schreyer et al. 2006). Another large outflow in the region, AFGL 490-iki, was discovered 7′ north of AFGL 490 (Lyder et al. 1998). One of the first mentions of a cluster associated with AFGL 490 is found in a paper by Hodapp (1994), which reported that the cluster was small (45 associated stars) and had a low density. Most recently, the AFGL 490 region was studied by Gutermuth et al. (2009), more than tripling the membership of the region; however, the field of view of the reported observations truncated the apparent distribution of the cluster.

Here we present an expanded infrared survey of the AFGL 490 region, including new Spitzer and deep ground-based near-IR imaging, with the aim of fully sampling its spatial extent. The paper is organized as follows. In Section 2, we describe the data, its reduction, and source catalogs. In Section 3, we describe...
2. DATA AND OBSERVATIONS

2.1. IRAC Imaging

AFGL 490 was initially observed using Spitzer Space Telescope’s IRAC instrument at 3.6, 4.5, 5.8, and 8.0 μm on 2004 October 8 (AOR ID 3654656, centered on right ascension 03h27m38.60 and declination +58°46′57.7″, J2000) as part of the Guaranteed Time Observation Proposal ID 6, “Structure and Incidence of Young Embedded Clusters.” These data were analyzed and presented by Gutermuth et al. (2009), who noticed that the YSO distribution of the region extended to the edge of the surveyed 15′ × 15′ field of view (orange overlay in Figure 1). The IRAC view of the region was expanded to 0.51 deg² as part of the GTO “Clusters Near Clusters” program (PID 40147). These data were obtained on 2007 October 23 (AOR ID 21894144) and 2008 March 9 (AOR ID 21894400). Integration time was 10.4 s pixel⁻¹ with four dithered images, giving an effective integration time of 41.6 s. All observations were obtained in high dynamic range mode, where 10.4 s and 0.4 s observations were taken at each pointing to extend the effective dynamic range of the survey.

The data were initially processed by the S18.7.0 software package at the Spitzer Science Center, producing standard basic calibrated data (BCD) products. Post-BCD data treatment was performed using Cluster Grinder (CG), a Spitzer data analysis package written in IDL (Gutermuth et al. 2009). In summary, bright source artifacts were removed, correcting “banding” and “pulldown,” as well as cosmic-ray hits and other transient artifacts. Mosaics were made at a pixel resolution of 0.′86 pixel⁻¹, with an effective resolution of 2′′2 at FWHM; a color image of the IRAC mosaics is found in Figure 1. CG incorporates our source classification and the products of our data, including extinction and nth nearest neighbor maps. In Section 4, we analyze the data products in the context of structure: we find the densest area in the region and compare it to a previous survey, and investigate the possible mass segregation of AFGL 490. In Section 5, we summarize our results.

Figure 1. Coverage of IRAC (background image, outlines in white), overlaid with the original IRAC coverage in Gutermuth et al. (2009) (orange), SQIID JHK coverage (blue), and expanded MIPS 24 μm coverage (green). For the color image, blue is 3.6 μm, green is 4.5 μm, and red is 8.0 μm.

(A color version of this figure is available in the online journal.)
PhotVis version 1.10 (Gutermuth et al. 2008) to automatically detect point sources using an algorithm that robustly isolates stars in fields of varying background emission. Source positions measured from the IRAC data were compared with Two Micron All Sky Survey (2MASS) counterpart coordinates to improve the astrometric calibration of each BCD image before making final IRAC mosaics. Aperture photometry was performed using an aperture radius of 2.4, with background inner and outer annuli of 2.4 and 7.2, respectively. Photometric zero points adopted (i.e., the magnitude assigned for 1 DN s⁻¹ flux in an aperture) were 20.207, 19.452, 17.251, and 17.644 mag for 3.6, 4.5, 5.8, and 8.0 μm bands, respectively. These zero points are derived from standard calibration values and aperture corrections (Reach et al. 2005), and account for our reduced pixel size. The field-averaged 90% differential completeness limits are 16.6, 16.4, 14.8, 13.3 mag in the same bands, respectively, with a signal-to-noise requirement of 5 or greater (0.2 mag). These are derived from artificial star insertion and retrieval testing following the method of Gutermuth et al. (2005).

2.2. MIPS Imaging

Initial 24 μm MIPS images for PID 6 (Gutermuth et al. 2009) were obtained on 2004 September 24 (AOR ID 3663104, centered on right ascension 03h28m31s and declination +58°25′37″. J2000.0). The field of view was expanded on 2007 October 23 (AOR ID 21894144) as part of PID 40147. MIPS data cover 0.38 deg² (green overlay in Figure 1), 0.26 of which are within IRAC coverage. All observations were taken at the medium scan rate with an effective integration time of 40.4 s.

The data were initially processed by version S16.1.0 of the standard MIPS BCD pipeline. Post-BCD processing was performed with CG (described in Section 2.1). Mosaics were made at a pixel resolution of 1.8 pixel⁻¹ with an effective resolution of 4.5 at FWHM. Aperture photometry was performed using an aperture radius of 7″ with background inner and outer annuli of 7″ and 17.8, respectively. The photometric zero point adopted was 15.35 mag (14.6 from Gutermuth et al. 2008, with conversion for smaller pixel size), and the field averaged 90% differential completeness limit is 8.4 mag with a signal-to-noise requirement of 5 or greater (0.2 mag).

