A comparison of protostars in diverse star-forming environments

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A Comparison of Protostars in Diverse Star-Forming Environments

by

Erin E. Kryukova

Submitted to the Graduate Faculty as partial fulfillment of the requirements
for the Doctor of Philosophy Degree in Physics

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The University of Toledo
December 2011
An Abstract of

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Star formation occurs in a variety of environments, from massive star forming clouds like Orion, to low-mass clouds like Ophiuchus, and in more clustered and more distributed regions within clouds as well. It is not yet well understood how the environment (the density and temperature of the surrounding gas) in which a star forms affects the properties i.e. mass, multiplicity, of the resulting star. This work investigates the youngest stars, which exist at or very near their birthplace, and examines the question, “How does Environment Affect Protostar Luminosity?” To assess this question, protostar candidates are identified in eleven star-forming clouds, particularly clouds within 1 kpc of the sun including the relatively nearby regions of Serpens, Perseus, Ophiuchus, Chamaeleon, Lupus, Taurus, Orion, Cep OB3, and Mon R2, which combined host over 500 protostar candidates, and the massive star forming region Cygnus-X at a distance of 1.4kpc, which hosts over 2000 protostar candidates. Mid-infrared photometry from the Two-Micron All Sky Survey (2MASS) J, H, and $K_s$ bands and Spitzer 3.6, 4.5, 5.8, 8.0, and 24 $\mu$m bands are used to identify the protostar candidates. In the nearby clouds (within 1 kpc) sources saturated at 24 $\mu$m are fit using a modified point-spread function (PSF) flux extraction technique. The photometry of these sources is used to create spectral energy distributions (SEDs) from 1 - 24 $\mu$m. A new technique is developed to estimate the bolometric luminosities of protostars from their 1-24 $\mu$m photometry. Estimations of the bolometric lumi-
nosities for protostar candidates are combined to create luminosity functions for each cloud. Contamination due to edge-on disks, reddened Class II sources, and galaxies are considered and removed from luminosity functions. The luminosity functions of the clouds which form high-mass stars (Orion, Cep OB3, Mon R2, and Cygnus-X) peak near 1 \( L_\odot \) and have a tail that extends to luminosities above 100 \( L_\odot \). The luminosity functions of the clouds which do not form high-mass stars do not show a common trend and many do not have significant peaks above the completeness limit. The low and high mass clouds show distinctly different protostellar luminosity functions. Luminosity functions are compared for populations of protostars in clustered and more dispersed regions within each cloud. In Orion and Cygnus-X, the two clouds with the largest samples of protostars, luminosity functions of protostars in crowded regions are significantly different from luminosity functions of protostars in more distributed regions. Additionally, the most luminous protostars in both of these clouds are in more clustered environments. The differences between the luminosity functions of clustered and distributed protostar ensembles may indicate differences in the emerging initial mass functions (IMFs) of the stars in these two environments.
Table of Contents

Abstract iii

Table of Contents v

List of Tables viii

List of Figures ix

List of Abbreviations xii

List of Symbols xiv

1 Current Problems in Protostellar Evolution 1

1.1 The Star-Forming Process .................................................. 1

1.2 Initial Mass Functions, Core Mass Functions, and Protostellar Luminosity Functions .................................................. 4

1.2.1 Accretion Models for Star-Formation ................................. 7

1.3 The Luminosity Problem ...................................................... 9

2 Identifying Protostars in Spitzer Surveys of < 1kpc Molecular Clouds 12

2.1 Photometry Data Sets ........................................................ 13

2.1.1 Orion, Cep OB3, and Mon R2 Cloud Samples ....................... 13
2.1.2 The c2d Cloud Samples: Serpens, Perseus, Ophiuchus, Chamaeleon,
And Lupus ............................................. 14
2.1.3 The Taurus Sample ..................................... 14
2.2 Spitzer Identification of Protostar Candidates ...................... 15
2.3 Comparison With Known Protostars ................................. 21

3 Building Protostellar Luminosity Functions 33
3.1 The Luminosity/Slope Relationship ................................. 34
3.2 Building the Luminosity Functions ................................. 42
3.3 Contamination ............................................. 43
  3.3.1 Extragalactic Contamination ................................. 44
  3.3.2 Edge-on and Nearly Edge-on Disk Sources .................... 45
  3.3.3 Reddened Disk Sources .................................. 48
  3.3.4 Contamination Removal .................................. 50

4 Comparison of Protostellar Luminosity Functions for Star-Forming
Regions Within 1kpc 53
4.1 Cloud-to-Cloud Comparisons .................................... 54
  4.1.1 The Effect of Reddening .................................. 59
  4.1.2 Flat vs. Rising SED Protostars ............................. 60
4.2 Comparison Between Clustered and Distributed Environments .... 62
  4.2.1 Identifying Clustered And Distributed Populations Of Protostars 62
4.3 Completeness in Orion ...................................... 67
  4.3.1 Possible Implications on the IMF .......................... 69

5 The Massive Star-forming Cloud Complex Cygnus-X 72
5.1 Protostar Candidate Sample .................................... 73
5.2 The Cygnus-X Protostellar Luminosity Function .................. 75
  5.2.1 Luminosity Functions of Clustered and Distributed Populations 78
List of Tables

2.1 Star Forming Region Properties ............................................. 21

4.1 Properties of Cloud (< 1kpc) Luminosity Functions .................... 56

4.2 Comparison of clustered and distributed protostars.................... 66

5.1 Properties of the Cygnus-X Luminosity Function ....................... 78
List of Figures

2-1  Distributions of $m_{24}$ for regions within 1kpc  . . . . . . . . . . . . . . . 20
2-2  Color-color diagrams for regions within 1kpc. . . . . . . . . . . . . . . . 23
2-3  Color-magnitude diagrams for regions within 1kpc. . . . . . . . . . . . . . 25
2-4  $A_V$ map of Ophiuchus YSOs  . . . . . . . . . . . . . . . . . . . . . . . . 26
2-5  $A_V$ map of Lupus I YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 26
2-6  $A_V$ map of Lupus III YSOs  . . . . . . . . . . . . . . . . . . . . . . . . 27
2-7  $A_V$ map of Taurus YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 27
2-8  $A_V$ map of Taurus YSOs in L1551  . . . . . . . . . . . . . . . . . . . . 28
2-9  $A_V$ map of Chamaeleon II YSOs  . . . . . . . . . . . . . . . . . . . . 28
2-10 $A_V$ map of Perseus YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 29
2-11 $A_V$ map of Serpens YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 30
2-12 $A_V$ map of Orion YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 31
2-13 $A_V$ map of Cep OB3 YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 32
2-14 $A_V$ map of Mon R2 YSOs  . . . . . . . . . . . . . . . . . . . . . . . . . 32

3-1  Example Spectral Energy Distributions of Protostar Candidates  . . . . 35
3-2  Bolometric/Mid-IR Luminosity vs. Slope  . . . . . . . . . . . . . . . . . . . 38
3-3  Comparison of bolometric luminosity with $c2d$ bolometric luminosity. 40
3-4  Comparison of bolometric luminosity with $c2d$ bolometric luminosity. 41
3-5 Distribution of difference in bolometric luminosity from \(c2d\) bolometric luminosity ................................................................. 42
3-6 Protostar candidate luminosity functions for regions within 1kpc. .......... 43
3-7 Protostar candidate luminosity functions for regions within 1kpc. .......... 46
4-1 Protostellar luminosity functions for regions within 1kpc. .................. 55
4-2 Distribution of K-S probabilities comparing high-mass star-forming clouds with low-mass star-forming clouds within 1kpc. ......................... 58
4-3 Bolometric luminosity vs. nearest neighbor distance for regions within 1kpc. 64
4-4 Distribution of K-S probabilities comparing clustered and distributed regions in Orion. ................................................................. 66
4-5 Luminosity functions for clustered and distributed Orion Protostars. ... 68
4-6 Distribution of \(m_{24}\) for clustered and distributed YSOs in Orion. ....... 69
5-1 Color-color diagram for Cygnus-X. ............................................... 74
5-2 Color-magnitude diagram for Cygnus-X. ........................................ 74
5-3 Cygnus-X \(A_V\) YSO map. ............................................................... 76
5-4 Luminosity function of Cygnus-X protostar candidates. ..................... 77
5-5 Cygnus-X protostellar luminosity function. ..................................... 77
5-6 Bolometric luminosity vs. \(nn4\) distance for Cygnus-X. ....................... 79
5-7 Luminosity functions for clustered and distributed Cygnus-X Protostars. 80
5-8 Distribution of \(m_{24}\) for clustered and distributed YSOs in Cygnus-X. ... 82
A-1 Saturated PSF residuals created for use in the ONC region. ................. 103
A-2 PSF-extracted flux residuals ......................................................... 105
A-3 Saturated sources in the ONC. ..................................................... 106
A-4 Saturated source residuals in the ONC .......................................... 107
A-5 ONC “fake” image. ................................................................. 109
| B-1 | Fraction of sources recovered within $D_c$ for YSOs in Orion. | 111 |
| C-1 | CO (1-0) map of G216-2.5 | 115 |
| C-2 | Color-color diagram for G216-2.5 YSOs. | 118 |
| C-3 | Color-magnitude diagram for G216-2.5. | 118 |
| C-4 | G216-2.5 $A_V$ map with YSOs locations. | 119 |
| C-5 | G216-2.5 protostar candidate luminosity function | 121 |
| C-6 | G216-2.5 protostellar luminosity function | 121 |
List of Abbreviations

2MASS ............... 2 Micron All Sky Survey, an all-sky survey scanning the entire sky at $J$, $H$, and $K_s$ bands
AGN .................. Active Galactic Nuclei
c2d ................... Cores 2 Disks, a Spitzer Legacy project mapping nearby star forming regions.
CMF ................... Core mass function, the distribution of masses of cores in a given environment
far-IR ................ Far-infrared, beyond 24 microns to the sub-milimeter regime
GMC ................... Giant molecular cloud
H ....................... $H$-band, wavelength band centered at $1.8 \, \mu m$
IMF ................... Initial mass function, the distribution of masses of the stars in a given environment
IRAC .................. InfraRed Array Camera, mid-infrared instrument aboard Spitzer
J ....................... $J$-band, wavelength band centered at $1.2 \, \mu m$
K_s ..................... Wavelength band used in 2MASS, centered at $2.2 \, \mu m$
K-S .................... Kolmogorov-Smirnov test
kpc ..................... Kiloparsec
log(prob) .............. For very small probabilities, probability is given in terms of log(probability)
mag .................... Magnitudes
mid-IR .................. Mid-infrared, between 1.2 (J-band) and 24 microns
MIPS ................ Multi-band Imaging Photometer for Spitzer
Myr .................... Million years
nn ....................... Nearest-neighbor
nn4 ..................... Nearest-neighbor distance using the distance to the 4th nearest neighbor young stellar object
RMEDSQ ................ Root-median-square deviation, the technique used to determine completeness in Orion by Megeath et al., in prep
SED ................ Spectral Energy Distribution, which plots flux density versus wavelength
pc .................. Parsec
PSF .................. Point spread function
YSO ................. Young Stellar Object, a young star with a disk, or envelope and disk
yr ..................... Year
List of Symbols

\( \alpha \) \ldots Slope of Spectral Energy Distribution from 3 \( \mu m \) to 24 \( \mu m \)

D \ldots Distance

Jy \ldots Jansky, a unit of flux

K \ldots Kelvin, temperature using the Kelvin scale

\( \mu m \) \ldots Micron

\( \nu \) \ldots Frequency

\( \lambda \) \ldots Wavelength

\( \odot \) \ldots Solar value, e.g., \( M_\odot \) is solar mass or \( L_\odot \) is solar luminosity.

\( \sigma_x \) \ldots Uncertainty in the photometric band ‘x’.

\( \sigma_{x,y} \) \ldots Uncertainty of two photometry bands, i.e., \( \sigma_{x,y} = \sqrt{\sigma_a^2 + \sigma_b^2} \)

\( \sigma_v \) \ldots Velocity dispersion

\( A_V \) \ldots Visual extinction

\( c_s \) \ldots Sound speed

\( D_c \) \ldots The median protostellar \( nn4 \) distance used to sort clustered and distributed protostars

\( F_x \) \ldots Flux in a given band, i.e., \( F_J \) is flux in the J-band

G \ldots Gravitational constant, \( 6.673 \times 10^{-11} m^3 kg^{-1} s^{-2} \)

K \ldots Color correction at MIPS 24 \( \mu m \)

L \ldots Luminosity

\( L_{acc} \) \ldots Accretion luminosity

\( L_{bol} \) \ldots Estimated bolometric luminosity using the relationship found in this work.

\( L_{c2d} \) \ldots Well-determined bolometric luminosity of \( c2d \) sources from (Evans et al., 2009)

\( L_{ext} \) \ldots External luminosity, from heating external to the central protostar

\( L_{int} \) \ldots Internal luminosity, the luminosity of the central protostar, disregarding luminosity from external heating

\( L_{MIR} \) \ldots Mid-Infrared luminosity, calculated between the J-band and 24 \( \mu m \) fluxes

\( L_{cut} \) \ldots Luminosity cutoff for comparison of protostellar luminosity functions, based on the 90% completeness limit
$M_*$ ....... Stellar mass
$M_{\text{env}}$ ....... Mass of the envelope of material surrounding a protostar
$M_{\text{disk}}$ ....... Mass of a circumstellar disk
$\dot{M}$ ....... Mass accretion rate
$m_{24} ....... \text{Magnitude at } 24 \, \mu\text{m}
$n$ ....... Chosen nearest-neighbor; a choice of $n = 4$ refers to the $4^{th}$ nearest-neighbor
$n_H$ ....... Hydrogen density
$N_{\text{edge}}$ ....... Number of edge-on disk contaminants estimated
$N^p_{\text{CepOB3b}}$ Number of protostar candidates in the low-$A_V$ region of Cep OB3b with $m_{24} < \text{cutoff}$
$N^d_{\text{CepOB3b}}$ Number of Class II sources with $m_{24} < \text{cutoff}$ in the low-$A_V$ region of Cep OB3b
$N_p$ ....... Number of protostar candidates with $A_V > 3$ and $m_{24} < \text{cutoff}$ in a given cloud
$N_{\text{CII}}$ ....... Number of Class II sources with $A_V > 3$ in a given cloud
$N^d_{\text{gal}}$ ....... Number of expected galaxy contaminants which fit the criteria for Class II sources
$N^p_{\text{gal}}$ ....... Number of expected galaxy contaminants which fit the protostar selection criteria
$r$ ....... Radius
$R$ ....... Ratio of edge-on disks to Class II objects used to determine the number of likely edge-on disk contaminants
$S$ ....... Signal
$T$ ....... Temperature
$\tau_{\text{acc}}$ ....... Accretion time, the duration of accretion
$[X]$ ....... Magnitude in the X-band, i.e. $[24]$ is the $24 \, \mu\text{m}$ magnitude, equivalent to $m_{24}$.
$L_{\odot}$ ....... Solar luminosity
$L_{\text{MIR}}$ ....... Mid-infrared luminosity, calculated from 1-24 microns
Chapter 1

Current Problems in Protostellar Evolution

1.1 The Star-Forming Process

The fundamental question that humans have asked themselves throughout the ages is, “How did we get here?” While science cannot thoroughly answer the metaphysical question, scientists can strive to piece together the creation and formation of planetary systems not dissimilar from our own. A step further removed has astronomers studying the formation of the stars around which these planets revolve. The field of star formation, like the protostars themselves, is yet evolving and with the recent success of space missions like Spitzer Space Telescope and the early results from Herschel Space Observatory there is a plethora of data that continues to shape the understanding of how stars form.

The current understanding of star formation is as follows. Stars form in molecular clouds in dense ($n_H > 100 \text{ cm}^{-3}$), cold ($T \sim 10-20 \text{ K}$), and opaque clumps comprised mainly of $H_2$ (Bergin and Tafalla, 2007). The densest ($10^4 - 10^5 \text{ cm}^{-3}$) pockets in these clumps are the cores which may form stars (Jijina et al., 1999). If these cores
become unstable, the gas then begins to collapse gravitationally, following an inside-out collapse (Shu, 1977). Each collapsing core may produce one or more protostars, an early phase of star-formation dominated by accretion characterized by a circumstellar disk and envelope of material infalling from the core which hosts the protostar or protostars. As the material gathers in the neighborhood of the protostar, angular momentum conservation creates the disk. This disk gathers material from the envelope and transfers it onto the star (Terebey et al., 1984). A collimated outflow of material aligned with the protostar’s rotation axis is launched from the disk. The disk will outlast the surrounding envelope of material. Eventually, the disk will dissipate and the pre-main sequence lifetime of the star will come to an end as it joins the main sequence as a fully-formed star.

The energy output of the central photosphere of a protostar peaks at \( \sim 1 \, \mu m \) (Lada and Wilking, 1984); the longer wavelength excess emission is from the surrounding shell of material. This excess peaks in the mid-infrared (mid-IR) to far-infrared (far-IR) wavelengths. The more evolved sources show less of an excess; this excess is dominated by the disk and does not consist of an envelope contribution. It is important, then, to include photometry at mid-IR wavelengths when identifying the evolutionary phases of protostars.

Observations of protostar spectral energy distributions (SEDs) have resulted in a system of “Classes”. The slope of the protostellar SED, defined as \( \alpha = d\log(\lambda F_\lambda)/d\log(\lambda) \) where \( \lambda \) is wavelength and \( F_\lambda \) is the flux at that wavelength, is calculated between 2-20 \( \mu m \) (Lada and Wilking, 1984). Class I sources have rising SED slopes over the mid-IR wavelengths, or \( \alpha > 0.3 \), and Class II sources have slopes \( \alpha < -0.3 \) (Greene et al., 1994). Flat spectrum sources may be a transitional period between Class I and Class II sources, or may be the result of observing a Class I source face-on (Calvet et al., 1994), and have \(-0.3 < \alpha < 0.3 \) (Greene et al., 1994). The collection of Class 0, Class I, Class II, and flat spectrum sources will be referred to as young stellar objects.
(YSOs) in the remainder of this work, and Class 0, Class I, and flat spectrum YSOs will be referred to as protostars.