2.3. SQUID Imaging

Near-infrared imaging in J, H, and Ks bands was obtained using the Simultaneous Quad Infrared Imaging Device (SQUID) on Kitt Peak National Observatory’s 2.1 m telescope on 2003 November 8. Four one-minute dithers were taken per position in a 3 × 3 position raster. The final mosaics have a mean integration time per position of 240 s, and cover 0.05 deg² (14′ × 14′, blue overlay in Figure 1), with a plate scale of 0.′70 pixel⁻¹ and an FWHM of 2.6, 2.5, and 2.6 pixels for J, H, and Ks bands, respectively. SQUID data were reduced using custom IDL routines for ground-based near-IR data reduction (Gutermuth et al. 2005). Those routines include modules for linearization, flat-field creation and application, background frame creation and subtraction, distortion measurement and correction, astrometric calibration, cosmic-ray filtering, and mosaicking. 2MASS data were used as the astrometric reference for distortion measurement and final position calibration. A source catalog was made using PhotVis version 1.10, with radii of the apertures and inner and outer limits of the sky annuli of 2′/1, 3′/5, and 5′/5, respectively, and a sigma threshold of 9. Photometric zero points were 22.43, 22.42, and 21.83 mag for J, H, and Ks bands, adopted in order to minimize residuals with 2MASS photometry (Figure 2).

The SQUID data greatly increased near-IR sensitivity relative to 2MASS coverage in the densest area of the region. These data are considerably deeper than 2MASS, reaching field-averaged 90% differential completeness limits of 17.8, 16.9, and 16.1 mag for J, H, and Ks bands, respectively, with a signal-to-noise requirement of 10 or greater (0.1 mag). For comparison, 2MASS is 99% complete at 15.8, 15.1, and 14.3 mag in J, H, and Ks bands. A comparison of the SQUID and 2MASS data can be found in Figure 3. The median residuals for bright objects are 0.035, 0.040, and 0.045 mag for J, H, and Ks, respectively; the dim source residuals are dominated by the poor signal to noise of the 2MASS detections: 0.08, 0.11, 0.11 mag.

2.4. Source Catalog

The final merged source catalog includes data in J, H, and Ks bands from 2MASS and SQUID; 3.6, 4.5, 5.8, and 8.0 μm from IRAC; and 24 μm from MIPS. Where 2MASS and SQUID data overlap, the SQUID data are used, provided detections are dimmer than saturation limits of J = 10, H = 10, and Ks = 9.5 mag and have a good signal-to-noise ratio (here, a signal-to-noise ratio of 5). If a detection in any SQUID band did not meet this criteria, that detection was replaced by the 2MASS data in each band in an effort for each source to have more consistent data. To make the final catalog, the IRAC and 2MASS source lists were merged with a limiting tolerance of 1″, then MIPS detections were included where IRAC or 2MASS detections existed using a tolerance of 2″. Finally, the SQUID data were merged, using a tolerance of 1″.

3. ANALYSIS

3.1. Source Classification

We applied the three-phase 1–24 μm point source classification scheme of Gutermuth et al. (2009) to our merged catalog. In each phase of the technique, we use a unique subset of the available bandpasses to securely identify YSOs while minimizing contamination by field stars, extragalactic sources, and local nebulosity. By mitigating bias from reddening by dust associated with the natal cloud material, we can confidently classify those YSOs as envelope-bearing protostars (called Class I below, but includes some Class 0 and flat spectrum YSOs) or pre-main-sequence stars with circumstellar disks (called Class II below, but includes transition disks). Tests performed on this classification scheme suggest that the likelihood of confusing a Class II with an edge-on disk as a Class I are less than 3.3% (Gutermuth et al. 2009). We do not classify diskless YSOs (Class III) because they are indistinguishable from field stars; we cannot reliably identify them using this data set.

In Phase 1 of this technique, we utilized only those sources detected in all of the Spitzer IRAC bands with photometric uncertainties of less than 0.2 mag. Unresolved star-forming galaxies have a very distinct 5.8–8.0 μm color caused by strong PAH feature emission; we used custom color–color diagram cuts to uniquely identify and remove these sources. Here, we also identified active galactic nuclei (AGNs), which look like low-luminosity YSOs with flat spectral energy distributions but follow unique conditions in 4.5 and 8.0 μm color space; they can be identified using cuts on a color–magnitude diagram (Figure 4). Unfortunately, this method does not find all AGNs: on average, it is estimated that 7 AGNs deg⁻² are misidentified...
Figure 2. Plot of the magnitude residuals from the merged SQIID and 2MASS catalog. The x-axis plots the 2MASS magnitudes, while the y-axis plots the difference between 2MASS and SQIID magnitudes. Dotted lines mark the saturation point for SQIID at $J = 10$, $H = 10$, and $K_S = 9.5$ mag.

as YSOs (Gutermuth et al. 2009), and some bona fide YSOs which are older or more distant are lost. In this phase, we also removed unresolved knots of shock emission, which are bright at 4.5 $\mu$m because of strong molecular hydrogen emission. Finally, we classified YSOs as Class I or II predominantly with the $[4.5]-[5.8]$ discriminant color (Figure 5), which is affected much less by dust reddening than $[3.6]-[4.5]$ (Flaherty et al. 2007). A color–color diagram showing the basic results from this process is found in Figure 6.

We applied Phase 2 to those sources which lack detections in 5.8 and 8.0 $\mu$m bands, a common occurrence among YSOs near the nebulous centers of embedded clusters, and which have high signal-to-noise detections in $H$ and $K_S$ bands (uncertainty less than 0.1 mag). First, we measured the photometric reddening of each source by dust along the line of sight as a ratio of $E_{H-K_S}$ using the source’s photometry and the reddening law of Flaherty et al. (2007). The primary means of taking this measurement was the $J-H$ versus $H-K_S$ color–color diagram with the Meyer et al. (1997) classical T Tauri star (CTTS) locus defining the intrinsic colors; if the source was not detected at $J$ band, the $H-K_S$ versus $[3.6]-[4.5]$ color–color diagram with the YSO locus of Gutermuth et al. (2005), calibrated against the $JHK$ CTTS locus, was used instead. We then converted the $E_{H-K_S}$ color excess to $E_{K-[3.6]}$ and $E_{[3.6]-[4.5]}$ using the reddening law of Flaherty et al. (2007), facilitating dereddening of those colors for use in YSO identification and classification. This allowed us to determine YSO classifications based on dereddened colors. Also, we set a brightness limit in this phase, requiring all Class II YSOs to have $[3.6]<14.5$ mag and protostars to have $[3.6]<15$ mag, which allowed for another pass at filtering out dim extragalactic contaminants.

In Phase 3, we re-examined the entire catalog, re-evaluating sources with a 24 $\mu$m detection with an uncertainty of less than 0.2 mag. Objects classified as lacking in IR-excess in the earlier phases but having excess emission at 24 $\mu$m were classified as transition disk YSOs. Those sources which had insufficient detections in $J$, $H$, $K_S$, and the IRAC bands but with bright 24 $\mu$m emission were considered deeply embedded objects (likely protostars). Those sources which lacked a strong 24 $\mu$m detection but had been classified as Class I YSOs in Phase 1 were reclassified as heavily reddened Class II YSOs.

In total, we have identified 360 YSOs with infrared excess emission in AFGL 490. Of those, 57 have excess consistent with Class I YSOs and 303 have excess consistent with Class II YSOs. There are 22 sources classified as transition disk YSOs and 10 as deeply embedded YSOs. For the purposes of the following analysis, the deeply embedded protostars were included in the Class I count as envelope-bearing protostars and the transition disk YSOs were included in the Class II count as pre-main-sequence stars with disks. A complete list of the YSOs identified here can be found in Table 1. The YSO completeness is nontrivial to characterize, as physical parameters like luminosity and mass are rendered
uncertain by poor constraints on heliocentric distance, age, and line-of-sight extinction by dust. By adopting a distance of 900 pc, a pre-main-sequence stellar age of 1 Myr, and the model color–magnitude tracks of Baraffe et al. (1998), we find that we are complete to diskless \(0.2 \, M_\odot\) stars. However, we have not identified any diskless YSOs as members, thus this represents an overestimate of the limiting mass for disk-bearing Class II YSOs. Under the assumption of a standard initial stellar mass function, we have detected over 90\% of the stars and over 99\% of the total stellar mass, modulated by the fraction of the membership that has a disk (Kroupa 2001). That fraction is expected to be greater than half. Completeness for Class I sources is more difficult to constrain based on a physical quantity, as the near- and mid-IR emission from these objects is dominated by the variable accretion luminosity which is reprocessed by the non-uniform, dusty outer envelope (Dunham et al. 2010).

3.2. nth Nearest Neighbor YSO Surface Density Map

We present the spatial distribution of YSOs in Figure 7, overlaid on the contours of near-IR extinction (described below). The YSOs are visually overdense near AFGL 490, as well as north and southwest of it, apparently correlated with the regions where extinction is greater than 7 mag. To more easily compare the surface density structure of the YSOs to the extinction map, we made a smoothed map of their surface density. To achieve this, we adopted the \(n\)th nearest neighbor surface density estimator smoothed over \(n = 6\) neighbors (Gutermuth et al. 2008). More specifically, at each location in a uniform grid, we calculated the radial distance to the sixth nearest YSO, \(r_6\), and then computed the local surface density following the standard formula:

\[
N(n) = \frac{(n-1)}{(\pi r_6^2)}
\]

(Casertano & Hut 1985). We chose a grid size of 9′′ to Nyquist sample the shortest \(r_6\) distance centered on each YSO. The typical (median) \(r_6\) is 70′′; given that we used an adaptive smoothing technique, the effective resolution varies at any given point. The range of surface densities in the map are 0.03–250 YSOs pc\(^{-2}\). Figure 8 shows a contour plot of the final surface density map, with contours increasing at intervals of 1\(\sigma\) (\(\sigma = 50\%\) in the case of \(n = 6\), Casertano & Hut 1985) from the next highest level overplotted.