Classes of YSOs are based on observation; a system of “Stages” have also been developed to identify the evolutionary phase of the protostar. Stage 0 and Stage I protostars have infalling envelopes, Stage II sources may have a residual envelope but are dominated by a circumstellar disk, and Stage III sources have only optically thin disks remaining (Robitaille et al., 2006). The more strict boundaries between Stages depend on the mass accretion onto the protostar and are as follows, where $\dot{M}_{\text{env}}$ is the envelope mass accretion, $M_*$ is the mass of the central protostar, and $M_{\text{disk}}$ is the mass of the circumstellar disk: Stage 0/I sources have $\dot{M}_{\text{env}}/M_* > 10^{-6}\,\text{yr}^{-1}$, Stage II sources have $\dot{M}_{\text{env}}/M_* < 10^{-6}\,\text{yr}^{-1}$ and $M_{\text{disk}}/M_* > 10^{-6}$, and Stage III sources have $\dot{M}_{\text{env}}/M_* < 10^{-6}\,\text{yr}^{-1}$ and $M_{\text{disk}}/M_* < 10^{-6}$ (Robitaille et al., 2006).

The “Stages” and “Classes” of protostars are often analogous; for example, Stage I protostars tend to show SEDs similar to a Class I protostar, however the “Stages” were introduced to minimize misclassification of YSOs typically due to inclination; for example, an edge-on YSO which has dissipated its envelope (Stage II) but is viewed through its disk may have an $\alpha$ typical of a Class I source (Robitaille et al., 2006). In the remainder of this work, the Stages and Classes systems of classification are presumed to be analogous (i.e., a protostar with a Class I SED is assumed to be at the same evolutionary phase as a Stage I source) and will only refer to the Classes of protostars because this classification is based on observational SEDs; however the possibility of contamination of a Class I sample by Class II sources is addressed in Section 3.3.

Young star-forming regions typically have a mixture of Class I and Class II sources. The ratio of Class II to Class I sources can be used as an indicator of the star-forming history of the region. Evans et al. (2009) found that in 6 nearby star-forming regions, with $>1000$ YSOs, 60% are Class II sources, 16% are Class I, 12% are flat spectrum
sources, and 12% are Class III sources. The Class I stage lasts about 0.5 Myr, while the Class II stage may take several million years, so it is not unsurprising that in most regions there are many more Class II sources relative to the number of Class I/0 sources (Evans et al., 2009).

The location of Class I sources are typically in regions of higher extinction, which is where these stars form. Jørgensen et al. (2008) found in an analysis of cores detected by SCUBA observations in Ophiuchus and Perseus 47% of Class I sources in Ophiuchus and 58% in Perseus are within 15” of a SCUBA-detected core, while only 3.1% of Class II sources in Ophiuchus and only 1.0% in Perseus are within 15” of a core, suggesting that many Class I sources are still associated with a core. Some Class II sources are found in small groups close to other Class II or Class I sources, while others are further away from other YSOs, but it is unclear whether these stars are formed in isolation or have drifted apart from the stars by which they formed. Massive stars tend to be observed at the centers of clusters, but it is under debate why these stars are found at the cluster centers.

1.2 Initial Mass Functions, Core Mass Functions, and Protostellar Luminosity Functions

Stars form in a diverse range of environments. These cloud environments include crowded, massive clusters heated by O stars (e.g. in Orion), smaller clusters without high mass stars (e.g. in Ophiuchus), or isolated, cold dark clouds containing low mass stars (e.g. in Taurus). Yet while it is known that stars form in these varied cloud environments, it still remains a question how these different environments affect the outcomes of the star formation process, and in particular, how environment may affect the most essential property of a star, its mass.

One way to study the origin of stellar masses is to create an Initial Mass Function
(IMF). The IMF gives the distribution of masses of stars in a given environment, but whether the IMF depends on cloud properties, such as temperature (Larson, 1985), or whether it is similar for all star forming regions regardless of cloud properties (Elmegreen, 1997; Selman and Melnick, 2008) is still under debate (Bastian et al., 2010). Despite the significant differences in gas temperature, column density, and turbulence, the star forming regions and clusters in the Galaxy exhibit remarkably similar IMFs (Bastian et al., 2010). There may be a few exceptions: Luhman et al. (2009) have compared IMFs from Taurus with Chamaeleon I and IC-348 and find that Taurus has a significant excess of stars between 0.6 and 0.8 M⊙. Nevertheless, the similarity between the IMFs of dark clouds like Chamaeleon I, clusters with B-stars such as IC-348 and massive clusters with O and B stars such as the ONC suggests that environment does not play a strong role.

Although the IMF averaged over a star forming region or cluster may be universal, there is growing evidence that variations may occur within specific environments of molecular clouds or within clusters. Massive stars are known to be found toward the centers of clusters. It is an open question whether this is evidence for the preferential formation of massive stars in the center (primordial mass segregation), or the result of dynamical evolution (Bonnell and Davies, 1998; Moeckel and Bonnell, 2009). The detection of compact groups of massive protostars in the centers of clusters argues that there is primordial mass segregation (Megeath et al., 2005; Hunter et al., 2006). Mass segregation is also observed in small groups of young stars: Kirk and Myers (2011) studied groups of 20 and 40 stars in the Taurus and Perseus molecular clouds and found that the most massive members (in some cases with a mass of only 1 M⊙) are found preferentially near the centers of the groups. In these small groups, it is unlikely that dynamical evolution has occurred since the relaxation time of the group is longer than the crossing time by a factor of ~5 (Kirk and Myers, 2011); thus, this suggests that mass segregation in these groups is primordial. An IMF biased toward
massive stars in dense regions may also explain why stars with spectral types earlier than B5 are rarely, if ever, formed in isolation (Testi et al., 1999; de Wit et al., 2005); however, a universal IMF cannot be ruled out from the current limits on the number of isolated OB stars (Bonnell and Clarke, 1999; de Wit et al., 2005). A variable IMF within a cloud or cluster has also been predicted on theoretical grounds (Bonnell and Bate, 2006; Krumholz et al., 2010), with more massive objects forming in regions of higher gas density.

The molecular cores which collapse to form stars show a core mass function (CMF) which also appears to be remarkably invariant (Sadavoy et al., 2010), although completeness and signal to noise issues may contribute to the observed shape (Reid et al., 2010). The similarity in the shapes of the IMF and CMF has led to the suggestion that the IMF reflects the CMF at later stages assuming that a constant fraction of the core gas mass goes into each star (e.g. Alves et al., 2007).

To understand the conversion of molecular cores into stars, and the CMF into an IMF, it is necessary to understand how the mass of the core collapses and is accreted onto the star. This occurs during the protostellar phase. Thus, the protostellar phase is the focus of this thesis. It is difficult to accurately measure the masses of protostars since the accuracy of conversion from an observable such as luminosity to protostar mass is strongly dependent on the assumed age and specific model predictions used. Therefore, instead of using ill-defined masses in this study, a measurable property will be used as a proxy. Protostellar luminosity is related to mass, however it is not determined by mass alone. The protostellar luminosity is a combination of the intrinsic stellar luminosity and the accretion luminosity, \[ L_{\text{acc}} = \frac{GM_*\dot{M}}{r}, \]

where \( G \) is the gravitational constant, \( M_* \) is the stellar mass, \( \dot{M} \) is the mass accretion rate, and \( r \) is the radius. The total bolometric luminosity is used in this study and, as will be discussed later, protostars undergoing accretion events may have higher total luminosities than expected for the assumed mass of the protostar due to heightened
\( \dot{M} \). The protostellar luminosity function, the distribution of bolometric luminosity of the protostars in an environment, will be used to compare the protostars in different environments.

1.2.1 Accretion Models for Star-Formation

Various models have attempted to explain the distribution of stellar masses seen in clusters of YSOs. The most basic process of star-formation is an idealized model for single star accretion. This model assumes a spherically-symmetric core of isothermal gas in hydrostatic equilibrium, with a density that decreases as \( 1/r^2 \), that will undergo inside-out collapse down onto a point-source (Shu, 1977). A more realistic model is the Bonner-Ebert sphere, which has finite radius and external pressure preventing expansion of the sphere. The infall rate, \( \dot{M} \) depends on the sound speed of the gas in the cloud, such that \( \dot{M} \sim c_s^3/G \), where \( c_s \) is the sound speed and \( G \) is the gravitational constant (Shu, 1977; Foster and Chevalier, 1993). However, in reality cores may not be spherically symmetric, and multiple protostars may be forming in the same core. This simplified model also does not explain how massive stars form, which may affect the surrounding region via stellar feedback (e.g. Larson and Starrfield, 1971) or by heating the surrounding gas and affecting the accretion rate (Stahler et al., 2000).

The turbulent core model also assumes inside-out collapse, but in this case the protostellar core is supported by non-thermal turbulent pressure (McKee and Tan, 2002, 2003). In this model, a turbulent core, which increases turbulence with radius provides a larger accretion rate and denser core (McKee and Tan, 2003). In this model \( \dot{M} \sim \sigma_v^3/G \), where \( \sigma_v \) is the standard deviation of the velocity profiles (McKee and Tan, 2003). If \( \sigma_v > c_s \), i.e., supersonic turbulence, the turbulent core model will have a higher accretion rate than the case of the Bonner-Ebert sphere. Additionally, McKee and Tan (2002) find that massive stars form in regions of high density and pressure, which is unaccounted for in the single isothermal sphere collapse model.
However, there is concern that the initial density profile is not sufficient to prevent fragmentation of the turbulent structure as the star accretes (Dobbs et al., 2005).

The competitive accretion model attempts to explain the mass segregation seen in clusters. The gas in a forming cluster is densest at the center of the cluster and stars which accrete the most gas fall to the center of the cluster, where the densest gas resides (Bonnell et al., 2001). In this model the infall rate is \( \dot{M} \sim \rho M^2_\star (v^2 + c^2_s)^{-3/2} \), where \( \rho \) is the density and \( v \) is the velocity profile (Bondi, 1952; Bonnell et al., 2001). Thus the larger the density, the higher the infall rate, which increases the mass and kicks up the infall rate; this allows massive stars to form more rapidly than in the previous models. However, this model does not take into account that protostars may first accrete from the small cores in which they exist, nor that the accretion time is fixed (Offner and McKee, 2011).

It may be that a more descriptive model of accretion should involve two components. A two-component turbulent core model, which blends a centrally condensed inner core dominated by thermal motions and an envelope dominated by non-thermal motions, has been proposed by McKee and Tan (2003) and uses the thermal and non-thermal component model of Myers and Fuller (1992). A two-component competitive accretion model introduced by Offner and McKee (2011) combines a constant accretion rate at the earliest phases of protostellar accretion, followed by competitive accretion afterward, such that half of the final mass comes from accretion of core envelope, as suggested by Smith et al. (2009). Offner and McKee (2011) compared the turbulent core, competitive accretion, two-component turbulent core, and two-component competitive accretion models and find that the models which best fit observed protostellar luminosity functions have a constant accretion time, with their competitive accretion model fitting best, though their two-component competitive accretion model is most like the competitive accretion model of Bonnell et al. (1997).

These models treat star formation as an isolated process, yet stars which form
in proximity to other forming stars may affect one another. One might expect to observe differences in protostar properties between those protostars found in close range to other forming stars (more clustered environments) and those found in relative isolation (more dispersed regions in which competitive accretion is not influential). These models assume the infalling material is immediately accreted onto the star. As we will discuss in the next section, this is not always the best assumption.

### 1.3 The Luminosity Problem

Kenyon et al. (1990) used photometry from the Infrared Astronomical Satellite (IRAS) of protostars in the Taurus-Auriga cloud to create a differential luminosity function for Class I protostars; the resulting luminosity function peaks near $1 \, \text{L}_\odot$. Comparison with a simple accretion model and using an accretion time, $\tau_{\text{acc}}$, of $10^5$ years produces approximately the same number of Class I protostars as observed, but a peak luminosity larger than $1 \, \text{L}_\odot$ and a median luminosity larger than observed. Increasing $\tau_{\text{acc}}$ to $10^6$ years gives a luminosity function which peaks near $1 \, \text{L}_\odot$ with a similar median luminosity, but produces far too many protostars and thus is not a realistic representation of the observations. Kenyon and Hartmann (1995) revisit luminosity functions of Class I protostars and find that the expected luminosities are a factor of 10 smaller than predicted for accretion luminosities using typical masses and accretion rates for Taurus sources. This so-called “luminosity problem” illuminates the discrepancy between observed luminosities and the models used to understand them.

Recently Dunham et al. (2010), also found the luminosity problem holds for the sample of protostars observed in the five $\c2d$ clouds. The generated model luminosity functions take into account several effects which could reduce protostellar luminosities: extending the protostellar lifetime, envelope clearing by outflows, the non-isotropic
emission of the protostellar luminosity, and tapering the infall at late times. The resulting model luminosity function peaks near $10 \, L_\odot$ (model 4 of Dunham 2010), above the observed luminosities presented in Dunham et al. (2010). One possible explanation for the lower observed luminosities is that the infalling material builds on protostellar accretion disks, and that the material on the disk is episodically dumped onto the protostar creating a large, but brief, jump in the source luminosity (Kenyon and Hartmann, 1995; Dunham et al., 2010). Dunham et al. (2010) find that models which include such episodic accretion can reproduce the observed luminosity function.

There are other alternatives to episodic accretion. One possibility is that many of the lower luminosity objects are effectively fully-formed pre-main sequence stars with residual envelopes (White et al., 2007). Most recently, Offner and McKee (2011) and Myers (2011) used two-component accretion models to predict luminosities. Offner and McKee (2011) compare isothermal sphere, turbulent core, competitive accretion, two-component turbulent core, and two-component competitive accretion models assuming that protostellar masses follow a Chabrier (2005)-like IMF, and compare the resulting predicted protostellar luminosity functions with observed luminosity functions from Class 0 and Class I sources in Serpens, Ophiuchus, Perseus, Lupus, and Chamaeleon from Enoch et al. (2009) and Evans et al. (2009), and find best agreement with the competitive accretion models. Myers (2011) use a model in which protostars accrete from surrounding cores and clumps with varying accretion durations to predict protostellar luminosity functions, which match well with the observed luminosity functions of Serpens, Perseus, and Ophiuchus, from Dunham et al. (2010).

One question is whether the more massive clouds also have a luminosity problem, as previous work demonstrating the luminosity problem has concentrated on nearby low mass regions such as Taurus, Perseus, Ophiuchus and Serpens, or whether certain star-formation models or episodic accretion can explain the discrepancies. This thesis will allow the luminosity problem to be “tested” for more distant clouds which form
low- and high-mass stars; if these more massive regions also exhibit a peak lower than expected, the luminosity problem will not be limited to nearby low-mass regions and may require further modeling.

This thesis will begin in Chapter 2 by discussing the cloud sample and sources of photometry. Section 2.2 will discuss the criteria used in the identification of protostar candidates, then the protostar candidate list will be compared with known protostars in Section 2.3. Chapter 3 introduces a new relationship between mid-infrared luminosity and bolometric luminosity using the SED slope. This relationship will be used to estimate bolometric luminosities for each of the protostar candidates. A rigorous contamination estimation made in Section 3.3. The luminosity functions of contamination-subtracted protostars are discussed in Chapter 4, and compared among clouds (Section 4.1), and between clustered and distributed regions within each cloud (Section 4.2). Chapter 4 winds down with a discussion on completeness in the Orion cloud.

Chapter 5 extends the protostar sample to a distant, massive star-forming complex, Cygnus-X. A similar protostar identification method is used to identify protostar candidates, and the method for estimating bolometric luminosities from Chapter 3 is used for these protostar candidates. Section 5.2 builds and discusses the contamination-subtracted protostellar luminosity function, comparing it to the Orion luminosity function and comparing luminosity functions of protostars in clustered and distributed environments.
Chapter 2

Identifying Protostars in *Spitzer* Surveys of < 1kpc Molecular Clouds

*Spitzer* surveys of nine nearby (< 1kpc) star-forming regions, including Lupus, Chamaeleon, Taurus, Ophiuchus, Perseus, Serpens, Orion, Cep OB3, and Mon R2 form the sample that will be studied in this chapter. These clouds range in distance, from Ophiuchus at 125pc (Evans et al., 2009) to Mon R2 at 830 pc (Racine, 1968), and in the stars they form, from dispersed low- and intermediate-mass stars in Taurus to high-mass stars in dense clusters in Orion.

The photometry of the clouds in this study was assembled from multiple sources, which will be described in this section. In addition to using existing source catalogs from the *c2d* program and the Taurus molecular cloud survey, photometry is extracted from the Orion, Cep OB3, and Mon R2 regions. The method for obtaining 24 μm photometry for sources for these three clouds, and the method for obtaining point-spread function (PSF) photometry for some saturated sources for which photometry is not available in the source catalogs will be described here.


## 2.1 Photometry Data Sets

### 2.1.1 Orion, Cep OB3, and Mon R2 Cloud Samples

Aperture photometry of Orion, Cep OB3, and Mon R2 sources at IRAC wavelengths was taken from Megeath et al. in prep (Orion), and from Gutermuth et al. in prep (Cep OB3 and Mon R2) with no modification. Point spread function (PSF) photometry extraction was used for the MIPS 24 $\mu$m sources in each of these regions due to nebulosity present at this wavelength and possible confusion of sources. The following methodology is used in PSF fitting photometry extraction for each image; each cloud consists of multiple images which together map the cloud.