3.3. Near-infrared Extinction Map

In order to characterize the structure of molecular gas in the region, we constructed a map of near-IR extinction from dust using the combined SQIID and 2MASS catalog. We achieved this by computing the mean \(H - K_s\) color excess of background stars (foreground stars are filtered via iterative outlier rejection) relative to an assumed intrinsic color \(H - K_s = 0.2\) for the nearest 20 sources to each point in a uniformly sampled grid (Gutermuth et al. 2005). As with the YSO surface density maps generated above, we adopt a
grid size of 37″ for the extinction map to Nyquist sample the median $r_{20}$ distance of low extinction, and thus high-density, field stars. Because of the diminishing brightness of stars at higher extinctions, the adaptively smoothed map loses some natural resolution in those places ($r_{20}$ ranges from 33″ to 129″ Gutermuth et al. 2011). The final extinction map has a range of 0–19.8 $A_V$ (magnitudes). The incorporation of the significantly deeper SQIID data into the near-IR catalog resulted in a much higher fraction of YSOs detected at the $H$ band, causing spurious extinction structure in the map where high IR-excess sources are found. To improve the quality of the map, we removed all Spitzer-identified YSOs from the catalog used to make the extinction map (Figure 7). Upon visual comparison of the extinction map, which shows gas structure, and YSO surface density map (Figure 8), which shows the structure in the YSO spatial distribution, the similarities are striking; we will investigate this similarity in Section 4.3.

3.4. Cluster Core Extraction and Structure

Figures 7 and 8 reveal that several locally overdense groupings, or cluster cores, are apparent in the smoothly varying spatial distribution of YSOs in AFGL 490. We isolate these cluster
Table 1

Spitzer-identified YSOs: IRAC, MIPS, and Near-IR Magnitudes

| Region Name | Index | R.A.\(^a\) | Decl.\(^a\) | \(J\) | \(H\) | \(K_s\) | [3.6] | [4.5] | [5.8] | [8.0] | \(A_k\)\(^b\) | \(\alpha_{IRAC}\)\(^c\) | Class(G09) | Class |
|-------------|-------|-------------|-------------|------|------|-------|------|------|------|------|-------|----------|--------|-------|
| AFGL490     | 1     | 03:27:15.48 | +58:50:00.6 | 17.80 ± 0.04 | 15.92 ± 0.02 | 14.74 ± 0.01 | 13.49 ± 0.01 | 12.92 ± 0.01 | 12.79 ± 0.05 | 12.47 ± 0.09 | 5.66 ± 0.03 | 1.07 | −1.74 | I*  |
| AFGL490     | 2     | 03:27:16.15 | +58:54:21.4 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0.93 | I*  |
| AFGL490     | 3     | 03:27:17.19 | +58:50:32.8 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0.81 | I*  |
| AFGL490     | 4     | 03:27:22.61 | +58:43:59.7 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0.83 | I*  |
| AFGL490     | 5     | 03:27:23.59 | +58:55:07.9 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0.06 | I*  |
| AFGL490     | 6     | 03:27:26.31 | +58:44:00.3 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0.32 | I*  |
| AFGL490     | 7     | 03:27:27.95 | +58:54:09.7 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1.70 | I*  |
| AFGL490     | 8     | 03:27:29.66 | +58:44:20.3 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 4.01 | I*  |
| AFGL490     | 9     | 03:27:31.90 | +58:50:12.3 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 2.58 | I*  |
| AFGL490     | 10    | 03:26:49.36 | +58:45:23.7 | 13.76 ± 0.01 | 12.00 ± 0.01 | 11.05 ± 0.01 | 9.58 ± 0.01 | 8.69 ± 0.01 | 7.88 ± 0.01 | 6.78 ± 0.01 | 2.36 ± 0.01 | 1.10 | 0.36 | I  |

Notes.

\(^a\) J2000 coordinates.
\(^b\) Only provided for sources with valid JHKs or HK[3.6][4.5] photometry.
\(^c\) Extinction is not accounted for in these values. High extinction can bias \(\alpha_{IRAC}\) to higher values.
\(^d\) Rejected as a member in this work.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 7. Contours of near-IR extinction from dust, beginning with \( A_V = 5 \) and increasing at intervals of 2 mag. The positions of YSOs are overlaid, with Class I and Class II sources represented in black and red, respectively. The intermediate-mass star AFGL 490, embedded within the cloud, and variable star CE Cam, which is exposed, are plotted in blue. The dark gray line delineates the IRAC field of view.

(A color version of this figure is available in the online journal.)

cores following the methodology of Gutermuth et al. (2009), summarized below.

We began by connecting all of the YSOs to their nearest neighbors through a unique, unified network of lines such that the total connection length is minimized, called a minimum spanning tree (MST; Cartwright & Whitworth 2004). Every point was connected by the minimum distance between the next point to form a “branch,” similar to the way the eye connects points in a constellation (Kirk & Myers 2011). It is worth noting that the nearest neighbor distances analyzed in Section 3.2 above are in fact a degenerate subset of the MST branches (Gutermuth et al. 2009). In other words, a sizable fraction of MST branches connect nearest neighbors and are double counted in the nearest neighbor distance distribution above.