First, 24 $\mu$m point sources are identified using the source finding routine in PhotVis (Gutermuth et al., 2008). The zero-point magnitude is 16.05, which includes the correction from the aperture size of 5 pixels to infinity. A subset of sources were selected to create the PSF; these sources were isolated and relatively bright but not saturated sources. The PSF was generated using ‘GETPSF’ from the IDL astronomy library. To allow some partially saturated sources to be fit, two PSFs were created, one with a larger PSF radius and fitting radius to fit the saturated sources, and a smaller PSF with a smaller fitting radius to fit the unsaturated sources. Often, only a source’s central pixels, which saturate first, may be saturated; these “partially saturated” sources are treated as saturated sources. The PSFs were fit to the appropriate sources (larger PSF for saturated source and sources very nearby and smaller PSF for all others) using a modified version of ‘NSTAR’ from the IDL astronomy library. The fluxes were extracted using ‘SUBSTAR’, also from the IDL astronomy library, and a residual image after flux extraction was created. The residual image was inspected to ensure that sources were not missing, which would appear as unsubtracted sources. If found, these sources were added into the source list and the process was repeated. This technique is described in more detail in Appendix A.
2.1.2 The c2d Cloud Samples: Serpens, Perseus, Ophiuchus, Chamaeleon, And Lupus

Photometry, extinction maps, and 24 µm mosaics for Serpens, Perseus, Ophiuchus, Chamaeleon, and Lupus were obtained from the Cores to Disks (c2d) Spitzer Legacy project 4th high-reliability data release\(^1\). In addition to the high-reliability catalog, the 24 µm images for these clouds were inspected to identify saturated sources which were not in the c2d catalogs. These images were the 24 µm image of Serpens from Winston et al. (2007), the 24 µm image of NGC 1333, the location of the brightest 24 µm sources in Perseus, from Gutermuth et al. (2008), and c2d images\(^1\) for the Ophiuchus, Lupus, and Chamaeleon II clouds. In each case, sources were selected which do not have photometry in the c2d catalog and appeared saturated in the images. These sources were then fit using the PSF technique described in Section 2.1.1 and in Appendix A. Twelve of the sources saturated in the c2d images obtained 24 µm fluxes in this way. Photometry extracted in this way from a sample of 95 unsaturated sources included in this sample and the c2d sample from the Ophiuchus cloud were compared to their corresponding fluxes from the c2d survey. The median difference between the magnitudes from these two sources is 0.012 mag. Similarly, in a comparison of extracted Serpens m\(_{24}\) fluxes with that from the c2d data release, the median difference among 178 sources is 0.034 mag.

2.1.3 The Taurus Sample

The Taurus photometry came from the Spitzer Legacy Taurus Molecular Cloud Survey data release S14\(^2\). The sources in this sample were compared with the list of 52 YSOs, including sources from the L1495 and L1551 region, from Gutermuth et al. (2009), for which 17 were not already included in the Spitzer Legacy photometry.

\(^1\)From http://irsa.ipac.caltech.edu

\(^2\)These data can be found at http://ssc.spitzer.caltech.edu/spitzermission/observingprograms/legacy/taurus/
Of the 17 sources which were added, 4 are in L1495, and 13 are in L1551; L1551 is a small satellite of the Taurus region with several well known protostars which was not covered by the *Spitzer Legacy* map of Taurus (Ungerechts and Thaddeus, 1987). L1551 contains some of the most luminous known protostars in Taurus and thus inclusion of these sources in the Taurus photometry sample is desired. For the 6 protostars in L1495 and 2 protostars from L1551 which do not have 24 $\mu m$ detections due to saturation, IRAS fluxes at 25 $\mu m$ from the Faint Source Catalog were used. The only exception is L1551 IRS5, which is from Beichman et al. (1988). The 25 $\mu m$ fluxes were converted to 24 $\mu m$ fluxes using the approximation $F_{24} = K \times F_{25}$ where $K = 0.986$ for a cool blackbody ($T = 70$ K) (*MIPS* Handbook, version 2.0, 2010). The sources receiving their 24 $\mu m$ photometry in this way are L1551 IRS5, IC 2087 IR, 04365+2535, HL Tau, GV Tau, 04239+2436, 04278+2253AB, and 04361+2547AB.

Taurus is a relatively well-studied cloud and it is important to ensure that known Taurus protostars are included or accounted for in this sample. A list of known protostars from Furlan et al. (2008) was compared with the protostars in the sample from this work. All but two of the 28 sources listed in their Table 1 are also in this photometry sample; the remaining sources fall out of the Taurus Survey coverage area.

### 2.2 *Spitzer* Identification of Protostar Candidates

*Spitzer* has dramatically improved the ability to identify protostars because it can rapidly map entire molecular clouds with $\leq 5$" resolution and high sensitivity between 3.6 and 24 $\mu m$. Protostars can be readily identified by their flat or rising spectral energy distributions over this wavelength range (Greene et al., 1994). Most of the schemes for identifying protostars rely either on fitting models to the SED (ranging from simple power-laws to detailed radiative models) or on measuring mid-
IR colors that depend on the SED slope (Allen et al., 2004; Megeath et al., 2004; Muzerolle et al., 2004; Whitney et al., 2004; Harvey et al., 2007; Winston et al., 2007; Gutermuth et al., 2009). This work utilizes the scheme first developed by Megeath et al. (2009) and Megeath et al. in prep. for protostars with 24 µm detections; this technique looks for SEDs which have a power-law slope between 4.5 µm and 24 µm greater than \( \alpha > -0.3 \). This corresponds to the lowest \( \alpha \) for flat spectrum sources in Greene et al. (1994). The selection criteria are based on 4.5 and 24 µm photometry; at 5.8 and 8.0 µm the IRAC detector is less sensitive and near 8 µm the protostellar SED dips. The sample is limited to protostars with detections in the MIPS 24 µm band, which detects thermal emission. In the next section, the necessity of the 24 µm band to estimate luminosities of the protostars will be discussed; thus likely protostars without 24 µm detections are ignored. Protostars which are located in saturated areas of the 24 µm maps, i.e. the Orion Nebula or the NGC 2024, will not be included in this survey.

The identification of protostar candidates begins with the assumption that they will be detected at 3.6 µm, 4.5 µm, and 24 µm; these are the most sensitive wavebands for most protostars (Megeath et al. 2009, Megeath et al. in prep.). If a source was not detected at 3.6 µm it is expected that the source should be faint, and these sources are given a photometric lower limit at 3.6 µm of 15.5 mag during the protostar selection process only to estimate colors for these sources. Finally, in each set of criteria, the photometry was required to have uncertainties limits, denoted \( \sigma_x \) for uncertainty in the ‘x’ band. These limits are \( \sigma_J, \sigma_H, \sigma_{Ks}, \sigma_{3.6}, \text{and} \sigma_{4.5} < 0.1 \) mag and \( \sigma_{5.8} \) and \( \sigma_{8.0} < 0.15 \) mag, and a detection at 24 µm. Before applying the protostar candidate selection criteria, other selection criteria were applied to minimize contamination. To minimize contamination from galaxies, protostar candidates were required to be projected on regions of the clouds where \( A_V > 3 \), as determined directly from the extinction maps, which will be discussed in Section 2.3.
A few alterations were made to the protostar selection criteria of Megeath et al. (2009) to select protostar candidates in more nearby regions; these changes are now discussed. For sources with uncertainty in \( m_{4.5} < 0.1 \) mag and with 24 \( \mu m \) detections, they were required to fulfill one of the following sets of criteria:

\[
\]

and

\[
[3.6] - [4.5] \geq 0.752 + \sigma_{3.6,4.5}
\]

or

\[
[4.5] - [24] \geq 5.303
\]

and

\[
[3.6] - [4.5] \geq 0.6520 + \sigma_{3.6,4.5}
\]

(2.2)

where for any two photometric bands a and b, \( \sigma_{a,b} = \sqrt{\sigma_a^2 + \sigma_b^2} \). For sources with detections at 4.5, 5.8 and 8 \( \mu m \) and uncertainties of \( \sigma_{4.5} \leq 0.1 \) and \( \sigma_{5.8} \) and \( \sigma_{8.0} \leq 0.15 \), the following criteria were used to find additional protostar candidates with colors

\[
[4.5] - [24] \geq 7
\]

(2.3)

and

\[
[5.8] - [8.0] \leq 1.75
\]

where the [5.8] - [8.0] criterion is used to eliminate star forming galaxies with strong PAH emission in the 8 \( \mu m \) band.
For sources with no 4.5 $\mu$m detection that may still be protostars (Fischer et al., 2010), detections in the 5.8 or 8.0 $\mu$m band were used. Sources with detections at the 5.8 $\mu$m band with $\sigma_{5.8} < 0.15$ were identified as protostar candidates if they satisfied the color criteria:

\[
[5.8] - [24] \geq 4.117
\]

and

\[
[3.6] - [5.8] \geq 1.296 + \sigma_{3.6,4.5}
\]

while for sources with 8 $\mu$m detections and $\sigma_{8.0} < 0.15$, protostar candidates were identified with the criteria:

\[
[8.0] - [24] \geq 3.20
\]

and

\[
[3.6] - [8.0] \geq 2.12 + \sigma_{3.6,4.5}
\]

A magnitude cutoff limit at 24 $\mu$m was imposed to minimize background galaxy contamination (Megeath et al., 2009). The protostar sample is not limited by sensitivity, but by the $m_{24}$ cutoff. Figure 2-1 shows the distribution of $m_{24}$ for sources which fit the above protostar candidate criteria and contaminating galaxies which also fit the protostar candidate criteria. To estimate galaxy contamination, a sample of galaxies from the Spitzer Wide-area Infrared Extragalactic Survey (SWIRE)\(^1\) survey was used. The SWIRE known galaxies were subjected to the same protostar selection criteria. The distribution of $m_{24}$ for the galaxies which fit the criteria for

\(^1\)The 4.2 deg$^2$ Elais-N2 field from http://swire.ipac.caltech.edu/swire/swire.html was used.
protostar candidates over the 4.2 deg$^2$ region of the SWIRE sample is scaled to the size of the $A_V > 3$ sub-region for each cloud, assuming the density of galaxies in the SWIRE field is similar to that toward the sample of molecular clouds. Thus, it is assumed that a similar distribution of galaxy contamination may be present in the star-forming region photometry sample, though the galaxies are assumed to be fainter at $m_{24}$ than the protostars. The $A_V > 3$ areas of the coverage maps for each region are 4.25, 8.88, 0.83, 0.45, 2.46, 0.86, 5.49, 1.37, and 0.32 deg$^2$ for Ophiuchus, Taurus, Lupus I, III, & IV, Chamaeleon II, Perseus, Serpens, Orion, Cep OB3, and Mon R2, respectively. The SWIRE $m_{24}$ histograms are also shown in Figure 2-1. The $m_{24}$ cutoff for each region was determined to be the maximum magnitude bin in which the contamination due to galaxies was likely less than 50%, using a bin size of 0.5 mag.

The protostar candidates that were selected must have $m_{24}$ detections because this sample seeks sources dominated by envelopes; these sources should have bright $m_{24}$. These envelope-dominated protostars were assumed to still be accreting, akin to the Class I sources of Lada and Wilking (1984). Sub-mm detections or envelope mass estimates are not available for all sources in each cloud in this sample. Thus, the protostar candidate sample is expected to include Class 0 sources and Class I sources with rising and flat SED slopes. Additionally, sources with less infrared excess and/or fainter $m_{24}$ that are likely more evolved YSOs with diminished envelopes using the criteria for Class II sources from Megeath et al. (2009) were identified and are listed in Table 2.1.
Figure 2-1: Distribution of 24 $\mu$m magnitudes for all sources fitting the protostar criteria and have $A_V > 3$ (black), and for SWIRE galaxy sources fitting the protostar criteria (blue) for each cloud. The $m_{24}$ cutoff is shown in red at the maximum magnitude such that less than 50% of sources in that bin are likely contamination from galaxies.
Table 2.1: Star Forming Region Properties

<table>
<thead>
<tr>
<th>Cloud</th>
<th>Distance. (pc)</th>
<th>$m_{24}$ cut</th>
<th>Class IIs*</th>
<th>Flat/Rising†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiuchus</td>
<td>125(^1)</td>
<td>5.5</td>
<td>218</td>
<td>15(10.4)/19(13.3)</td>
</tr>
<tr>
<td>Tau/Lup/Cha</td>
<td>140(^2)</td>
<td>5.0</td>
<td>162</td>
<td>9(6.2)/25(21.6)</td>
</tr>
<tr>
<td>Perseus</td>
<td>230(^3)</td>
<td>6.0</td>
<td>344</td>
<td>13(11.1)/50(40.1)</td>
</tr>
<tr>
<td>Serpens</td>
<td>415(^4)</td>
<td>7.0</td>
<td>205</td>
<td>13(9.1)/39(31.6)</td>
</tr>
<tr>
<td>Orion</td>
<td>420(^5)</td>
<td>7.0</td>
<td>2071</td>
<td>89(68.1)/217(161.4)</td>
</tr>
<tr>
<td>Cep OB3</td>
<td>700(^6)</td>
<td>8.0</td>
<td>887</td>
<td>43(28.3)/104(72.9)</td>
</tr>
<tr>
<td>Mon R2</td>
<td>830(^7)</td>
<td>8.0</td>
<td>486</td>
<td>31(28.8)/82(67.1)</td>
</tr>
</tbody>
</table>

\(^1\) From Evans et al. (2009).

\(^2\) Taurus distance from Kenyon et al. (1994), Lupus I, II, & IV and Chamaeleon II are assumed at this distance.

\(^3\) From Cernis (1990).

\(^4\) From Dzib et al. (2010).

\(^5\) From Menten et al. (2007).

\(^6\) From Kharchenko et al. (2005).

\(^7\) From Racine (1968).

* Class II sources in regions with $A_V > 3$.

† Numbers in parenthesis are after removal of contamination.

### 2.3 Comparison With Known Protostars

The sample of protostar candidates from this work was compared with the sample of sources from the $c2d$ clouds with envelopes detected at 1.3 mm. It is important to include sources with known envelopes, as the goal is to identify Class I/0 type sources which still have envelopes. Of the known envelope sources, 92 of these sources were
classified as protostar candidates and 13 were identified as Class II sources. Of the remaining 25 \(c2d\) envelope sources, 14 were rejected as protostar candidates because of missing 24 \(\mu m\) detections or \(m_{24} > \) cutoff, 4 are rejected for uncertainties above the requirements for protostar candidate selection, 3 have colors of protostar candidates using the criteria but are rejected because they fall off the available \(A_V\) maps or do not have an \(A_V > 3\), 3 sources are rejected because they are not consistent with the \(\alpha\) criteria, and 3 sources have photometry which came from the full \(c2d\) source catalog and are not found in the \(c2d\) high reliability catalog, which was used in creating the sample. Additionally, 65 of the protostar candidates from this work were not identified as likely envelopes in the \(c2d\) YSO catalog; these sources which do not have 1.3 mm envelopes detected likely have envelope mass less than 0.5 \(M_\odot\) (Evans et al., 2009).

Comparison of Taurus protostars selected using the protostar selection criteria with the source list of Class I objects from Furlan et al. (2008) finds that of the 26 sources from their Table included in the photometry from this work, 18 sources are common to both protostar lists, though one source has \(A_V < 3\). Additionally, 5 of the protostars from Furlan et al. (2008) were identified as Class II sources and 7 do not have 24 \(\mu m\) detections so they are rejected as protostar candidates.

In Figures 2-2 and 2-3 and in the remainder of this analysis, the Taurus region is combined with the \(c2d\) Lupus and Chamaeleon regions. These star forming regions are all at nearly the same distance (Taurus is at 140 pc, Lupus I and IV are at 150 pc (Merín et al., 2008), and Chamaeleon II is at 178 pc (Whittet et al., 1997) and have relatively similar dispersed star formation. The photometry of Lupus I, III, and IV, and Chamaeleon II are adjusted to the distance of Taurus. Combining these regions allows for better statistics in otherwise individually sparse star forming environments.
Figure 2-2: Color-color diagrams for Spitzer identified protostars. The rising spectrum protostars are shown in red and flat spectrum protostars are in green. The sources identified as Class IIs are shown in blue. The remaining sources, shown as black dots, are stars without disks, AGN, and star forming galaxies. In the panel showing combined Taurus, Lupus, and Chamaeleon cloud data, Taurus protostars are shown as diamonds, Lupus protostars are shown as stars, and Chamaeleon II protostars are shown as squares.
Color-color and color-magnitude diagrams for protostar candidates and identified Class II sources are shown in Figures 2-2 and 2-3, respectively. These objects will be referred to as protostar candidates because a fraction of these sources may be galaxies, reddened Class II objects, and edge-on disks. For each protostar candidate, the spectral slope, $\alpha$, is calculated by using a best-fit line to the plot of $\log(\lambda F_\lambda)$ vs. $\log(\lambda)$ over IRAC and MIPS 24 $\mu$m detections. In Figures 2-2 and 2-3 the flat spectrum $-0.3 \geq \alpha \leq 0.3$ and rising spectrum $0.3 \geq \alpha$ protostars are distinguished. Class II sources are also shown; these were identified using the criteria described in Gutermuth et al. (2009).

Figures 2-4 through 2-14 shows the spatial distributions of all protostar candidates found in this study using the protostar selection criteria. Shown are extinction maps with contours denoting the $A_V = 3$ cutoff. The extinction maps from the $c2d$ clouds are from the $c2d$ 4th high-reliability data release$^2$, the maps of Mon R2, and Cep OB3 are from Gutermuth et al. (in prep), the map of Orion is from Megeath et al. (in prep), and the Taurus extinction map is from Lombardi et al. (2010). Sources which fit the selection criteria but reside in $A_V < 3$ regions are also identified in this figure.

$^2$From http://irsa.ipac.caltech.edu
Figure 2-3: Color-magnitude diagrams for *Spitzer* identified protostars. Rising spectrum protostars are shown in red and flat spectrum protostars are in green, and Class II sources are shown in blue. The solid lines show the $m_{24}$ cutoff and the [4.5] - [24] color cutoff. The 24 µm magnitude is corrected for distance but not reddening. Galaxies comprise a distinct clump of fainter (at 24 µm) yet higher excess (at [4.5] - [24]) sources, falling near [4.5] - [24] = 6. Symbols and colors are the same as Figure 2-2.
Figure 2-4: Ophiuchus $A_V$ map. Shown are all Class IIIs (blue), rising spectrum (red), and flat spectrum (green) protostar candidates with $A_V > 3$ (circles) and with $A_V < 3$ (diamonds), as well as $A_V = 3$ contours.

Figure 2-5: Lupus I $A_V$ map. Symbols are same as Figure 2-4.
Figure 2-6: Lupus III $A_V$ map. Symbols are same as Figure 2-4.

Figure 2-7: Taurus $A_V$ map. Symbols are same as Figure 2-4.
Figure 2-8: L1551 $A_V$ map. Symbols are same as Figure 2-4.