Once the MST was constructed, we defined cluster cores by adopting a threshold branch length, \( L_{\text{crit}} \). Any connections longer than this length, we erased. To avoid choosing an arbitrary length to define a core (Schmeja & Klessen 2006), we used the algorithm defined in Gutermuth et al. (2009) to determine the threshold length from the cumulative distribution of branch lengths. First, we plotted the cumulative distribution function (CDF) of the MST branch lengths. The CDF can be approximated by two intersecting line segments; one is steep and the other shallow, corresponding to the denser and more isolated areas in the region, respectively. We assign \( L_{\text{crit}} \) as the branch length of the point where these two lines intersect. The CDF, overplotted with the line segments and threshold branch length, can be found in Figure 9. We adopted this technique because it robustly identifies relative overdensities among the YSO distribution. In essence, we have traded away the systematic grouping ambiguities that accompany the application of strict, uniform density thresholds (e.g., Evans et al. 2009) caused by incomplete membership counts (uncertain disk fraction) and heliocentric distances, in favor of a relative threshold definition that references the lowest density YSOs observed, and it is thus prone to uncertainty from a limited field of view.
The surface density map of YSOs, as determined from adaptively smoothing over the nearest six neighbors. The gray scale is chosen such that 0 YSOs pc$^{-2}$ is white and 200 is black. Contours are overplotted, increasing at intervals of 1σ (σ = 50% in the case of n = 6) from the next highest level (Casertano & Hut 1985). The dark gray line delineates the IRAC field of view.

We find $L_{\text{crit}} = 0.319$ pc with the above technique; under this threshold, we identify only a single, large core with membership greater than the adopted $N_{\text{min}} = 10$ (Gutermuth et al. 2009). This core contains 219 YSO members: 47 Class I protostars and 172 Class II pre-main-sequence stars with disks. The core makes up 60.8% of the region’s membership. It contains 82.5% of the region’s Class I population and 56.8% of the Class II population. Because of the relatively different durations of the Class II and Class I evolutionary phases, the ratio of the number of Class II members to Class I members is a proxy for the relative age of similarly observed regions. The AFGL 490 cluster core has a Class II/Class I ratio of 3.7 (smaller than the regional Class II/Class I ratio of 5.3). We draw a convex hull, a polygon whose vertices are the outermost members of a group of points, around the cluster core members to define the core’s area and size. Because of the nature of the convex hull, it was not capable of tracing the unique shape of the core; visually, the hull encompasses four extra sources that are not included in the cluster core.

It is interesting to note that when $N_{\text{min}}$ was reduced to five sources, three other overdense groupings were found in the diffuse area surrounding the massive cluster core. However, these local overdensities had insufficient membership to allow any statistical conclusions, and subsequent analyses will focus on the main cluster core. We report the position and membership count of all cluster cores in Table 2, and all cores are plotted in Figure 10.
The nearest neighbor peaks for both classes, shown in Figure 11, correspond closely to those found in similarly aged nearby clusters studied with Spitzer. In NGC 1333 (Gutermuth et al. 2008), all YSOs have nearest neighbor distances peaking between 0.02 and 0.05 pc, both separately by class and as a total YSO count. While the peaks found in Gutermuth et al. (2008) are similar to those found here, the Class II spacing peak here is not prominent compared to the larger distribution. In NGC 2264, nearest neighbor distances for Class I YSOs peaked at a distance of 0.078 pc (Teixeira et al. 2006), but the study ignored Class II YSOs that appear mixed among the protostars.

4.2. Comparison with Gutermuth et al. (2009) Cluster Survey

With our expanded field of view, it is clear that the region is much larger than the area studied by Gutermuth et al. (2009). We have also increased near-IR sensitivity in the densest region. Previous coverage of the region was only large and deep enough to reveal 161 YSOs; this study has found 202 new YSOs (34 within the original field of view) and rejected three YSOs from the previous study, with a new total of 360. Some YSOs changed class from those by Gutermuth et al. (2009) considering the addition of new data. Five objects previously considered deeply embedded protostars (2, 5, 7, 8, 9) are now more confidently classified as Class I members, but in terms of the analysis by Gutermuth et al. (2009), this does not change the overall classification, as noted in Section 3.1. A small number of objects switched class from Class I to Class II (25) or vice versa (91, 130), since they lie close to the color boundary between these classes. For similar reasons, one object previously classified as Class II (148) is now considered a transition disk YSO; two Class II YSOs (51, 151) are now considered photospheric (i.e., non-excess) sources; and one transition disk YSO (156) is now similarly classified as a photosphere. Those exhibiting no excess emission are rejected as high confidence members, as they are most likely field stars, and are thus not included in the analysis presented below. We have increased the Class I count by 58%, from 36 to 57, and found the region to contain 2.4 times as many Class II YSOs, an increase from 125 to 303. While this changes the region’s Class II/Class I ratio from 3.5 to 5.3, the ratio within the cluster core increased only slightly, from 3.1 to 3.7. The differences in YSO counts between Gutermuth et al. (2009) and this study can be found in Table 3.