Figure 2-9: Chamaeleon II $A_V$ map. Symbols are same as Figure 2-4.
Figure 2-10: Perseus $A_V$ map. Symbols are same as Figure 2-4.
Figure 2-11: Serpens $A_V$ map. Symbols are same as Figure 2-4. Nearly the entire map has extinction $A_V > 3$. 
Figure 2-12: Orion $A_V$ map. Symbols are same as Figure 2-4.
Figure 2-13: Cep OB3 $A_V$ map. Symbols are same as Figure 2-4. The black outline shows the location of the low-$A_V$ region in Cep OB3b used in the edge-on disk contamination analysis in Section 3.3.2.

Figure 2-14: Mon R2 $A_V$ map. Symbols are same as Figure 2-4.
Chapter 3

Building Protostellar Luminosity Functions

This thesis focuses on using bolometric luminosity as an observable for comparing protostars in different environments. The majority of protostellar luminosity is emitted at wavelengths longward of 24 \( \mu \text{m} \), wavelengths at which data are not available for most sources in this work. The bolometric luminosity, \( L_{\text{bol}} \), is dominated by these longer wavelengths, and thus a method for estimating \( L_{\text{bol}} \) using the luminosities integrated over the available wavelength bands is needed.

This chapter includes a discussion on the calculation of \( \alpha \), the determination of mid-infrared (mid-IR) luminosity, and the estimation of bolometric luminosity for each protostar candidate. Protostellar candidate luminosity functions are created for protostar candidates in clustered and distributed environments in each cloud, however these luminosity functions may yet contain contamination. Three sources of possible contamination are considered: background galaxies, reddened Class II sources, and edge-on disks. Finally, luminosity functions of representative of contamination are removed from the protostar candidate luminosity functions, and a protostellar luminosity function (comprised of the luminosity functions for protostars in both clustered
and distributed environments) is created for each cloud.

### 3.1 The Luminosity/Slope Relationship

For each protostar candidate, the *Spitzer* 3.6 - 24 $\mu$m bands were used to determine SED slope. The slope, $\alpha$, was calculated by using a best-fit line to the plot of $\log(\lambda F_\lambda)$ vs. $\log(\lambda)$ over *IRAC* and *MIPS* 24 $\mu$m detections. Figure 3-1 shows a small sample of SEDs for protostar candidates in Orion. Mid-IR luminosities were calculated by integrating the SED over the available fluxes from J, H, $K_s$, and *IRAC* bands. Detections were converted to fluxes $F_\lambda$, using zero point fluxes of 1594, 1024, 666.8 Jy for J, H, and $K_s$ (Cohen et al., 2003) and 280.9, 179.7, 115.0, 64.13 (IRAC Instrument Handbook, version 1.0), and 7.17 Jy (*MIPS* Instrument Handbook, version 2.0) for $F_{3.6}$, $F_{4.5}$, $F_{5.8}$, $F_{8.0}$, and $F_{24}$, respectively. The central wavelength for the J, H, and $K_s$ bands and approximate bandwidths were from Cohen et al. (2003). The bandwidths were estimated using the wavelengths at which the transmission is 21%, 23%, 25%, 36%, and 50% the maximum transmission for 3.6, 4.5, 5.8, 8.0, and 24 $\mu$m bands respectively. The 2MASS bandpasses are 1.073 - 1.397 $\mu$m for $F_J$, 1.411 - 1.913 $\mu$m for $F_H$, 1.897 - 2.420 $\mu$m for $F_{K_s}$. The bandpasses from the *IRAC* and *MIPS* handbooks are 3.175 - 3.925 $\mu$m for $F_{3.6}$, 3.986 - 5.000 $\mu$m for $F_{4.5}$, 5.019 - 6.443 $\mu$m for $F_{5.8}$, 6.420 - 9.324 $\mu$m for $F_{8.0}$, and 20.800 - 26.100 $\mu$m for $F_{24}$. Rectangular integration over each band was done by multiplying the flux density by the above bandwidths. The mid-IR luminosity was then calculated using the following equation:

$$L_{MIR} = \left[19.79F_J + 16.96F_H + 10.49F_{K_s} + 5.50F_{3.6} + 4.68F_{4.5}
+ 4.01F_{5.8} + 4.31F_{8.0} + 0.81F_{24}\right] \times 10^{-6} \times D^2L_\odot$$  \hspace{1cm} (3.1)
Figure 3-1: A sample of protostar candidate SEDs from Orion. Shown are the detected fluxes for J, H, $K_s$, 3.6, 4.5, 5.8, 8.0, and 24 $\mu$m, and the slope fit to the fluxes between 3.6 and 24 $\mu$m used to determine $\alpha$. 
where $D$ is the distance to the cloud in $pc$ and $F_\lambda$ is the flux density in $Jy$. The adopted distances are listed in Table 2.1.

Dunham et al. (2008) compared the protostellar flux density, $\nu F_\nu$, to the internal luminosity, $L_{int}$, from the central protostar for a grid of radiative transfer models and protostars with complete SEDs from the $c2d$ survey. These models did not include external heating. For the far-IR 70 $\mu m$ band, they found a linear correspondence between $\nu F_\nu$ and $L_{bol}$. An approximately linear relationship was also evident at shorter wavelengths, particularly at the mid-IR 24 $\mu m$ band, but the scatter was much higher, with an order of magnitude variation in luminosity for a given 24 $\mu m$ flux.

Because 70 $\mu m$ photometry is unavailable for the majority of the Spitzer-identified protostar candidates, an attempt to reduce the scatter between the mid-IR luminosity and $L_{bol}$ is prudent. A linear relationship between the mid-IR and bolometric luminosities implies a constant $L_{MIR}/L_{bol}$. It is clear this ratio is not constant. Here the slope of the SED was used as an extra parameter to reduce the scatter.

To establish a relationship between the SED slope $\alpha$ and $L_{MIR}/L_{bol}$, protostars were selected from the $c2d$ program with well-established bolometric luminosities ($L_{c2d}$). Evans et al. (2009) determined bolometric luminosities for YSOs in the $c2d$ catalog using available photometry between 0.36 $\mu m$ and 1300 $\mu m$ and the method described in Dunham et al. (2008). The uncorrected (not de-reddened) luminosities were used, since the photometry of protostar candidates in this work have not been de-reddened. This should not have a large effect on the protostellar luminosity function, and is discussed later in Section 4.1.1. These luminosities were re-scaled to the distances adopted in this study, listed in Table 2.1. The 88 YSOs from Serpens, Perseus, Chamaeleon II, and Ophiuchus, which are identified as protostar candidates using the criteria and had $L_{bol}$ flagged as good quality in Evans et al. (2009), and 70 $\mu m$ detections were selected to determine the fit. Then, the photometry from this
sample was used to determine the slope of the SED and $L_{MIR}/L_{bol}$ using $L_{bol} = L_{c2d}$, the bolometric luminosity from Evans et al. (2009).

By trial and error, what resulted was a relationship between the SED slope and ratio of $L_{MIR}/L_{bol}$ using 67 rising spectrum c2d protostars. To determine the relationship, multiple fits were attempted, including: a linear fit to $\sqrt{L_{MIR}/L_{bol}}$ vs. $\log(\alpha)$, $\log(L_{MIR}/L_{bol})$ vs. $\log(\alpha)$, $\log(L_{bol}/L_{MIR})$ vs. $\log(\alpha)$, $\sqrt{L_{bol}/L_{MIR}}$ vs. $\log(\alpha)$. The bands over which $\alpha$ was calculated were experimented with, and the best fit was given by $\alpha$ determined using 3.6 - 24 $\mu$m fluxes. The parameter $\alpha$, calculated from all the photometry between 3.6 and 24 $\mu$m, was chosen because it shows a stronger trend than $\alpha$ calculated using only the 4.5 and 24 $\mu$m photometry, which are preferentially used in determining protostar candidate status, or the entire range of available wavelengths for all clouds (J-band through 24 $\mu$m). The 24 $\mu$m flux is useful because it is less affected by inclination effects or outflow cavities, but again using $L_{MIR}$ gives a better fit than using the 24 $\mu$m flux alone. The smallest residuals were found using the relationship $\sqrt{L_{MIR}/L_{bol}}$ vs. $\log(\alpha)$. Additionally, a polynomial fit to this relationship was attempted, but again the linear fit has smallest residuals. Thus, a linear fit of $\sqrt{L_{MIR}/L_{bol}}$ vs. $\log(\alpha)$ was the best fit. Some intrinsic scatter is expected in the relationship, which is not due to the uncertainty in measurements. Figure 3-2 shows the best fit for this relationship, and a plot relating $\log(\alpha)$ and the $L_{bol}/L_{MIR}$ luminosity fraction using $L_{bol} = L_{c2d}$. This adopted relationship is found to be

$$\frac{L_{MIR}}{L_{bol}} = (-0.46 \times \log(\alpha) + 0.33)^2. \quad (3.2)$$

The flat spectrum sources did not follow the same trend. For these sources, the adopted the ratio of $L_{MIR}/L_{bol}$ is given in Equation 3.2 for $\alpha = 0.3$:

$$\frac{L_{MIR}}{L_{bol}} = 0.33. \quad (3.3)$$
Figure 3-2: Bolometric/Mid-IR Luminosity ratio vs. log(α) relationship. Protostars from the c2d sample with well-constrained bolometric luminosities are plotted as black circles. The Taurus protostars with established bolometric luminosities are plotted as red squares, but are not used to determine the fit. Left panel: The best fit correlation (solid line) to c2d sources used to derive the relationship using rising spectrum protostars: the square-root of the fraction of mid-IR to the bolometric luminosity vs. log(α). Right panel: The fraction of bolometric to mid-IR luminosity as a function of log(α). The solid line shows the fit for the rising spectra protostars and adopted ratio occurring at log(α) < -0.5. The break was introduced to fit the flat spectrum sources, which are included in this plot.
The mean value of $L_{\text{MIR}}/L_{\text{c2d}}$ for the 21 flat spectrum sources not used to create the fit is 0.30 with a standard deviation of 0.11, which is the same as the adopted ratio of Equation 3.3 for $-0.3 < \alpha < 0.3$.

In addition to the internal heating of protostars, the contribution from external heating, $L_{\text{ext}}$ may also affect the measured luminosity. Evans et al. (2001) estimate the effect of $L_{\text{ext}}$ is typically of order of 0.1 $L_\odot$, which is a small contribution for all but the faintest sources. Therefore, the effect of $L_{\text{ext}}$ on $L_{\text{bol}}$ is neglected.

To test the relationship and the effect of the scatter, a comparison of the luminosities derived using Equations 3.2 and 3.3 with the bolometric luminosities from Evans et al. (2009) is shown in Figure 3-3 and 3-4. Figure 3-3 shows the bolometric luminosity estimated from this work vs. the well-determined luminosity from Evans et al. (2009). The left panel of Figure 3-4 compares the luminosity function constructed from the estimated luminosities to that constructed from the bolometric luminosities in Evans et al. (2009). The luminosity functions are similar; a Kolmogorov-Smirnov (K-S) test comparing the two distribution results in a probability of 0.91 that they are from the same parent distribution. The protostars from Evans et al. (2009) used to determine Equation 3.2 range in bolometric luminosity from $0.03 L_\odot \leq L_{\text{c2d}} \leq 19.6 L_\odot$.

In Figure 3-5, a histogram of the difference between the estimated $\log(L_{\text{bol}}/L_{\text{MIR}})$ from this work and $\log(L_{\text{bol}}/L_{\text{MIR}})$ derived with the Evans et al. luminosities is shown. The standard deviation of the difference is 0.36. From this analysis, it is concluded that despite any discrepancy between individual luminosity $L_{\text{bol}}$ calculated using the relationship and $L_{\text{c2d}}$, the overall luminosity function of the protostar candidates is recovered with reasonable fidelity.

The protostar candidates in Taurus can be tested as to whether or not they follow a similar relationship to what was found in the c2d clouds. A number of Taurus protostar candidates also have relatively well-determined bolometric luminosities. The bolometric luminosities from Furlan et al. (2008) combined with $L_{\text{MIR}}$ and the slopes
Figure 3-3: Estimated bolometric luminosities for c2d sources from this work (black), vs. actual bolometric luminosities from Evans et al. (2009). The c2d sources are the same used to fit the relationship in Figure 3-2. Shown as squares (in red) are Taurus sources from Furlan et al. (2008).
Figure 3-4: Left panel: Luminosity functions using estimated bolometric luminosities for 88 $c2d$ sources from this work (black), and actual bolometric luminosities from Evans et al. (2009) (red). The $c2d$ sources are the same used to fit the relationship in Figure 3-2. These distributions look similar, and a K-S test gives the probability that they are from the same parent distribution as 0.91.

Right panel: Luminosity functions of Taurus protostars from this work (black) and from Furlan et al. (2008) (red). A K-S test gives a probability of 0.93 that these are from the same parent distribution, though only 17 sources are used in the luminosity functions.
calculated in this work were used to compare to the fit derived in this work. Figure 3-3 includes the relationship between Taurus protostar candidate bolometric luminosity estimated from this work, and well-determined luminosities from Furlan et al. (2008). These sources encompass luminosities between $0.2 \, L_\odot \leq L_* \leq 28.0 \, L_\odot$. The Taurus protostar candidates with well-determined bolometric luminosities agree well with the fit. The luminosity functions of the Taurus sources from this work and from Furlan et al. (2008) are also shown in Figure 3-4, and have a K-S probability of 0.93 that they are from the same parent distribution.

### 3.2 Building the Luminosity Functions

The method above was used to calculate luminosities for each of the protostar candidates in the nine clouds. In Figure 3-6 the resulting luminosity functions are shown. The protostar candidates of Taurus, Lupus and Chameleon are again com-
Figure 3-6: Protostellar luminosity functions for the protostellar candidates in each of the clouds. In the combined Tau/Lup/Cha plot, the combined luminosity function is shown in black, the Taurus contribution is shown in red, the Lupus contribution is shown in green, and the Chamaeleon contribution is shown in blue.

combined because of the similar distances and dispersed star formation of these clouds, and are shown as a single luminosity function. Also shown are the combined luminosity function for the high mass star forming clouds (Orion, Cep OB3 and Mon R2) and for the clouds forming low to intermediate mass stars (Perseus, Ophiuchus, Taurus, Lupus and Chameleon).

### 3.3 Contamination

While the selection technique is designed to minimize the contamination in the final protostar sample, there are still possible sources of contamination. The most likely contaminants are background galaxies, highly extinguished Class IIs, and edge-
on disk sources. A pre-main sequence star with a prominent disk observed at an edge-on inclination can show colors similar to those of a protostar (Crapsi et al., 2008). Additionally, it has been shown that highly reddened disks in Ophiuchus may look like protostars (Evans et al., 2009; McClure et al., 2010). To assess the contamination, the Class II sources are first identified using the criteria from Gutermuth et al. (2009).

The extent of contamination for each cloud is estimated in turn for each type of contaminant, as described in the following subsections. A Monte Carlo method was employed to estimate the contamination, which consisted of 1000 trials for each of the protostar candidates in clustered and in distributed environments for each cloud. In each trial, an estimation of the luminosity function of reddened Class II sources and an estimation of a luminosity function of likely edge-on disks were created, while the luminosity function of the galaxy contamination remained unchanged from trial to trial. After each of the 1000 trials, the contamination luminosity functions are removed from the clustered or distributed protostar candidate luminosity function. Finally, a single protostellar luminosity function is created, combining these clustered and distributed protostellar luminosity functions. The number of protostellar candidates is listed for each region in Table 2.1 both before and after contamination removal (in parenthesis), and the number of protostars and protostar candidates with flat and rising spectra.

### 3.3.1 Extragalactic Contamination

Galaxies can have colors very similar to those of YSOs (Harvey et al., 2006; Gutermuth et al., 2009). Although contamination from galaxies is minimized by applying the $m_{24}$ cutoff to each of the clouds (Section 2.2), a small number of extragalactic sources brighter than this limit is expected. To quantify the contamination from the remaining galaxies on the luminosity functions, a sample of SWIRE galaxies from the Elias N2 region is chosen, scaled to the size of the coverage maps for each cloud, and
subjected them to the protostar selection criteria including the $m_{24}$ cutoff. Any of these known galaxies which were identified as protostars are considered to be contamination. Using the method derived for protostars, galaxy contaminants were given bolometric luminosities (i.e. the luminosities they would have if they were protostars in the observed cloud) and created luminosity functions for the contaminants. These are shown in Figure 3-7. Although present, galaxies are the smallest source of contamination, comprising an estimated 2 - 3% of the protostar candidate sample.

### 3.3.2 Edge-on and Nearly Edge-on Disk Sources

Pre-main sequence stars seen through their flared disk may have a rising SED and be mis-identified as a protostar candidates using the criteria. The fraction of Class IIs seen through their disk is difficult to estimate theoretically, since it depends on poorly constrained properties of the disks, including the amount of flaring and the outer radius of the disk. Instead, an empirical estimate was employed using the technique of Gutermuth et al. (2009). A large cluster of young stars in a region where the gas has been dispersed and the extinction is low was identified in the Cep OB3b cluster (Allen et al. in prep). Although the gas has been cleared by the OB stars in the cluster, objects with protostellar-like colors were detected in this low extinction cavity. Following Gutermuth et al. (2009), YSOs with protostellar-like colors in the low-extinction regions were assumed to be edge-on or nearly edge-on disks (hereafter the use of ‘edge-on disks’ to refers to disks that are close enough to an edge-on inclination that they are observed through their disks). This ratio was then multiplied by the number of Class II objects to calculate the number of expected edge-on sources. Since some of the sources in Cep OB3b may be actual protostars which have survived gas dispersal, this assumption gave an upper limit to the number of edge-on disks sources that have colors similar to protostar candidates. In the following analysis, the number of edge-on disks will be set equal to this number.
Figure 3-7: Protostellar luminosity functions for the protostellar candidates in each of the clouds (black). The color histograms show the contamination, including reddened Class II contamination (red), edge-on Class IIs (green), and star forming galaxy (blue) contamination. The majority of the contamination is from edge-on Class II sources, mostly falling in the lower ($L < 1L_\odot$) luminosity bins. It should be noted that the level of edge-on Class II contamination may be overestimated.
A region within the Cep OB3b cluster where the total extinction is \( A_V < 3 \) was identified; this low extinction region contained 34 protostar candidates and 568 Class II sources and is shown in the map of Cep OB3 in Figure 2-13. The number of Class IIs, however, was for the entire range of magnitudes and did not include a cutoff in \( m_{24} \). Furthermore, these sources were not corrected for possible extragalactic contamination. To calculate the appropriate ratio, \( R \), which imposed a cutoff at \( m_{24} \), the ratio of edge-on disks to Class II objects was calculated using the following equation,

\[
R = \frac{N_{p}^{CepOB3b} - N_{p}^{gal}}{N_{d}^{CepOB3b} - N_{d}^{gal}}
\]

(3.4)

where \( N_{p}^{CepOB3b} \) is the number of sources with protostellar-like colors in Cep OB3b with \( m_{24} < \) cutoff, \( N_{d}^{CepOB3b} \) is the number of Class II sources with \( m_{24} < \) cutoff, and \( N_{p}^{gal} \) and \( N_{d}^{gal} \) are the expected contamination from galaxies with protostellar-like and disk-like colors, respectively. Although \( R \) is an upper limit, \( R \) is treated as the actual fraction of edge-on disks in the remainder of this work and thus the contamination by edge on disks may be overestimated. The number of edge-on disks was calculated as

\[
N_{edge} = R \times [N_p + N_{CII} - N_{d}^{gal} - N_{p}^{gal}]
\]

(3.5)

where \( R \) is calculated for Cep OB3b using the cutoff of that cloud, but \( N_{CII} \) and \( N_p \) are determined for the \( A_V > 3 \) region of the cloud for which \( N_{edge} \) was calculated.
is the number of protostars \( (N_p) \) since a fraction of the protostars may have been edge-on disks. This may overestimate slightly the number of edge-on disks; however, not including \( N_p \) would have resulted in slight underestimation. The number of edge-on disks was corrected by subtracting the expected extragalactic contamination.

To determine the number of Class II sources \( (N_{CII}) \), the criteria from Gutermuth et al. (2009) were used. All Class II sources with de-reddened \( m_{24} \) brighter than the cutoff were counted. The relatively large size of the Taurus map (44 deg\(^2\)) along with the proximity of the region resulted in more contamination to the Class II sample. To minimize the contamination, the criteria were modified for this cloud as well as the Lupus and Chamaeleon clouds which were combined with the Taurus region in the analysis. The AGN identification criteria for Taurus were adjusted to include both of these conditions by decreasing the value of \( m_{4.5} \) by 1 magnitude in the criteria developed by Gutermuth et al. (2009). This adjustment was also used for the Lupus and Chamaeleon clouds.

For each of the potential protostar candidates in the \( A_V < 3 \) region of Cep OB3b (i.e. the sample of likely edge-on disks), a “faux” bolometric luminosity was calculated using Equation 3.2 and assuming that \( \alpha \) and \( L_{MIR} \) can be determined like that of a protostar candidate. In each of the Monte Carlo trials, a luminosity function for these sources is created. Individual sources were randomly selected from this luminosity function. A total of \( N_{edge} \) luminosities were chosen, and from this collection of randomly selected luminosities, the luminosity function of edge-on disks was constructed for each of the 1000 Monte Carlo trials.

### 3.3.3 Reddened Disk Sources

Highly reddened Class II YSOs can have colors and 24 \( \mu m \) magnitudes which may fit the classification criteria for protostars. To find the amount of contamination due to these sources and estimate the luminosities which would be derived for these con-
taminants, a Monte-Carlo simulation was utilized, which randomly applied a realistic
distribution of extinctions to the observed colors and magnitudes of a fiducial sample
of Class II objects.

The fiducial sample was constructed from Class II objects identified in low $A_V$
regions. Class II sources were first identified in the low extinction ($A_V < 3$) region
of the extinction map. The selected Class II sources were then de-reddened using
the reddening law from Flaherty et al. (2007). Sources with dereddened $m_{24}$ brighter
than the cutoff magnitude were selected for the fiducial sample. These objects
were used as a fiducial sample of Class II objects, with the accompanying assumption
that the colors and magnitudes of this sample is representative for all Class II objects
in the cloud.

Then, the full sample of Class II objects and protostar candidates in the $A_V >$
3 region were identified. Protostar candidates were included, since a fraction of the
protostar candidates may be the reddened Class II sources. Furthermore, protostar
candidates are in more highly reddened locations and failure to include them would
bias the distribution of $A_V$ to lower values. The Class II objects and protostar
candidates were sorted into clustered and non-clustered regions by using the distance
to the 4th nearest YSO neighbor: sources with 4th nearest neighbor distances less
than the median value of the protostar candidate sample in a particular cloud were
considered “clustered”, and exist in a more dense stellar environment and those with
distances greater than the median value were “distributed”, and thus exist in a less
dense stellar environment. The following analysis was executed for the clustered and
distributed sources independently. This was done because clustered sources may be
in regions of systematically higher gas column density (and reddening) compared to
distributed sources. The $A_V$ values corresponding to each YSO were extracted using
the $A_V$ maps; this gave two $A_V$ distributions, one for the clustered sources, and one
for the distributed. These were the maximum $A_V$ values ($A_{V_{\text{max}}}$) at the position of
a particular YSO. Since the YSOs are embedded in the cloud, the $A_V$ value to that
YSO is between 0 and $A_{V_{max}}$.

For each YSO with a de-reddened $m_{24}$ greater than the cutoff for that cloud, a
randomly selected $A_{V_{max}}$ value was chosen and the $A_V$ was set to a value drawn
from a uniform distribution of extinctions between 0 and $A_{V_{max}}$. Then, a randomly
selected Class II was chosen from the fiducial sample and the $A_V$ was applied using
the reddening law from Flaherty et al. (2007) to that source in all of the bands. To
estimate the fraction of (clustered or distributed) reddened disks masquerading as
protostar candidates, these sources were subjected to the protostar selection criteria
to see how many of the reddened Class IIs were identified as protostar candidates.
This process was repeated for 1000 iterations for the clustered and distributed sources
independently. In each of the 1000 iterations, the “faux” bolometric luminosities
of these likely contaminants were estimated using the same technique used for the
protostar candidates. For each cloud, two distributions of luminosities were created,
one for the clustered sources and one for the distributed sources.

3.3.4 Contamination Removal

Once the luminosities for the contaminating sources are estimated, the protostar
candidates with similar luminosities as the contaminants must be removed from the
protostar candidate sample. It was assumed that the luminosity distributions of the
contaminants were contained in the luminosity functions of the protostar candidates.
Instead of binning the data, and subtracting the differential luminosity distributions
of the contaminants from those of the candidates, individual protostar candidates
were eliminated from the sample using the following method.

First, the sources were divided into clustered and distributed protostar candidates
in each cloud using the method described in Section 3.3.3. It should be noted that this
division between clustered and distributed YSOs made a difference for the reddened
disk contamination, since the clustered regions have systematically higher extinctions and will likely have more contaminants, and for the galaxy contamination because likely background galaxies are assumed to be found among the more distributed sources and thus are only considered for the distributed protostar trials.

For each clustered and distributed sample, 1000 realizations of estimated luminosities were generated for each type of contaminant: galaxies, edge-on disks and reddened Class II sources. In each of the 1000 trials, the protostar candidate with the closest luminosity to each contaminant luminosity, such that the difference in $\log(L/L_\odot) < 0.2$, was flagged as contamination and removed from the (clustered or distributed) protostar candidate sample. If there was no protostar candidate which satisfied these criteria, no source was removed. The final product is 1000 realizations of the contamination subtracted protostar sample. These realizations are used to generate luminosity functions and do statistical analyses.

For each of the clouds, a single “averaged” contamination subtracted luminosity function was generated from the 1000 realizations of the protostar candidate sample. After each of the 1000 trials, resulting in 1000 contamination-subtracted realizations, the average number of remaining protostars per bin was used to generate the luminosity functions for the clustered and distributed protostars, creating one combined realization per trial. All 1000 clustered plus distributed realizations were stacked together to create one luminosity function; the average number of sources per bin were then randomly selected from this stacked luminosity function and used to create the final, averaged luminosity function shown in Figure 4-1. A luminosity cutoff, $L_{\text{cut}}$, corresponding to the $m_{24}$ cutoff magnitude, was calculated by assuming an SED slope steeper than that for 90% of all sources in the region and a mid-IR luminosity equal to the 24 $\mu m$ luminosity at the cutoff magnitude and the relationship in Equation 3.2. The luminosity cutoff is found from the $m_{24}$ cutoff used to reduce the number of galaxies (Figure 2-3). Thus, the luminosity distributions are expected to be complete.
down to the cutoff, except in regions with very bright nebulosity. A more detailed description of incompleteness is given in Appendix B and in Section 4.2.
Chapter 4

Comparison of Protostellar Luminosity Functions for Star-Forming Regions Within 1kpc

In this chapter, the luminosity functions of the clouds within 1kpc will be discussed. The clouds are divided into two environment groups: clouds which form high-mass stars and clouds which do not form high-mass stars. The luminosity functions of the clouds in each group will be combined, and the resulting luminosity functions of the two groups will be compared. To test how reliable these comparisons of luminosity functions may be, two tests are evoked. First, the effect of using uncorrected (not de-reddened to correct for extinction) photometry is examined, particularly for the Ophiuchus cloud which contains few luminous protostars and for which extinction may most affect the luminosity function. The second tests the choice of combining flat spectrum and rising spectrum protostars is tested by comparing luminosity functions of flat spectrum protostars with the luminosity functions of rising spectrum protostars.

In Section 4.2, two other environments are compared. The nearest-neighbor dis-
stance is used to determine how crowded an environment a protostar candidate is currently in. To classify protostar candidates as residing in a clustered or in a distributed environment, the median 4th-nearest neighbor distance is used as a cutoff. The luminosity functions of protostars in these two environments are compared for Orion, the cloud with the largest number of protostar candidates.

Finally, this chapter ends with a section that tests completeness, particularly at $m_{24}$, in one of the clouds for which this may be most problematic, Orion.

### 4.1 Cloud-to-Cloud Comparisons

The protostellar luminosity functions and $L_{\text{cut}}$ are shown in Figure 4-1. Also shown are the combined luminosity functions for the clouds with high mass star formation (Orion, Cep OB3 and Mon R2, hereafter the high mass star-forming clouds) and for the clouds forming low to intermediate mass stars (Serpens, Perseus, Ophiuchus, Taurus, Lupus I, III, and IV, and Chameleon II; hereafter the low mass star-forming clouds). Table 4.1 gives the average number of estimated contaminants (calculated over all 1000 realizations), and $L_{\text{cut}}$ for each cloud.
Figure 4-1: Calculated bolometric luminosities for each region with estimated contamination from reddened disk sources, edge-on Class IIs, and background galaxies removed. The vertical line shows the limiting $L_{bol}$ based on the $m_{24}$ cutoff. The panel showing combined Taurus, Lupus, and Chamaeleon luminosity function also shows the components from each cloud: Taurus is the thin red histogram, Lupus is the green, and no Chamaeleon protostars remain after contamination removal.
Table 4.1: Properties of Cloud (< 1kpc) Luminosity Functions

<table>
<thead>
<tr>
<th>Cloud</th>
<th>Red/Edge-on/Gal.†</th>
<th>$L_{\text{cut}}$‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiuchus</td>
<td>3.8/6.5/0.0</td>
<td>-2.07</td>
</tr>
<tr>
<td>Tau/Lup/Cha</td>
<td>2.0/4.2/0.0</td>
<td>-1.67</td>
</tr>
<tr>
<td>Perseus</td>
<td>3.7/8.2/0.0</td>
<td>-1.32</td>
</tr>
<tr>
<td>Serpens</td>
<td>4.24/5.1/1.9</td>
<td>-1.33</td>
</tr>
<tr>
<td>Orion</td>
<td>11.9/58.8/5.80</td>
<td>-1.45</td>
</tr>
<tr>
<td>Cep OB3</td>
<td>5.3/31.2/9.25</td>
<td>-1.49</td>
</tr>
<tr>
<td>Mon R2</td>
<td>3.0/11.1/2.8</td>
<td>-1.36</td>
</tr>
</tbody>
</table>

† Estimated average number of each type of contamination.
‡ Luminosities in $\log L_\odot$.

The high mass star-forming clouds have well defined luminosity function peaks near $1 L_\odot$ and tails extending toward higher luminosities upward of $100 L_\odot$. A combined luminosity function for these regions shows a similar peak and tail. The median luminosity in each of the high mass star-forming clouds is $\sim 1 L_\odot$. Cep OB3 has the highest mean luminosity of the high mass star-forming clouds, at $11.57 L_\odot$.

The low peak luminosity and low median luminosity of these regions shows that the luminosity problem does indeed exist in these high-mass star-forming regions, which indicates that it is a problem common to many diverse star forming environments. It should be noted, however, that in Orion some of the most luminous sources in the saturated regions of the Orion nebula and NGC 2024 are missing from the protostar candidate sample; this will be discussed further in Section 4.2.

The low mass star-forming cloud luminosity functions do not show a consistent trend. Perseus does not show a peak in the luminosity function above $L_{\text{cut}}$, but rises toward lower luminosities. The Serpens luminosity function does not show a
distinctive peak. Ophiuchus shows a marginal peak in its luminosity function at \(0.1 \, L_\odot\), but with small/ number statistics this peak is not significant. The luminosity function of Tau/Lup/Cha peaks near \(1 \, L_\odot\), similar to the high mass star-forming clouds. The mean protostar luminosities for each of the low mass star-forming clouds is \(\sim 1 \, L_\odot\), with exception of Ophiuchus at 0.44 \(L_\odot\), and the median luminosity for each cloud \(\sim 1 \, L_\odot\). The low mass star-forming clouds do not contain protostars at luminosities at or above \(1000 \, L_\odot\), with no distinct tail near \(100 \, L_\odot\) as in the high mass star-forming luminosity functions. The combined luminosity function of these low-mass star-forming regions does not show a peak, but rises toward lower luminosities, a feature akin to the Perseus luminosity function. These luminosity functions also peak low enough to show the luminosity problem, as found in previous studies (e.g., Dunham et al., 2010).

Of particular interest is the differences between the high-mass star-forming clouds and the low-mass star-forming clouds. The luminosity functions of high-mass star-forming clouds peak at and extend to higher luminosities than the low-mass star-forming clouds, which do not show distinct peaks in their luminosity functions. To establish whether the observed differences in the luminosity functions are statistically significant, a K-S test is performed on each of the 1000 realizations of the contamination-subtracted luminosity functions. In all of the 1000 realizations, the individual high-mass star-forming cloud luminosity functions are combined, and the individual low-mass star-forming cloud luminosity function realizations are combined. Thus, the combined realization from trial 1 of the high-mass star-forming clouds is compared with the combined realization from trial 1 of the low-mass star-forming clouds, the combined realization from trial 2 of the high-mass star forming clouds with the combined realization from trial 2 of the low-mass star-forming clouds, and so on. In Figure 4-2 the resulting distribution of K-S probabilities for the high-mass star-forming clouds compared with the low-mass star-forming clouds is shown. The
Figure 4-2: The distribution of K-S probabilities that the combined protostellar luminosity function of the high-mass star-forming clouds are from the same parent distribution as the low-mass star-forming clouds. Shown are $\log(\text{prob})$ from each of the 1000 Monte Carlo realizations. The vertical red bar shows the median value, the blue bar shows the mean, and vertical blue dashed lines show $1\sigma$.

median probability $\log(\text{prob}) = -5.96$. Among the high mass star-forming clouds, the possibility that they are all drawn from the same parent distribution cannot be ruled out. Comparison between the lower mass star-forming regions shows no trend: Perseus is consistent with Tau/Lup/Cha and Serpens, Ophiuchus is not consistent with any other cloud, and Tau/Lup/Cha is consistent with every cloud except Orion and Ophiuchus, likely because of the low number of protostars in Ophiuchus. It is concluded that there are significant differences between the luminosity functions of the observed clouds, with some clouds showing relatively similar luminosity functions and others showing distinctly different luminosity functions.
4.1.1 The Effect of Reddening

Protostars are often found in regions of extended high extinction, which can further redden the observed colors of protostars. Class II sources are easily de-reddened since we directly observe their photospheres, which have well-defined colors. These sources can be de-reddened by estimating the extinction in the $K_s$-band and applying a reddening law, which assumes a certain interstellar extinction, to the photometry of the Class II source. Protostars are expected to be reddened, but de-reddening their photometry cannot be done reliably because of the difficulty in distinguishing extinction due to the surrounding cloud from that due to the protostellar envelope, and also because the central source is often detected in scattered light and not directly.

The effects of reddening are assessed by de-reddening protostars using methods developed for pre-main sequence stars. Although the de-reddening values determined for individual protostars are unreliable, this was attempted as an experiment to assess the magnitude of the effect of reddening on the overall luminosity function. By comparing the shapes of the de-reddened and the uncorrected protostar luminosity functions, the effect of reddening on the overall properties of the luminosity functions can be assessed. Protostar candidates were de-reddened. H, $K_s$, 3.6, and 4.5 $\mu$m band photometry were used in color-color diagrams to estimate $A_{K_s}$, the extinction in the $K_s$ band (Gutermuth et al. 2009, Gutermuth thesis). Then, the reddening law of Flaherty et al. (2007) was applied to determine the extinction in the 3.6, 4.5, 5.8, 8.0, and 24 $\mu$m bands. The extinction in each band is then subtracted from the corresponding magnitude detection in that band. After de-reddening, the SED slope and $L_{MIR}$ are recalculated, and find de-reddened bolometric luminosities are estimated. The de-reddened luminosity functions peak at the same luminosity as those for the uncorrected protostar candidates. Serpens and the combined Tau/Lup/Cha luminosity functions do not have significant peaks in their un-corrected or de-reddened luminosity functions. K-S tests comparing the un-corrected and de-reddened lumino-
nosity functions give probabilities that range from 0.06 in Orion to 0.87 in Cep OB3. The de-reddened luminosity functions do keep the same peak (1 \( L_\odot \)) and high luminosity tail present in the uncorrected luminosity functions of the clouds which form high-mass stars, the clouds with the most protostars and least subject to the effects of small variations.