Gutermuth et al. (2009) compared physical size by measuring the effective radius, $R_{\text{hull}}$, defined as $\sqrt{\langle A_{\text{hull}}/\pi \rangle}$, where $A_{\text{hull}}$ is the area of the core within the convex hull drawn in Section 3.4. With the expanded coverage, the region’s effective radius is now 5.36 pc, 2.9 times larger than its previous radius of 1.84 pc. While Gutermuth et al. (2009) does not include large nearby clustered star-forming regions such as Orion or Cep OB3b, the AFGL 490 region is considerably larger than the Mon R2 region, the largest region in their study with 235 total YSOs and an effective radius of 2.02 pc. It is worth noting that the full spatial extent of Mon R2 as studied by Gutermuth et al. (2009) may suffer from a truncation similar to that work’s survey of the AFGL 490 region. The full Mon R2 cloud, untruncated, is studied in Gutermuth et al. (2011).

Where the previous study found two small cluster cores in the AFGL 490 region with 130 YSOs combined, this study finds 219 YSOs in one large cluster core. This is partly due to the increased field of view, enabling a complete survey of the zone of overdensity, and to the change in $L_{\text{crit}}$. We added 80 YSOs to the higher-density area and 110 YSOs to the transition and background YSOs in the CDF. This created a more shallow line fit in the background area of the CDF, causing the two fit lines to intersect at a longer length. As a result, $L_{\text{crit}}$ increased from 0.241 pc in Gutermuth et al. (2009) to 0.319 pc, which caused the two cores found in Gutermuth et al. (2009) to combine into one large core. If we apply the $L_{\text{crit}}$ used by Gutermuth et al. (2009), we retrieve the two smaller cluster cores from that work; however, those cores are now spatially complete, and the extra sensitivity from SQUIID fills in the area. The new populations are 183 and 21 YSOs in Gutermuth et al. (2009) cluster cores 1 and 2, respectively.

A summary of the comparison of the AFGL 490 cluster core structural parameters measured here to the 25th, median, and 75th percentile values for the entire cluster survey by Gutermuth et al. (2009) can be found in Table 4. AFGL 490’s cluster core is comparatively very large. It contains 8.4 times more
Figure 10. Complete MST, with connections less than the threshold length $L_{\text{crit}}$ in black. Cluster cores are overlaid in color. The large cluster core in the middle includes 219 YSOs, and is the only core to be large enough to be considered according to the method followed in Gutermuth et al. (2009). In the surrounding cores, one has six and the others have five members.

(A color version of this figure is available in the online journal.)

Table 3
AFGL 490 Membership Statistics, Previous versus Expanded Surveys

| Survey            | $N_{\text{cores}}$ | $L_{\text{crit}}$ (pc) | Total YSOs | Class I | Class II | Class II/Class I |
|-------------------|---------------------|-------------------------|------------|---------|----------|------------------|
|                    |                     |                         | All Core(s) Bkgd$^a$ | All Core(s) Bkgd$^a$ | All Core(s) Bkgd$^a$ | All Core(s) Bkgd$^a$ |
| Gutermuth et al. (2009) | 2                   | 0.241                   | 161 130 31           | 36 32 4          | 125 98 27         | 3.5 3.1 6.8        |
| Expanded           | 1                   | 0.319                   | 360 219 141         | 57 47 10         | 303 172 131       | 5.3 3.7 13.1       |

Note. $^a$ Background here refers to YSOs in the region not considered part of the cluster (not field stars), in keeping with Table 5 by Gutermuth et al. (2009).

YSOs than the median YSO count from the survey (26), with 7.8 times as many Class I members and 8.1 times as many Class II members (6 and 21 being the median values from Gutermuth et al. (2009), respectively). These values are outliers of those recorded by Gutermuth et al. (2009); however, the core Class II/Class I ratio of 3.7 is identical to the survey median. The core not only has a large population but also an abnormally large spatial extent. It has an effective radius of 1.68 pc, 4.3 times larger than the median radius (0.39 pc) and far larger than the 75th percentile of the survey cores. Its aspect ratio of 2.07 is greater than the median aspect ratio of 1.82, making it more elongated than the typical core. Despite its large physical size, the cluster core has a relatively low surface density of stars. With a mean surface density of 22 sources pc$^{-2}$, it falls even lower than the 25th percentile of the survey cores and is only 37.4% of the median survey value of 60 sources pc$^{-2}$. The mean $A_K$ of 0.87 mag is only slightly greater than the survey average of 0.8 mag.
Figure 11. Histograms of nearest neighbor YSO spacings, by class. Dot-dashed lines show the median nearest neighbor length in parsecs.

Table 4
Cluster Core Comparison: Gutermuth et al. (2009) versus AFGL 490

| Property                          | 25th Percentile | Median | 75th Percentile | Expanded Survey |
|----------------------------------|-----------------|--------|-----------------|-----------------|
| No. Class I                      | 3               | 6      | 9               | 47              |
| No. Class II                     | 14              | 21     | 46              | 172             |
| No. YSOs                         | 20              | 26     | 55              | 219             |
| No. Class II/No. Class I         | 2.0             | 3.7    | 8.0             | 3.7             |
| Effective radius $R_{\text{hull}}$ (pc) | 0.26           | 0.39   | 0.56            | 1.68            |
| Aspect ratio                     | 1.59            | 1.82   | 2.20            | 2.07            |
| Mean surface density (pc$^{-2}$) | 30              | 60     | 120             | 24.1            |
| Mean $A_K$                       | 0.6             | 0.8    | 1.1             | 0.87            |

4.3. Correlation between Star Formation and the Natal Cloud

This cluster core resembles a normal core in all aspects but surface density and size when compared with the sample studied by Gutermuth et al. (2009). The curious spatial distribution of YSOs in the AFGL 490 region led us to wonder whether the parsec-scale surface densities of YSOs correlate with associated gas column densities, as was observed in several other nearby molecular clouds (Gutermuth et al. 2011). In order to investigate this, we replicate their analysis in Figure 12 using our YSO surface densities sampled at an equivalent spatial resolution as the extinction map, which we use to estimate the molecular gas column densities (Figure 7). We calculate YSO surface density by computing the 11th nearest neighbor surface density and sampling at each source’s position; assuming an average of 0.5 $M_\odot$ per YSO, we can easily find the mass surface density in $M_\odot$ pc$^{-2}$. To find gas column density, we first sample the nearest pixel in the extinction map to a YSO and use that value. To get from extinction to gas column density, we assume that dust traces molecular gas and adopt the canonical conversion assuming $N(\text{H}_2)/A_V = 10^{21}$ molecules cm$^{-2}$ mag$^{-1}$ (Bohlin et al. 1978); thus, 1 $A_V$ corresponds to 15 $M_\odot$ pc$^{-2}$. In this plot, the expected rate of contamination of 7 AGNs deg$^{-2}$ would normally be used to limit the applicability of this plot, but because of the distance to the region, the contamination...
rate corresponds to a surface density too low to plot (0.03 contaminants pc$^{-2}$). An extinction limit is placed on the plot in order to reject data where $A_V$ is less than 1, where our signal-to-noise ratio is too low to rely on those extinction measurements.

The AFGL 490 region generally follows the power-law behavior put forward by Gutermuth et al. (2011), confirming that the star formation in this region is driven by the structure of the cloud. The low surface density of the YSOs therefore corresponds to a relatively low density of natal gas and dust. Also, there is a decline in the Class II/Class I ratio as gas column density increases, meaning that there are more Class I stars in the denser part of the cloud. We confirm this by performing a two-sided Kolmogorov–Smirnov test on the gas surface density values of the Class II and Class I samples; the resulting null hypothesis probability is $6.3 \times 10^{-4}$. Similar trends were found in several other clouds studied by Gutermuth et al. (2011). In summary, it seems that the anomalous cluster core size and YSO density compared to those of the other cores studied by Gutermuth et al. (2009) is likely caused by atypical attributes of the cloud: the natal gas and dust is disorganized, dispersed over a large area with an intermediate column density rather than over a small area with high column density.

4.4. Mass Segregation

The intermediate-mass source AFGL 490 is visually offset from the center of the cluster core (see Figure 10). This raises questions about the primordial mass segregation of the cluster core, namely, does a core’s most massive star form in the center, or does it migrate into the center after undergoing dynamical interactions? A more detailed analysis may provide an interesting constraint on the degree of primordial mass segregation in this region. Kirk & Myers (2011) recently investigated mass segregation in four nearby star-forming regions, finding that in most identified cluster cores the most massive star tends to be centrally located. They also quantified the range of statistical variation expected for uniformly random positioning of the most massive member, that is, one that has no preferred position in its core.

Regions studied by Kirk & Myers (2011) are close enough to consist mostly of spectroscopically confirmed members, including the diskless sources that we cannot identify in this survey, as noted in data section above. Regardless, the low Class II to Class I ratio in the AFGL 490 region suggests that this core is relatively young and has a relatively high disk fraction. This minimizes the bias from using only IR-excess source member identifications (Hernández et al. 2007), making this study comparable to that of Kirk & Myers (2011). Fortunately, Kirk & Myers (2011) use the same method of cluster core extraction as in this paper, and so the groupings are comparably derived.

Kirk & Myers (2011) measured the ratio of the offset of the most massive member of a cluster core to the median offset of the YSOs ($O_{1st}/O_{med}$) against the ratio of the mass of the most massive star in the core to the median mass of the YSOs in the core ($M_{max}/M_{med}$). Using different methods to calculate the center of the cluster core, including mean and median positions of the members and the geometric center of the convex hull, we
found the offset of the most massive source to be 0.74–0.95 pc.
The median offset of all YSOs from the center of the core was
found to be 1.11 pc. We adopted a mass of 9 $M_\odot$ for AFGL
490 (Schreyer et al. 2006) and 0.5 $M_\odot$ as the median mass of
the YSOs, assuming a normal initial mass function. We plot
the values for the 14 cluster cores identified in Kirk & Myers
(2011), as well as the cluster core from this work, in Figure 13.
We find that this cluster core’s offset ratio falls between
the 25th and 50th percentile of the simulated random position
results found in Kirk & Myers (2011), suggesting that we see no
preferential position of the most massive member to the other
members of the cluster core. When we adopt the $L_{\text{crit}}$ used by
Gutermuth et al. (2009), AFGL 490 still falls within Core 1; the
offset ratio for this cluster core still falls within the expected
statistical range for a non-preferential core position (with the
data point moving right on the $x$-axis in Figure 13), suggesting
that this analysis is relatively secure regardless of the change
in $L_{\text{crit}}$.