Ophiuchus is one of the most highly reddened clouds in the sample, and also one of the least luminous, and is the only cloud in which the luminosity function does not extend over 100 \( L_\odot \). It is speculated that the lack of more luminous sources in the Ophiuchus protostellar luminosity function may be caused by reddening. The median Class II \( A_V \) in Ophiuchus is \( A_V = 11.68 \), which indicates that the YSOs in Ophiuchus are deeply embedded and that reddening from the surrounding cloud is the cause for the protostellar luminosity function peaking at a lower luminosity than the low-extinction clouds Tau/Lup/Cha. The de-reddened Ophiuchus protostar candidate luminosity function is compared to the observed (un-corrected) Tau/Lup/Cha protostar candidate luminosity function, and a K-S test finds a probability = \( \log(\text{prob}) = -6.95 \) that they are from the same parent distribution, lower than the probability that the uncorrected Ophiuchus luminosity function is similar to the Tau/Lup/Cha luminosity function, \( \log(\text{prob}) = -2.66 \). Thus, it is unlikely that the large extinction found in Ophiuchus is to blame for the differences seen between the luminosity functions of Ophiuchus and Tau/Lup/Cha. Given the problem with de-reddening, the protostar photometry is not de-reddened, since it is typically not a large effect and the results of this work should not be altered by reddening.

### 4.1.2 Flat vs. Rising SED Protostars

Protostar candidates are identified as sources with a flat or rising spectrum in the mid-IR, and the bolometric luminosity of the flat spectrum sources is estimated using Equation 3.3. There has been some question of the relationship between flat
spectrum sources and rising spectrum sources. Some flat spectrum sources may be rising spectrum sources observed from a face-on orientation through which emission from the warm inner layers can escape through the outflow cavity (Calvet et al., 1994; Whitney et al., 2003). Alternatively, protostars resulting from the collapse of a flattened sheet-like cloud can also give a flat SED (Hartmann et al., 2006). Finally, sources with tenuous envelopes can give a flat spectrum, in part because of the backwarming of the envelope (Natta, 1993); such sources may be protostars at the later stages of envelope dissipation. Winston et al. (2007) also find that some flat spectrum sources may be reddened disks, although these sources have been accounted for in the sample.

The fraction of Spitzer protostar candidates which have flat SED slopes ranges from $\sim 29.2\%$ in Orion to $\sim 20\%$ in Perseus, though it should be noted that Ophiuchus has $44\%$ of its protostar candidates with $\alpha$ between -0.3 and 0.3. The luminosity functions of the rising and flat spectrum sources in each cloud are compared by using K-S tests to determine the probability that the luminosity functions are drawn from the same parent distribution. In each case, only the distribution above the luminosity cutoff set for each region is used in the comparison. This analysis yields the following probabilities for each region: Orion (0.54), Cep OB3 (0.69), Mon R2 (0.20), Serpens (0.31), Perseus (0.01), Ophiuchus (0.01), and Tau/Lup/Cha (0.51). The distributions for the flat and rising stars are found to be statistically indistinguishable, although the distributions for Perseus show a lower probability than the other regions. Given the similarity of the luminosity functions, and given that the sample of flat spectrum sources may contain many rising sources observed at a face-on orientation, only the combined luminosity function for each set of sources is analyzed.
4.2 Comparison Between Clustered and Distributed Environments

Molecular clouds host a variety of star forming environments, including regions of clustered and distributed YSOs. Although it has been shown that OB stars are typically found in clusters (Testi et al., 1999), it is unclear whether this is because of the fact that massive stars are rare and thus are only likely to be found in groups of low mass stars (Bonnell and Bate, 2006), or because these stars preferentially form in clusters (Bontemps et al., 2010). Since the luminosity of a protostar is a combination of accretion luminosity and intrinsic luminosity, the masses of the protostar candidates in this sample cannot be determined; however the most luminous protostars tend to be the most massive protostars (McKee and Tan, 2003). The luminosity functions of clustered and distributed protostars are now compared to determine if the luminous protostars are found preferentially in clustered environments.

4.2.1 Identifying Clustered And Distributed Populations Of Protostars

To determine the degree of clustering around each protostar candidate, the nearest-neighbor distances are computed. The nearest-neighbor distance is the distance to the $n^{th}$ nearest Class II or protostar candidate. The choice of $n = 4$ was made after considering $n = 2$ and $n = 10$ distances; $n = 4$ gives a better indication of clustering in both distributed and highly clustered star forming clouds while $n = 2$ is dominated by random fluctuations (Casertano and Hut, 1985) and $n = 10$ is not sensitive to clustering in smaller groups (hereafter, the distance to the 4th nearest YSO will be denoted “nn4 distance”).

Figure 4-3 shows the bolometric luminosity vs. $nn4$ distance for all protostar candidates. For the three high-mass star forming clouds, Orion, Cep OB3, and Mon R2,
a trend can be noted between the $nn4$ distance and luminosity of the most luminous protostar at that $nn4$ distance. In these clouds, as the $nn4$ distance decreased the luminosity of the most luminous protostar increased. This can also be seen in the combined plot for all three high mass star-forming clouds. Thus, the most luminous sources ($L_{bol} > 10 L_\odot$) are typically found with $nn4 < 0.50$ pc.

This trend is clearer for the Orion cloud, which has the largest sample of protostar candidates. However, the most luminous protostar in the Orion sample has an $nn4$ distance of 0.52 pc. In addition, the fourth most luminous protostar in Orion has an $nn4$ distance of 0.38 pc, greater than the typical distance for sources of comparable luminosity in the Orion cloud. These sources, Reipurth 50 and V883 Ori, are thought to be undergoing FU Ori eruptive events (Strom and Strom, 1993). Thus, these sources appear to be low mass protostars undergoing large outbursts. In these outbursts, the accretion luminosity is thought to dominate the intrinsic luminosity (Hartmann and Kenyon, 1996). Additionally, an outlier is seen in Cep OB3 at an $nn4$ distance of 0.47 pc. This may be an outburst source as well, though there is no observational evidence to indicate this yet.

The low-mass star-forming clouds do not show the same trend. Instead, no convincing correlation between the most luminous protostars and $nn4$ distance is found. Even in the combined plot of low mass star-forming clouds, the trend apparent in high mass SF clouds is not seen. The low-mass star-forming clouds are different from high-mass star-forming clouds because they contain few sources above 10 $L_\odot$. In addition, the broad range of $nn4$ distances found in the high mass star-forming clouds is not apparent in most of the low-mass star-forming clouds.

A statistical comparison of protostellar luminosity at different $nn4$ distances requires classification of protostar candidates as residing in clustered or distributed environments. The classification is determined using the median $nn4$ distance: if the $nn4$ distance for a given source is shorter than the median protostar candidate $nn4$
Figure 4-3: Nearest neighbor distances (for 4th nearest neighbor YSO) and calculated bolometric luminosity for all protostar candidates. The final panels show the protostars for Orion, Cep OB3, and Mon R2 and for Tau/Lup/Cha, Perseus, and Ophiuchus. Orion, Cep OB3, and Mon R2 each have protostar candidates above 100 L⊙ and show sources at larger nn4 distances only at lower luminosities. The low-mass star-forming clouds do not show this relationship individually or in the combined plot.
distance, $D_c$, then the source is said to be in a more crowded or clustered environment. Although this is different than a variety of other definitions used for clustering (Allen et al. 2007, Gutermuth et al. 2009, Megeath et al. in prep), this definition has the advantage of creating equal number of clustered and non-clustered objects. Thus, this classification should be considered as simply a way to separate protostars into two equal sized samples based on the density of YSOs in their surrounding. The use of the $nn4$ distance allows us to include small groups in the sample of clustered regions, which is important especially in the L1641 region in Orion which contains many small dense groups of YSOs and contains many of the protostars in the Orion sample. Given the individual nature of the diverse clouds in the sample, $D_c$ varies from cloud to cloud. The Tau/Lup/Cha clouds have a large $D_c$, because of the lack of clusters in these clouds. In comparison, Ophiuchus has a very small $D_c$ because of the lack of a significant distributed population in this cloud.

To test whether the differences and similarities which appear in Figure 4-3 and discussed above are real, K-S tests are performed comparing the luminosity functions of the clustered and distributed regions in a given cloud. Figure 4-4 shows the distribution of the K-S probabilities for Orion. For Orion, there is a population of more clustered protostars distinct from the population of more distributed protostars. Similar tests are performed for the other clouds and results are shown in Table 4.2. Listed are the median K-S probabilities over all 1000 trials that clustered and distributed protostars are from the same parent distribution using $D_c$. With the exception of Orion, the luminosity functions of clustered and distributed regions cannot be statistically distinguished. This may be due to the smaller number of protostars in Mon R2 and Cep OB3. In Orion, K-S tests determine with significance that clustered and distributed populations of protostar candidates are very likely not from the same parent distribution.
Figure 4-4: Distribution of K-S probabilities that clustered and distributed populations of protostars in Orion are from the same parent distribution for each of the 1000 Monte Carlo realizations. The median is shown as a vertical red bar, mean as vertical blue bar, and 1σ shown as vertical blue dashes.

Table 4.2: Comparison of clustered and distributed protostars.

<table>
<thead>
<tr>
<th>Cloud</th>
<th>P(Dc)</th>
<th>Dc (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiuchus</td>
<td>0.135</td>
<td>0.08</td>
</tr>
<tr>
<td>Tau/Lup/Cha</td>
<td>0.807</td>
<td>0.39</td>
</tr>
<tr>
<td>Perseus</td>
<td>0.318</td>
<td>0.15</td>
</tr>
<tr>
<td>Serpens</td>
<td>0.851</td>
<td>0.10</td>
</tr>
<tr>
<td>Orion</td>
<td>0.00011</td>
<td>0.19</td>
</tr>
<tr>
<td>Cep OB3</td>
<td>0.367</td>
<td>0.26</td>
</tr>
<tr>
<td>Mon R2</td>
<td>0.0508</td>
<td>0.22</td>
</tr>
</tbody>
</table>
4.3 Completeness in Orion

Could the difference observed between the clustered and distributed populations in the Orion cloud result from biases due to saturation and/or incompleteness in the 24 $\mu m$ band? For many of the saturated sources, photometry is recovered using the method described in Section A. The brightest sources are missing in the regions of extended saturation in the Orion nebula and NGC 2024 nebula. It is in these clustered regions where the most luminous sources and densest clusters are found. Inclusion of these regions would likely enhance the differences seen between clustered and distributed environments in the Orion cloud. However, because of the mid-IR nebulosity that exists most prominently in the MIPS 24 $\mu m$ images, there is a bias toward recovering fainter sources in less nebulous regions than in more nebulous regions. Source crowding is not expected to affect the sample, since PSF photometry extraction was used at 24 $\mu m$. Appendix B discusses the effect of completeness on the sample. This analysis shows that in both the clustered and distributed regions, not all protostars are expected to be detected down to the luminosity cutoff. The bright nebulosity and sources common in clustered regions affects the sample by preferentially hiding the faintest protostars in those regions.

One way of addressing the issue of incompleteness is to change the limiting $m_{24}$ used in the Orion luminosity function. Since the incompleteness comes primarily at the faintest magnitudes (Appendix B), changing the magnitude limit should reduce the effect of incompleteness. Figure 4-5 shows the luminosity function of the contamination-subtracted protostars from Figure 4-1 and using only those protostars with $m_{24} < 6$. The clustered and distributed protostar distributions have a K-S probability of 0.0017 of being drawn from the same parent distribution for the original $m_{24} < 7$ cutoff. If a cutoff of $m_{24} < 6$ is used, the probability is 0.0019. If the outbursting sources are excluded, the results have a K-S probability of 0.0022 for $m_{24} < 7$, and 0.084 for $m_{24} < 6$. Thus, the result does not change after raising the limiting $m_{24}$ by
Luminosity functions for clustered (green) and distributed (blue) contamination-subtracted protostars for $m_{24} < 7$ (left) sources and after $m_{24} > 6$ sources are removed (right). The K-S probability that the clustered and distributed luminosity functions are from the same parent distribution is 0.0017 for the $m_{24} < 7$ sources and 0.0019 for the luminosity functions of sources with $m_{24} < 6$.

Another way to assess the incompleteness is to compare the distribution of $m_{24}$ for Class II sources in clustered and distributed regions in Orion. Class II sources are identified in Orion which are within $D_c$ of a protostar candidate, then classified as being clustered or distributed based on the classification of the nearest protostar candidate. The $m_{24}$ is used, since the conversion to luminosity is not valid for Class II objects. Figure 4-6 shows the $m_{24}$ distribution for clustered and distributed regions. A K-S test gives a 0.61 probability that the distributions of clustered and distributed Class II sources are from the same parent distribution. The protostar candidates have a probability of 0.0090 that the two distributions are drawn from the same parent population. If the two outbursting sources are removed, this probability drops to 0.0050.

Unfortunately, this result is at only the $3 \sigma$ level because of the relative rarity of protostars and the small sizes of the sample. Although the same trend of increasing
Figure 4-6: Histograms of 24 µm detections for Orion clustered (green) and distributed (blue) YSOs. Orion disk sources within $D_c$ of a clustered or distributed protostar candidate (left panel) show similar distributions of 24 µm detections for clustered and distributed sources and have a K-S probability of 0.61 for $m_{24} < 7$ sources. Distributions of $m_{24}$ for the clustered and distributed Orion protostar candidates (right panel) do not show similarities, and have a K-S probability of 0.0090 (at $m_{24} < 7$) that they are from the same parent distribution.

Luminosity with decreasing $nn4$ is also apparent for Cep OB3 and Mon R2, the differences cannot be statistically distinguished due to the smaller numbers of protostars in these regions and the fact that the most luminous regions in Mon R2 are highly saturated and the luminosities of the embedded protostars are unrecoverable. In Chapter 5, the clustered and distributed environments are compared in a more distant active star forming cloud, Cygnus-X, which is much more rich in luminous protostars.

### 4.3.1 Possible Implications on the IMF

Of particular interest is whether the different luminosity functions imply a difference in the emerging IMFs of the stars forming in clustered and distributed regions. It should be stressed that the bolometric luminosities estimated are the sum of the intrinsic luminosity of the protostar and the accretion luminosity resulting from gas falling onto the protostar. In low mass protostars, the accretion luminosity probably
dominates, but for higher mass objects the intrinsic luminosity becomes increasingly important (McKee and Tan, 2003; Offner and McKee, 2011). With the data here, it is not possible to estimate the contribution of each of these luminosity sources, and thus, it is not clear whether the most luminous protostars are those with the highest intrinsic luminosity or whether they have the highest accretion rates. If they are the sources with the higher intrinsic luminosity, then these sources probably are higher in mass, particularly if they follow a stellar birthline (Hartmann et al., 1997; Palla and Stahler, 1991). In the case that the luminosity is dominated by accretion, then a higher luminosity might imply a higher protostellar mass or a higher accretion rate (Young and Evans, 2005; Myers, 2011). A higher accretion rate might also imply a higher outcome mass for the protostar; however, if the accretion time is short, the final protostar may not be a high mass star. If this is the case, then sources in clusters may exhibit higher luminosities but have the same outcome IMF. Thus, although one interpretation of the different luminosities is that the clustered regions contain protostars that are more massive or that will form stars of higher mass, this is not a unique interpretation.

If variations in the initial mass functions are indeed seen in the luminosity functions, they would suggest that the presence of massive stars in clusters is a deterministic effect, and not due to the statistical sampling of a constant IMF (Elmegreen, 1999; Bonnell and Clarke, 1999). This result is predicted in simulations of star formation in a turbulent massive core by Bonnell et al. (2004), who find a correlation between the density of stars in cluster and the mass of the most massive member. They explain this as due to a large mass of gas drawn in by the gravity of the entire cluster of stars and accreted onto the most massive members of the cluster. Alternatively, Gutermuth et al. (2011) find a correlation between the YSO surface density and the gas column density. Gutermuth et al. (2011) show that the correlation may be the result of a simple star formation law where the star formation rate is proportional
to the gas density squared and they suggest that Jeans fragmentation in a sheet-like molecular cloud may be able to reproduce the observed result. In this case, the density of YSOs may be just tracing the overall column density of the natal gas and the suggested dependence of the IMF on YSO density may in fact be a dependence of the IMF on gas column density. This may be demonstrated by a direct comparison of the gas column density towards protostars; unfortunately, current extinction maps of the massive clouds made with 2MASS are not sufficient for such analysis, since 2MASS doesn’t have the sensitivity to detect significant numbers of background stars in the dense regions around protostars. This is particularly true for the Orion molecular cloud which is found at a high galactic latitude where there are few bright background stars. Existing $^{13}$CO maps of Orion can be used to determine gas column density (Bally et al., 1987; Miesch and Bally, 1994), but these maps saturate at a few magnitudes of extinction (Pineda et al., 2008) and may not be useful in the densest, brightest regions of Orion. Future mapping of the column density around protostars with higher sensitivity near-IR observations or with sub-millimeter bolometer arrays is needed to explore the relationship between protostellar luminosity and gas density.
Chapter 5

The Massive Star-forming Cloud Complex Cygnus-X

Beyond 1kpc lies the massive star-forming cloud complex Cygnus-X. Cygnus-X contains multiple OB associations, including the Cygnus OB2 association which hosts more than 50 O stars and hundreds of B stars (Wright et al., 2010). It also contains the well-studied star-forming region DR21, which makes it a desirable target for active star formation study. Due to the large number of objects within Cygnus-X, it was once thought to be a superposition of multiple clouds along a line-of-sight, between 1kpc and 4kpc (Dickel et al., 1969). However, later observations support a single cloud complex (Schneider et al., 2006).

The Cygnus-X cloud was the target of a Spitzer Legacy survey\(^1\), which mapped \(\approx 25 \text{ deg}^2\) of the cloud. The IRAC aperture photometry and MIPS 24 \(\mu\)m PSF extracted photometry catalogs from Data Release 1 were used, with no alteration. An extinction map covering the Spitzer-mapped region is from Sylvain Bontemps (private communication).