5. SUMMARY

We have presented an analysis of the star-forming region
AFGL 490, 900 pc distant. It is an expansion of the work on a
portion of this region reported by Gutermuth et al. (2009). In
summary:

1. We have identified 360 YSOs in the entire star-forming
region AFGL 490. Of those, 57 are identified as Class I and
303 as Class II YSOs.
2. We find that the distribution of nearest neighbor distances
among these YSOs peaks in the same range as other
similarly studied embedded clusters.
3. We isolated one denser subregion, or cluster core; it contains
219 YSOs, 60.8% of the region’s members. The core is
defined at a lower threshold surface density than that found
by Gutermuth et al. (2009), effectively merging the two
distinct cores previously reported in that work.
4. We have performed several structural measurements of the
cluster core, finding it to be evolutionarily similar to most
partially embedded cluster cores (Class II/Class I ratio of
3.7), 1.68 pc in radial size and elongated (aspect ratio of
2.07), with a surface density of 24.1 pc$^{-2}$, and partially
embedded (mean $A_K = 0.87$ mag).
5. Of all the regions studied by Gutermuth et al. (2009), we
find that this region is the largest in YSO count and effective
radius, but also has a low surface density and no particularly
dense area.
6. We find that despite the unusual size and surface density
of the AFGL 490 cluster core, it bears the same YSO
surface density to gas column density correlation shown
by Gutermuth et al. (2011) in eight nearby molecular
clouds. This result suggests that the large size and low
surface density of the region are due to star formation in
an unusually large, intermediate column density molecular
cloud clump.
7. We find that the most massive member of the cluster core,
AFGL 490, has no preferential position among the other
members of the core according to the methods of Kirk & Myers (2011).

This publication makes use of data products from the
Two Micron All Sky Survey, which is a joint project of the
University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. This work is based in part on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract 1407 with NASA. Support for the IRAC instrument was provided by NASA through contract 960541 issued by JPL. R.A.G. gratefully acknowledges support from NASA grant NNX11AD14G. L.C.M. wishes to acknowledge funding support from the Smith College Summer Research Fellows (SURF) Program, the Massachusetts Space Grant Consortium, and the Five College Astronomy Department.

Facility: *Spitzer*

REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Bressert, E., Bastian, N., Gutermuth, R., et al. 2010, MNRAS, 409, L54
Cartwright, A., & Whitworth, A. P. 2004, MNRAS, 348, 589
Casertano, S., & Hut, P. 1985, ApJ, 298, 80
Dunham, M. M., Evans, N. J., II, Terebey, S., Dullemond, C. P., & Young, C. H. 2010, ApJ, 710, 470
Evans, N. J., II, Dunham, M. M., Jørgensen, J. K., et al. 2009, ApJS, 181, 321
Flaherty, K. M., Pipher, J. L., Megeath, S. T., et al. 2007, ApJ, 663, 1069
Gutermuth, R. A., Megeath, S. T., Myers, P. C., et al. 2009, ApJS, 184, 18
Gutermuth, R. A., Megeath, S. T., Pipher, J. L., et al. 2005, ApJ, 632, 397
Gutermuth, R. A., Myers, P. C., Megeath, S. T., et al. 2008, ApJ, 674, 336
Gutermuth, R. A., Pipher, J. L., Megeath, S. T., et al. 2011, ApJ, 739, 84
Harvey, P. M., Chapman, N., Lai, S.-P., et al. 2006, ApJ, 644, 307
Heideman, A., Evans, N. J., II, Allen, L. E., Huard, T., & Heyer, M. 2010, ApJ, 723, 1019
Hernández, J., Hartmann, L., Megeath, T., et al. 2007, ApJ, 662, 1067
Hodapp, K.-W. 1994, ApJS, 94, 615
Jones, T. J., Bryla, C. O., Gehrz, R. D., et al. 1990, ApJS, 74, 785
Jørgensen, J. K., Harvey, P. M., Evans, N. J., II, et al. 2006, ApJ, 645, 1246
Kirk, H., & Myers, P. C. 2011, ApJ, 727, 64
Kroupa, P. 2001, MNRAS, 322, 231
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Lyder, D. A., Belton, D. S., & Gower, A. C. 1998, A1, 116, 840
Megeath, S. T., Allen, L. E., Gutermuth, R. A., et al. 2004, ApJS, 154, 367
Meyer, M. R., Calvet, N., & Hillenbrand, L. A. 1997, AJ, 114, 288
Muench, A. A., Lada, C. J., Luhman, K. L., Muzerolle, J., & Young, E. 2007, AJ, 134, 411
Porras, A., Christopher, M., Allen, L., et al. 2003, AJ, 126, 1916
Reach, W. T., Megeath, S. T., Cohen, M., et al. 2005, PASP, 117, 978
Rebull, L. M., Guieu, S., Stauffer, J. R., et al. 2011, ApJS, 193, 25
Rebull, L. M., Padgett, D. L., McCabe, C.-E., et al. 2010, ApJS, 186, 259
Schmeja, S., & Klessen, R. S. 2006, A&A, 449, 151
Schreyer, K., Semenov, D., Henning, T., & Forbrich, J. 2006, ApJ, 637, L129
Snell, R. L., Scoville, N. Z., Sanders, D. B., & Erickson, N. R. 1984, ApJ, 284, 176
Teixeira, P. S., Lada, C. J., Young, E. T., et al. 2006, ApJ, 636, L45