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\(^1\)From [http://irsa.ipac.caltech.edu/data/SPITZER/Cygnus−X/](http://irsa.ipac.caltech.edu/data/SPITZER/Cygnus−X/)
5.1 Protostar Candidate Sample

The protostar candidates in Cygnus-X are selected using the same technique from Section 2.2. However, due to the distance of Cygnus-X, at 1.4 kpc, an additional criterion is included for sources to be identified as protostar candidates, which already satisfy the following criteria:

\[
[5.8] - [24] > 4.117 \tag{5.1}
\]
\[
[3.6] - [5.8] > 1.296 + \sigma_{3.6,4.5}
\]

These sources are also subject to the following condition:

\[
[3.6] - [4.5] \geq 0 \tag{5.2}
\]

which eliminates sources which have falling [3.6] - [4.5] colors and which are not likely to have infrared excesses consistent with protostar candidates. In total, there are 2007 protostar candidates with \( A_V > 3 \) in the Cygnus-X sample. For each protostar candidate, an SED is created using available J-band - 24 \( \mu \text{m} \) fluxes, and \( \alpha \) is determined. Figure 5-1 shows a color-color diagram with these sources, and Figure 5-2 shows a color-magnitude diagram for protostar candidates with rising SED slopes (\( \alpha > 0.3 \)) and for protostar candidates with flat SED slope (\( 0.3 > \alpha > -0.3 \)). Class II sources are identified using the technique from Gutermuth et al. (2009) and are also shown in these figures.

The locations of the protostar candidates with \( A_V > 3 \) are shown in Figure 5-3, as well as the locations of protostar candidates with \( A_V < 3 \) not used in the remainder of the analysis. Protostar locations tends to trace the areas of highest extinction in
Figure 5-1: Color-color diagram for Cygnus-X. Protostar candidates with rising SED slope are shown in red, candidates with flat spectrum SED slopes are shown in green, and Class II sources are shown in blue.

Figure 5-2: Color-magnitude diagram for Cygnus-X. Symbols are the same as in Figure 5-2. The $m_{24}$ cutoff is shown.
5.2 The Cygnus-X Protostellar Luminosity Function

The technique from Chapter 3 was used to calculate SED slope, mid-IR luminosity, and estimate bolometric luminosity for the protostar candidates in Cygnus-X. The luminosity functions of sources of contamination are estimated and removed from the protostar candidate luminosity function using the same method as in Chapter 3 for the star-forming regions within 1kpc. Figure 5-4 shows the protostar candidate luminosity function and the contribution from the three types of contamination estimated. In Cygnus-X, the dominant source of contamination is from edge-on disk sources. As expected, the contribution from background galaxies is small, due to the conservative $m_{24}$ cutoff. Most of the contamination has luminosity less than $1 \, L_\odot$.

Figure 5-5 shows the resulting protostellar luminosity function after the removal of contamination. The protostellar luminosity function shows a tail extending to high luminosities, similar to the protostellar luminosity functions of the clouds within 1kpc which form high-mass stars: Orion, Cep OB3, and Mon R2. These protostellar luminosity functions peak near $1 \, L_\odot$; however due to the distance of Cygnus-X, the completeness luminosity $L_{\text{cut}}$ restricts a determination of the peak of the Cygnus-X luminosity function. A K-S test comparing the combined Orion/Cep OB3/Mon R2 protostellar luminosity function with the Cygnus-X protostellar luminosity function for each of the 1000 realizations gives a median probability of 0.42 that they come from the same parent distribution, which neither excludes the possibility they are from the same parent distribution nor strongly supports it. Comparison of the 1000 realizations of the Cygnus-X protostellar luminosity function with the 1000 realizations of the Orion protostellar luminosity function gives a median K-S probability of
Figure 5-3: Symbols are same as Figure 2-4.
Figure 5-4: Luminosity functions for protostar candidates (black), estimated contamination due to galaxies (blue), edge-on disks (green), and reddened Class II sources (red).

Figure 5-5: Protostellar luminosity function with contamination due to edge-on disk sources, reddened Class II sources, and galaxies removed. The vertical red bar is shown at $L_{\text{cut}}$. 
Properties of the Cygnus-X cloud and its luminosity function can be found in Table 5.1.

Table 5.1: Properties of the Cygnus-X Luminosity Function

<table>
<thead>
<tr>
<th>Protostars</th>
<th>Dist. (pc)</th>
<th>$m_{24}$ cut</th>
<th>Class IIs*</th>
<th>Flat/Rising†</th>
<th>$L_{cut}$‡</th>
<th>$D_c$</th>
<th>$P(D_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>7.5</td>
<td>11038</td>
<td>512(416)/1495(1279)</td>
<td>0.98</td>
<td>0.61</td>
<td>log(prob) = -17.25</td>
<td></td>
</tr>
</tbody>
</table>

* Class II sources in regions with $A_V > 3$.
† Numbers in parenthesis are after removal of contamination.
‡ Luminosities in $L_\odot$.

5.2.1 Luminosity Functions of Clustered and Distributed Populations

Figure 5-6 plots the luminosity vs. $nn4$ distance for Cygnus-X protostar candidates. The sources with the highest luminosity, above a few hundred $L_\odot$, have smaller maximum $nn4$ distances for a given luminosity than do the sources below a few hundred $L_\odot$. This is similar to the trend shown in the Orion panel of Figure 4-3, and also seen in the combined high-mass star-forming cloud panel.

To separate the protostar candidates in more clustered environments from the protostar candidates in more distributed environments, the $nn4$ distance is again used. The median protostar candidate $nn4$ distance for Cygnus-X is 0.61pc, which is much larger than for Orion ($D_c = 0.19$ pc). Each of the protostar candidates above a few 100$L_\odot$ are considered clustered using this definition. The probability that the luminosity function of the clustered protostars and the luminosity function of the distributed protostars are from the same parent distribution, in log(prob) = -17.25, low enough to rule out with some certainty that these two luminosity functions are from the same parent distribution.
Figure 5-6: Luminosity vs. Clustering using the \textit{nn4} distance for protostar candidates in Cygnus-X. A similarity can be drawn between the shape of this plot for Cygnus-X and the corresponding plot for the regions which form massive stars from Figure 4-3.
Figure 5-7: Luminosity functions for clustered (green) and distributed (blue) contamination-subtracted protostars for \( m_{24} < 7.5 \) (left) sources and for \( m_{24} < 6.5 \) (right) sources. The K-S probability that the clustered and distributed luminosity functions are from the same parent distribution is \( \log(\text{prob}) = -22.11 \) for the \( m_{24} < 7.5 \) sources and \( \log(\text{prob}) = -11.66 \) for the luminosity functions of sources with \( m_{24} < 6.5 \).

5.3 Completeness in Cygnus-X

As in Section 4.3, it is important to test the observed differences between the clustered and distributed populations for biases due to saturation and/or incompleteness in the 24 \( \mu m \) band. In this section, a similar analysis is performed comparing the \( m_{24} \) cutoff for protostars and disk sources in Cygnus-X.

The \( m_{24} \) cutoff used in Cygnus-X is 7.5, and the choice of \( m_{24} = 7.5 \) is now compared with \( m_{24} = 6.5 \). Figure 5-7 shows the luminosity function after adopting a limited magnitude of \( m_{24} < 6.5 \). The clustered and distributed protostar distributions have a K-S probability of \( \log(\text{prob}) = -22.11 \) of being drawn from the same parent distribution for the original \( m_{24} < 7.5 \) cutoff. This probability becomes \( \log(\text{prob}) = -11.66 \) using a \( m_{24} \) cutoff = 6.5. Since both of these probabilities are low enough to rule out a likely common parent distribution, raising the limiting \( m_{24} \) by one magnitude does not change the result.

Again, incompleteness can be assessed through a comparison of the distribution
of $m_{24}$ for Class II sources in clustered and distributed regions. This comparison is now performed on the distributions of Class II sources and protostar candidates in Cygnus-X. Class II sources are identified in Cygnus-X using the same technique as Orion Class II sources were found in Section 4.3, such that those Class II sources within $D_c$ of a protostar candidate are used, then classified as being clustered or distributed based on the classification of the nearest protostar candidate. Figure 5-8 shows the $m_{24}$ distribution for clustered and distributed regions. A K-S test gives a 0.05 probability that the distributions of clustered and distributed Class II sources are from the same parent distribution using $m_{24} = 7.5$. For the protostar candidates, the probability that clustered and distributed $m_{24}$ distributions are from the same parent distribution is $\log(\text{prob}) = -28.72$. Thus, while the distributions of $m_{24}$ for Class II sources may not be ruled out as being from the same parent distribution, it is possible to rule out the distributions of clustered and distributed protostar candidates as being from the same parent $m_{24}$ distribution and incompleteness in $m_{24}$ is not expected to bias the protostar candidate sample.

The most luminous protostar candidates are in clustered environments. Massive protostars have been observed in the centers of clustered environments (Kirk and Myers, 2011). While the masses of the most luminous protostar candidates are not known, the high luminosities may be due to large protostar masses, since protostellar luminosity is a combination of intrinsic stellar luminosity and accretion luminosity. More analysis needs to be done to determine the masses of these protostars, which requires detailed modeling of a full SED. However, since none of the most luminous protostars are found in distributed regions, the IMF of crowded sources may differ from that of the sources with large $nn4$ distances.
Figure 5-8: Histograms of 24 $\mu m$ detections for Cygnus-X clustered (green) and distributed (blue) YSOs. Cygnus-X disk sources within $D_c$ of a clustered or distributed protostar candidate (left panel) show similar distributions of 24 $\mu m$ detections for clustered and distributed sources and have a K-S probability of 0.05 for $m_{24} < 7.5$ sources. Distributions of $m_{24}$ for the clustered and distributed Cygnus-X protostar candidates (right panel) do not show similarities, and have a K-S probability of $\log(\text{prob}) = -28.72$ (at $m_{24} < 7.5$) that they are from the same parent distribution.
Chapter 6

Summary

Protostars form in a variety of cloud environments: in both crowded clusters and relative isolation, and in molecular clouds with a variety of properties. Since the protostellar phase lasts 0.5 Myr (Evans et al., 2009), protostars do not move far from their birthsites and the properties of the molecular clouds, rather than dynamical interaction, will affect the clustering of the protostars. Thus, the study of protostars is the study of nascent stars in their birth environment.

The question is, how does this environment affect star formation? The density and temperature of cores will influence the protostellar mass and infall rate; thus it may be expected that clouds with different gas column densities and kinetic temperatures may form different distributions of protostar masses. The above question is at the core of this work, which elects to study the influence of cloud and cluster environment on protostars through the comparison of protostellar luminosity functions. Protostellar luminosity is chosen as the most easily observable property; this luminosity is the sum of the intrinsic luminosity of the central protostar and the luminosity generated by accretion onto the protostar. The protostellar luminosity functions for ensembles of protostars in different environments are compared.

This work is the first systematic comparison of the properties of protostars in the
nearest 1kpc. This research was enabled by molecular surveys by the *Spitzer Space Telescope*, which used IRAC and MIPS 24 µm photometry to identify over 1000 proto-star candidates in 9 molecular clouds within 1kpc, in the Cygnus-X cloud at 1.4kpc, and make the first identifications of YSOs in G216-2.5. These regions represent a wide range of star-forming environments, from dispersed low- and intermediate-mass star formation in regions, like Taurus, to low- and intermediate-mass star formation in more clustered environments, like Serpens, to regions which form massive stars in clustered environments, like Orion and Cygnus-X.

Many of the brightest sources are saturated in the MIPS 24 µm images, but using a new technique developed for this work to fit a PSF to partially saturated sources recovered fluxes for many of these sources. The inclusion of 24 µm photometry for these saturated sources is needed to extend the protostellar luminosity functions to high luminosities. It should be noted that the most massive stars are too saturated for obtaining luminosities; these are not included.

A new method for estimating bolometric luminosity using the slope of the spectral energy distribution (SED) and the ratio of bolometric luminosity to mid-infrared luminosity is also developed. This relationship was found using a sample of protostars from the Cores 2 Disks (c2d) *Spitzer* Legacy Survey with known bolometric luminosities. The c2d protostars used in determining this relationship have an SED slope, calculated between 3.6 and 24 µm, steeper than 0.3, typical of a Class I protostar. The relationship is extended to protostars with flat SED slopes (between -0.3 and 0.3). Comparison with Taurus protostars with well-determined bolometric luminosities from Furlan et al. (2008) shows good agreement between estimated luminosities from this work and known luminosities.

The scheme used for identifying protostars minimizes contamination (Megeath et al., 2009, e.g.); however, some residual contamination remains. Monte Carlo simulations were used to estimate contamination in each cloud from reddened Class II
sources, edge-on disk contamination was estimated by extending the technique used by Gutermuth et al. (2009), and background galaxies contamination was estimated using data from a Spitzer galaxy survey (SWIRE). The contamination luminosity functions were then removed from the protostellar candidate luminosity function to create a protostellar luminosity function.

The protostellar luminosity functions show variations between different environments. Protostars in clouds which form high-mass stars (Orion, Cep OB3, Mon R2, and Cygnus-X) show luminosity functions statistically different from those in clouds forming only low- to intermediate-mass stars (Serpens, Perseus, Ophiuchus, and Taurus). The high-mass star forming clouds have luminosity functions that peak at 1 \( L_\odot \), and exhibit a tail that extends above 100 \( L_\odot \). Clouds not forming high-mass stars have luminosity functions that do not have significant peaks above the luminosity cutoff at the completeness limit, but rather increase toward lower luminosity and do not extend above 100 \( L_\odot \). Differences also exist between luminosity functions of protostars in crowded regions and protostars in distributed regions in Orion and Cygnus-X, with the most luminous protostars being found in the clustered regions. These differences may indicate differences in the formation processes of stars in these environments and possibly in the properties of the emerging stars.

Protostars reside at the sites of their formation, and thus can provide unique information about the properties of stars before gas dispersal and dynamical interactions erase the natal conditions. The universality of the IMF is uncertain. Yet the differences found in this work between luminosity functions of protostars found in clustered and distributed environments within a single cloud may mean that not all environments produce similar ensembles of stars. Differences may be expected in environments within molecular clouds as well. Variations in the protostellar luminosity function are of key interest, since they may trace how differences in the environment affect the star formation process. Furthermore, these variations may
provide a hint as to how the IMF may vary. Although the relationship between the current luminosity and the ultimate mass is uncertain for protostars, they have the advantage of being at their birth sites. In contrast, stars used to determine IMFs have typically dispersed their birth environments. Thus, protostars provide the means to more directly connect the properties of a forming star and the environment in which it forms.

Of particular interest is whether objects with high protostellar luminosities evolve into more massive stars. High protostellar luminosity implies a high accretion rate and/or a high intrinsic source luminosity. Such objects may be the progenitors of the more massive stars of these regions: a high accretion rate could lead to a high mass, and a high intrinsic source luminosity would suggest a high current mass. The variations in the protostellar luminosity function could imply variations in the IMF within a cloud. On the other hand, accretion may be episodic and a high accretion rate could just be the result of a short burst. Thus, the connection between the observed variation in the protostellar luminosity function and potential variations in the IMF requires more work.

This work can be extended in two ways: the first by expanding the sample of star-forming regions, and the second by investigating the relationship between protostellar luminosity function and the current accretion models of star-formation. Inclusion of protostars from other publicly available surveys (i.e. the Spitzer GLIMPSE, MIPSGAL, and Gould Belt surveys and the WISE all-sky survey) will increase the statistics of both clouds that form high-mass stars and clouds not forming high-mass stars, and can be tested for consistency with the results found from nearby low- and intermediate-mass star-forming regions. The addition of longer band photometry to extend the SEDs of protostars would refine the bolometric luminosity estimates further; the Herschel Gould Belt and HOBYS surveys utilize the SPIRE and PACS instruments and map nine of the star-forming regions common to the sample from
This sample can also be used to test models of star-formation. Recently, Offner and McKee (2011) compared observed protostellar luminosity function from the c2d clouds with luminosity functions created using combinations of the isothermal sphere, turbulent core, and competitive accretion models. Myers (2011) predicts the IMF in dense clusters with time-dependent accretion and finds that protostellar mass functions are time-independent and protostellar luminosity functions are time-dependent, and that initial core structure does not directly determine protostar mass. A future comparison of protostellar luminosity functions from a broader range of clouds (including clouds forming high-mass stars) with the proposed models could support or differ from the various currently proposed models of star formation.
References


N. J. Evans, II, J. M. C. Rawlings, Y. L. Shirley, and L. G. Mundy. Tracing the Mass...


B. Merín, J. Jørgensen, L. Spezzi, J. M. Alcalá, N. J. Evans, II, P. M. Harvey, T. Prusti, N. Chapman, T. Huard, E. F. van Dishoeck, and F. Comerón. The


J. E. Pineda, P. Caselli, and A. A. Goodman. CO Isotopologues in the Perseus


F. J. Selman and J. Melnick. The Scale-Free Character of the Cluster Mass Func-


Appendix A

MIPS Photometry and PSF Flux

Extraction of Saturated Sources

*MIPS* 24 $\mu$m sources were first identified using the source finding routine in PhotVis (Gutermuth et al., 2008). The aperture photometry was then extracted by PhotVis using an aperture size of 5 pixels and sky annulus between 12 and 15 pixels, with each pixel having a size of 1.25”. Point-like sources were automatically selected by PhotVis, but careful visual inspection of the images added a few sources per image, mostly in nebulous regions. A zero-point magnitude of 16.48 was adopted; this included the aperture correction from 5 pixels to infinity. The images were in units of DN/s.

Next, two PSFs were created using a sample of bright but not saturated stars; these were selected to be relatively isolated and in regions with little nebulosity. Typically 15 sources were used for a given mosaic, but in a subset of mosaics there were fewer than 15 suitable sources available and thus fewer were used to create the PSF. Two PSFs were used; one which would be used to extract photometry from the unsaturated sources and one used for the saturated sources, the latter of which was larger to encompass the full extent of illuminated pixels in these brighter sources. The
Figure A-1: The saturated PSF residuals used in the ONC, created using isolated, relatively bright but not saturated sources in the ONC 24\(\mu\)m image. The unsaturated source PSF was created using the same stars, but has a smaller size.

The larger PSF used for saturated sources has a radius of 35 pixels and a fitting radius of 10 pixels, while the PSF used on unsaturated sources has a radius of 25 pixels and fitting radius of 2 pixels. An example of a PSF used in the ONC image is shown in Figure A-1.

The appropriate PSF was then fit to the sources using the IDL implementation of \textit{NSTAR} from the IDL astronomy library (Landsman, 1993). To minimize the effect of crowding on the photometry, the sources were first grouped together in clusters of potentially overlapping source PSFs using the routine \textit{GROUP}. This routine groups together sources which were within 8 pixels of one of the other group members; the sources in the group were then fit simultaneously using \textit{NSTAR}. Sources which contained pixels with signals greater than the saturation limit were flagged. To fit the saturated sources, \textit{NSTAR} was modified to ignore saturated pixels, which were flagged
by a “NaN” value in the image. Unsaturated sources were fit with the smaller PSF while saturated stars were fit with the PSF with the larger size and fitting radius to ensure there were enough unsaturated pixels to provide a robust fit. Any unsaturated sources which were grouped together with saturated sources were then treated like saturated sources for PSF fitting and fit using the larger PSF. \textit{NSTAR} was then used to extract fluxes by first extracting fluxes for unsaturated grouped sources and then for saturated grouped sources. Afterward, the PSFs were scaled by the photometry and subtracted out with the \textit{SUBSTAR} routine; this process was done twice, once for the saturated and once for the unsaturated sources. The residual image was then inspected for sources which had not been extracted. These sources, typically one or fewer per image, were added into the photometry. The process of grouping, fitting, and extraction was iterated until no more new sources were found. Figure A-2 shows a residual image in which the sources have been correctly fit by the PSF and flux extracted.

Very saturated sources (those with many saturated pixels and for which PhotVis had difficulty estimating fluxes) may not be easily fit by \textit{NSTAR}. These sources were then given estimated magnitudes and run through \textit{NSTAR} using these estimations. After flux extraction, a residual image was created by \textit{SUBSTAR}, and visually inspected for poorly subtracted PSFs. Saturated sources were typically over-subtracted and were apparent in the residual image. The input magnitudes initially from PhotVis aperture photometry were adjusted until the residual in the image was minimized. Photometric uncertainties for these sources are due to the varied environments of these sources, including areas of crowding or nebulosity, and were then found by determining the change in magnitude needed to create a noticeable over or under-subtracted residual. This constrains the source magnitude to within typically $\pm 0.25$ mag, although a few sources have a larger range. For some sources, positions needed to be adjusted after \textit{NSTAR} fitting as well, which was done so that the center of the PSF
fell directly over the center of the source. Additionally, the residual image is inspected for under-subtracted sources which appear as though no flux extraction had occurred. These sources, typically only one or two per image, were added. The process of grouping, fitting, and extraction was iterated while new sources were found. Figure A-3 shows a sample of sources in a crowded region of the ONC. The saturated sources in this image need to be fit “by hand”. Figure A-4 shows the residuals after the PSF is fit to the sources in Figure A-3, in which the residuals have been minimized for the saturated sources.

Since each MIPS frame is the subtraction of readouts from the beginning and end of the integration, some very saturated pixels had values below the adopted threshold for saturation. These saturated pixels can be identified by comparing the original image with a “fake” image. The “fake” image was built by first creating an image of the background nebulosity with the stellar sources subtracted. This was done by
Figure A-3: This crowded region includes a few saturated sources which need to be fit “by hand”, as even the modified version of NSTAR does not fit the PSF well to these sources.
Figure A-4: The sources from Figure A-3 have been fit with the PSF by NSTAR for the fainter sources, and with magnitudes estimated and input into NSTAR until residuals were minimized for the saturated sources. Shown are the residuals for all PSF extractions in this region, with scaling slightly different than Figure A-3.
first running \textit{SUBSTAR} and smoothing the resulting image to minimize the artifacts from the subtraction, including the reduction of “holes” in the image due to the over-subtraction of saturated sources. The subtracted stars were then added back to the smoothed image. The resulting “fake” data (which used one of the two PSFs scaled to the best fit photometry) exceeded the actual pixels values for highly saturated sources. Figure A-5 shows an example of part of the ONC “fake” image. The shape of the PSF is clearly seen around the sources, and the background has been smoothed. Pixels for which the value of the corresponding pixel in the “fake” image were greater than the saturation threshold were masked out. The entire photometric extraction process was then repeated for the saturated sources and the stars in their groups, and the creation of the “fake” image was redone with the new photometry to find new saturated pixels. This process was repeated until no new saturated pixels were found. These saturated pixels were then masked out in the PSF fitting process, as described previously.
Figure A-5: The ONC image has been smoothed and PSF-extracted source fluxes have been added to represent stars in this “fake” image.
Appendix B

Completeness in Protostar Candidate Samples

The completeness of the protostar catalog is important to assess. The search for protostars in Spitzer cloud surveys is typically not limited by sensitivity, but by the $m_{24}$ cutoff applied to minimize contamination from extragalactic sources. Figure 2-1 shows that faint sources are detected 2 magnitudes or more fainter than the $m_{24}$ cutoff. Furthermore, at the cutoff, the number of 24 $\mu$m sources is increasing with increasing magnitude. For these reasons, this sample should be complete in most of the surveyed molecular clouds; however, because of the presence of bright nebulosity, subregions of each cloud may be affected by incompleteness. Regions with very bright nebulosity, such as the Orion Nebula or NGC 2024, are typically saturated in the MIPS 24 $\mu$m image; these saturated regions are ignored in this analysis. However, regions with signal levels well below saturation can be incomplete due to the confusion with the spatially varying nebulosity. Furthermore, clustered regions can be systematically less complete due to the crowding and brighter nebulosity in clusters (Megeath et al. in prep).
Figure B-1: The fraction of sources recovered within the cluster radius $D_c$ (0.19 pc) for the Orion clouds. The RMEDSQ technique of Megeath et al. (in prep.) is used to determine the expected fraction of sources detected with magnitudes equal to the cutoff magnitude. The distribution of the fraction of expected detected sources is shown in clustered (green) and distributed (blue) regions. The top row of plots uses a cutoff magnitude $m_{24} = 6$, and the bottom row of plots use $m_{24} = 7$. The left column of plots show the distribution of the expected fractions for all of the protostar candidates. The right column of plots show the expected detection fraction vs. the luminosity of the protostar candidate. Using the $m_{24} = 6$ cutoff gives higher median expected detection fractions for both clustered and distributed sources than the $m_{24} = 7$ cutoff.
To assess the impact on the analysis in this work, an experiment focusing on the Orion molecular clouds is conducted. Orion contains the most luminous and nebulous star forming regions of the cloud sample. Perhaps more importantly, Orion is the one cloud in which the luminosity functions in clustered and distributed regions are statistically different. Thus, it is necessary to ascertain whether the difference between clustered and distributed regions is real or is because of spatially varying completeness. Megeath et al. (in prep.) measure the completeness using artificial star tests in the Orion data. They find that the completeness at a given magnitude varies with position depending on the amount of bright, saturated nebulosity. They parameterize the amount of nebulosity using the root median square deviation, 
\[ \text{RMEDSQ} = \sqrt{\text{median}(S - \text{median}(S))^2} \], where \( S \) is the signal for a given source, calculated in an annulus around each source. The RMEDSQ gives a measure of the spatially varying signal from neighboring stars and structured nebulosity surrounding each source; in the Spitzer bands the variations are dominated by the bright mid-IR nebulosity. Using the fraction of synthetic 24 \( \mu \)m point sources recovered as a function of RMEDSQ. (Megeath et al in prep.), the completeness surrounding each of the protostar candidates has been estimated. The adopted RMEDSQ value is the mean value for all the YSOs within the clustering length of \( D_c = 0.19 \) pc. The fraction of sources detected with magnitudes equal to the cutoff magnitudes is found. The results of this analysis is shown in Figure B-1. for both clustered and distributed regions in Orion. For the combined clustered and distributed regions, 55% of Orion protostars are in regions where the fraction of stars recovered is \( > 0.90 \); nevertheless, both the clustered and distributed region have regions where the fraction of recovered sources at \( m_{24} = 7 \) drops to close to 0. The incompleteness can be minimized by reducing the cutoff magnitude. Figure B-1 shows the same analysis for \( m_{24} = 6 \). Using the \( m_{24} = 6 \) cutoff, 73% are found in regions where \( > 0.90 \) sources are recovered.
Appendix C

Maddalena’s Cloud: a Distant, Quiescent Molecular Cloud?

The weak CO emission from the cold giant molecular cloud G216-2.5 was first discovered by Maddalena and Thaddeus (1985) in a survey of the Orion-Monoceros region. The cloud is unusual for having the size (Maddalena and Thaddeus, 1985, $250 \times 100$ pc) and mass (Lee et al., 1994, $1 - 6 \times 10^5 \ M_\odot$) typical of giant molecular clouds (hereafter: GMCs), yet having a kinetic temperature of only 10 K (Williams and Blitz, 1998). The low temperature is unusual for GMCs and is more typical of dense cores in the Taurus dark cloud (Jijina et al. 1999). Perhaps the most unusual characteristic of the cloud is the lack of star formation. Maddalena and Thaddeus (1985) found no clear evidence for star formation within the G216-2.5 GMC (hereafter: G216); a result supported by subsequent IRAS maps showing a distinct absence of emission from dust heated by internal young stars (Lee et al., 1996). Considering the current distance estimate of 2.2 kpc (Lee et al., 1991), the absence of bright far-IR emission only rules out the presence of young high mass stars. Young low to intermediate mass stars could have escaped the detection by IRAS. Nevertheless, the evident lack of massive star formation is in itself unusual since GMCs almost
ubiquitously contain young massive stars (Williams and McKee, 1997).

Because of the lack of evident star formation, G216 has been considered the best example of a quiescent GMC and potentially, a rare example of a GMC before the onset of star formation (Maddalena and Thaddeus, 1985). In the 1990s, near-IR imaging by Lee et al. (1996) revealed two small groups of young stars in satellite clouds on the northern edge of G216, shown in Figure C-1. One of these regions is associated with a radio source/HII region which was first noted by Maddalena and Thaddeus (1985), but Maddalena et al. could not reliably associate the radio source with the satellite cloud. Near-IR observations of the main body of the cloud failed to detect any stellar groups similar to those in the satellite clouds.

Recent observation of the core of Maddalena’s cloud by the Spitzer Space Telescope hoped to reveal signs of star formation. This core shows an extended region of relatively high column density gas (Lee et al., 1991; Heyer et al., 2006), but previous to this study showed little evidence for ongoing star formation.

C.1 IRAC, MIPS, and FLAMINGOS Photometry

Photometric magnitudes in the four IRAC bands were extracted with PhotVis (Gutermuth et al., 2004). The aperture size was 2 pixels (2.4") and the sky annulus extended from 2 (2.4") to 6 (7.2") pixels. To convert the signal (measured in DN s\(^{-1}\)) to magnitudes, zero points of 18.427, 17.672, 15.470 and 14.864 were used in the 3.6, 4.5, 5.8 and 8 \(\mu\)m bands respectively (Reach et al., 2005).

The 24 \(\mu\)m images were processed using the MIPS instrument team Data Analysis Tool (Gordon et al., 2005). MIPS 24 \(\mu\)m PSF photometry was extracted using PhotVis and the technique described in Section 2.1.1. The aperture was set to 5 pixels (6.225") and the sky annulus extended from 12 (14.94") to 15 (18.675") pixels. The zero point magnitude was 16.05: this assumed a 6.4 \times 10^{-6} Jy/DN s\(^{-1}\) pix\(^{-1}\).
Figure C-1: CO (1-0) map of G216. The quiescent core where Spitzer observations were taken is shown in the white box.
calibration factor, a zero flux of 7.17 Jy, and a correction from 12 pixels to infinity of 1.146 (Engelbracht et al., 2007). A single PSF was created; no sources were saturated in the 24 µm image. The PSF had a 15 pixel radius and 2 pixel fitting radius.

Point source identification was performed on the photometry of the MIPS 70 µm mosaics with Photvis. An aperture size of 16″ and a sky annulus extending from 18″ to 39″ were used. The adopted zero magnitude was of −1.57; this was based on an aperture correction of 2.07, a calibration factor of 1.6 Jy (DN/s/pix)$^{-1}$, and a zero flux of 0.778 Jy (Gordon et al., 2007).

Deep near-IR data from the FLAMINGOS camera on the Kitt Peak National Observatory 2.1-m telescope was added into the photometry. The photometry was calibrated by measuring the magnitude offset between the instrumental magnitudes derived from the FLAMINGOS data and the apparent magnitudes from the 2MASS point source catalog. For the $K$-band data, the offset was dependent on position. A position dependent offset was derived by fitting a 3rd order polynomial to the offset as a function of row and column number.

C.2 Detection of YSOs

The combined FLAMINGOS J, H, and K-band, IRAC, and MIPS 24 µm and 70 µm photometry were then set through protostar selection criteria of Winston et al. (2007) to identify protostar candidates and Class II sources. Due to the distance of G216, a modified protostar candidate selection criteria was implemented. The sample of infrared excess objects can be contaminated by galaxies with strong PAH emission and AGN (Stern et al., 2005). Galaxies were identified using the criteria given in the appendix of Gutermuth et al. (2008). The color-magnitude criteria developed by Gutermuth et al. was adjusted to identify likely AGN to account for the greater distance to G216. Specifically, the threshold magnitudes were lowered so as not to
reject faint YSOs. Sources which satisfied each of the following three criteria were rejected:

\[ [4.5] - [8.0] > 0.5 \]
\[ [4.5] > 14. + ([4.5] - [8.0] - 2.3)/0.4 \]
\[ [4.5] > 14 \]

In addition, a source would have to satisfy one of the following three criteria before it is rejected:

\[ [4.5] > 14.5 + ([4.5] - [8.0] - 0.5) \]
\[ [4.5] > 15 \]
\[ [4.5] > 15 - ([4.5] - [8.0] - 1.2)/0.3 \]

A color-color diagram for G216 is shown in Figure C-2. The division between sources selected as YSO and AGN is shown in the [4.5] vs. [4.5]-[8] diagram displayed in Figure C-3. Converting the \( \alpha \) for Class I and flat SED sources into colors using the IRAC and MIPS bandpasses, protostar candidates should exhibit the following colors:

\[ [3.6] - [4.5] \geq 0.652, \quad [4.5] - [24] \geq 4.761 \] \quad (C.1)

Figure C-3 shows the color-magnitude diagram for G216. To minimize contamination from extragalactic sources, the following \( m_{24} \) criteria is used:

\[ [24] \leq 9.15 \] \quad (C.2)
Figure C-2: Color-color diagram showing rising SED protostar candidates (red), flat spectrum SED protostar candidates (green), and Class II sources (blue).

Figure C-3: Color-magnitude diagram showing rising SED protostar candidates (red), flat spectrum SED protostar candidates (green), and Class II sources (blue).
Figure C-4: Protostar candidates with rising spectrum SEDs (red), flat spectrum SED slopes (green), and Class II sources (blue) in G216.

In total, 30 protostar candidates were identified by the above criteria. The 70 µm band adds an additional means to identify cold protostars. One additional source is identified as a protostar candidate on the basis of the 70 µm data, however this source only has detections in the MIPS bands. Figure C-4 shows the locations of the Class II sources and protostar candidates on the extinction map of the core of G216. The protostar candidates follow the dense $A_V > 3$ regions, though only 22 protostar candidates fall in the $A_V > 3$ boundaries.
C.3 The Protostellar Luminosity Function

In previous chapters, the protostellar luminosity functions of nearby low- and intermediate-mass star-forming clouds and high-mass star-forming clouds have been found. G216 has fewer protostar candidates (22) than any of the other regions, yet even this small detection was unexpected due to previous observations of the quiescent nature of G216. In this section, the protostellar luminosity function of this rather unusual GMC will be found, and compared to some of the luminosity functions of nearby star-forming clouds.

For each protostar candidate in G216, an SED is created, $\alpha$ calculated, $L_{\text{MIR}}$ determined, and $L_{\text{bol}}$ estimated using the techniques from Chapter 3, with the exception of the source detected only in the MIPS bands; the SED slope cannot be determined using only the MIPS 24 $\mu$m detection and thus $L_{\text{bol}}$ cannot be estimated. From the protostar candidates for which $L_{\text{bol}}$ is able to be determined, a protostar candidate luminosity function is created, and is shown in Figure C-5. While there are few protostar candidates in this cloud, it can be noticed that there is a peak in the protostar candidate luminosity function at $1L_{\odot}$.

Estimations of contamination are made using the method from Chapter 3 using the 1000 realization Monte Carlo method. Due to the conservative $m_{24}$ cutoff and small number of Class II sources, 14.7 rising $\alpha$ sources and 4.3 flat $\alpha$ protostars remain after contamination removal, down from 16 rising $\alpha$ protostar candidates and 5 flat $\alpha$ protostar candidates.

Figure C-6 shows the resulting protostellar luminosity function after the estimated contamination is removed. The protostellar luminosity function shows a peak near $1L_{\odot}$, similar to the protostellar luminosity functions of the clouds which form high-mass stars (Orion, Cep OB3, and Mon R2). Megeath et al. (2009) show the YSO densities of G216 to be similar to that of low-mass clouds like Taurus. A K-S test comparing the 1000 Monte Carlo realizations with the combined low-mass star-forming
Figure C-5: Protostar candidate luminosity function for G216.

Figure C-6: Left panel: G216-2.5 Protostar candidates luminosity function (black), contamination due to reddened Class II sources (red), edge-on disks (green), and galaxies (blue). Right panel: Protostellar luminosity function with contamination due to reddened Class II sources and galaxy contamination removed.
region protostellar luminosity function gives a median probability of 0.04, which does not rule out the possibility that these distributions are from the same parent distribution. A K-S test comparing each realization to the combined high-mass star-forming region luminosity function gives a median probability of 0.86 that they are from the same parent distribution. It should be noted that the small number of protostars in G216 may be hindering further statistical interpretation.

Since there are so few protostars in G216, a thorough comparison of the luminosity functions of protostars in clustered and distributed environments would not have strong statistical significance. The median protostar candidate $nn4$ distance, $D_c$ is 0.47pc, much larger than the corresponding $D_c$ for any of the star-forming regions within 1kpc, with the exception of the Tau/Lup/Cha regions, which have $D_c = 0.39$pc. This indicates a very dispersed population of YSOs in G216.

Indeed, G216 is not a quiescent cloud devoid of star-formation; it hosts 31 protostar candidates, 22 of which have $A_V > 3$, and 43 Class II sources. The protostellar luminosity function shows a peak near $1 L_\odot$, akin to the luminosity functions of high-mass star-forming regions. A large $D_c$ indicates G216 hosts a small, but distributed YSO population a small in its cold, dense core.