A study of four galactic small H II regions:
Searching for spontaneous and sequential star formation scenarios

by

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DEDICATION

This thesis is dedicated to my parents, Sang-soo Kang and Nan-Hee Kim, and the rest of my precious family and friends who have showed invaluable supports, consolations, and encouragement throughout my entire studies in the United States. Thank you.
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This thesis describes observational studies of four small star-forming H II regions (KR 7, KR 81, KR 120 and KR 140) and star-formation scenario associated with the Young Stellar Objects (YSOs) in each region. In addition to that, we also present an analysis of HCO\(^+\) (J=3→2) and H\(^{13}\)CO\(^+\) (J=3→2) observations of the Massive (\(M \sim 20 M_\odot\)) submillimeter/infrared source IRAS 01202+6133 located on the periphery of the H II region. In this research, we improved existing 1-D radiative transfer model for a collapsing core that happens in the early phase – Class I protostar – of star formation.

The molecular gas surrounding an H II region is thought to be a place where star formation can be induced. We selected four small H II region in order to minimize the feedbacks and dynamics from multiple exciting sources. These regions are very young and ionized by the single O or B spectral type stars.

A space based telescope Wide-field Infrared Survey Explorer (WISE) used for identifying and classifying the YSOs population surrounding a sample of H II regions.

First, we used WISE data from AllWISE catalog with some constrains such as spatial coordinates, signal-to-noise ratio and contaminations. After we retrieved sources from catalog in each region, we classified YSOs with two different methods; color-color diagram and spectral index (\(\alpha\)). Based on the color-color diagram using WISE 3.4 \(\mu\)m, 4.6 \(\mu\)m and 12 \(\mu\)m bands, we classified the YSOs as Class I, Class II and using 3.4 \(\mu\)m, 4.6 \(\mu\)m and 22 \(\mu\)m, we were able to classify Transition Disks and Class III YSOs. 2MASS and WISE combined color-color diagram also used in order to compare the classification only use of WISE color-color diagram. Considering a reddening effect from 2MASS \(K_s\) band, the classification from both WISE only and 2MASS, WISE combined color-color
A Spectral index (α) also can be used as classifying YSOs. Based on the WISE magnitude, spectral index (α) can be derived from the flux of mid-infrared observation provides a quick and easy way to classify YSOs. However, this method is less accurate then color-color diagrams because we cannot filter out all the contaminants and lack of data sets. Therefore, color-color diagrams can be used as primary methods to identify and classify YSOs. Based on the spatial distribution and number ratio of YSOs, a sequential star-formation scenario is dominant for KR 7, KR 81 and KR 120. In KR 140 region both a sequential star-formation scenario and a spontaneous star-formation scenario can be used to explain the origin of star-forming scenario.

Next, we observed HCO\(^+\) line profile to investigate the infall motion of the protostar in KR 120 region. The HCO\(^+\) line profile has a classic blue-asymmetric shape with the optically thin H\(^{13}\)CO\(^+\) line peaking at the position expected if the HCO\(^+\) line arises from a combination of self-absorption and infall motion. We have modified existing analytic radiative transfer models to allow for the fitting of submm line profiles that have both self-absorption features and optically thin wings and applied these models to our HCO\(^+\) spectrum of IRAS 01202+6133 in KR 120. We conclude that it is a young Class I YSO with a substantial envelope undergoing slow infall and having some outflow motions. The young age of the H II region rules out a "collect and collapse" scenario. While we cannot eliminate the possibility that IRAS 01202+6133 formed spontaneously at its current location, considering its early evolutionary state and its proximity to the H II region, we think that the formation of IRAS 01202+6133 was triggered by the expansion of KR 120 (Sh 2-187).
CHAPTER 1. INTRODUCTION

Stars are the very basic element of constitution in the universe, and the question of how stars form is at the center of much of contemporary astrophysics. Star formation determines the structure and the evolution of galaxies. Most of the elements composing the matter around us came from and/or formed in the stars.

The formation of stars arises in molecular clouds. The interior structure of molecular clouds is not perfectly uniform, thus regions more dense than others inside the molecular cloud begin to collapse and form a premature form of protostar, called a “core”. These cores can be either stable or unstable based on their environment. Unstable cores begin to collapse inward then gas and dust fall into these cores ultimately forming a protostar. If a massive star (O-type or B-type stars) formed in a molecular cloud, UV light from this massive star will ionize gas and dust in this molecular cloud and form an H II region. The hot plasma in the H II region will then expand outward. On the other hand, cores also can be stable before they begin to collapse. However, if exterior effects such as expansion of H II regions, supernova shock or stellar winds are applied to stable cores, they become unstable and begin to collapse. If the core becomes unstable and begins to collapse due to H II expansion, this process is called ”sequential or triggered star-formation.” On the contrary, if the core becomes unstable without any exterior effects and forms a star, we call this process ”spontaneous star-formation.”

In this dissertation, we are going to explore triggered star-formation associated with the expansion of H II regions. To examine this, we investigate the identification and classification of the young stellar objectss (YSOs) population surrounding a sample of H
II regions with the goal of determining the relative importance of triggered star-formation to the star-formation activity associated with H II regions.

Figure 1.1 Artist’s conceptions of the Spitzer Space Telescope (Left) and Wide-field Infrared Survey Explorer (WISE) (Right). Image credits to NASA.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Spitzer</th>
<th>WISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection bands</td>
<td>3.6µm, 4.5µm, 5.8µm, 8.0µm (IRAC)</td>
<td>3.4µm, 4.5µm, 12µm, 22µm</td>
</tr>
<tr>
<td></td>
<td>24µm, 70µm, 160µm (MIPS)</td>
<td></td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1.7” ~ 2”</td>
<td>6.1” ~ 12”</td>
</tr>
<tr>
<td>Diameter of Telescope</td>
<td>0.85 m</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Field of view</td>
<td>5 arcmin</td>
<td>47 arcmin</td>
</tr>
</tbody>
</table>

It is very difficult to detect protostars directly in optical wavelength because the protostars are surrounded by optically thick dust and dense gas, which absorb and scatter all the light emitted from the center where the protostar is located. However, infrared, sub-mm and radio observations allow us to investigate these star-formation regions because at these wavelengths, we are able to penetrate optically thick dust and gas. In the last decade, with the launch of the Spitzer Space Telescope in 2003 and the Wide-field Infrared Survey Explorer (WISE) in 2009 (Figure 1.1), star-formation studies have made
a big leap both in terms of observations and corresponding theories. Both telescopes have very sensitive instruments designed to take images and spectra in the infrared. Table 1.1 shows the specification of *Spitzer* (Werner et al., 2004) and *WISE* (Wright et al., 2010).

Young stellar objects (YSOs), which denote protostars in very early stages of evolution, can be classified as different stages based on their features and evolutionary stages. Figure 1.2 is a cartoon describing how early evolutionary stages can be classified. The formation of a star begins inside dark interstellar clouds containing a high-density region (Figure 1.2a). This dense region becomes gravitationally unstable by gravitational potential energy of dust and gas around it. This infalling gas and dust convert gravitational potential energy into thermal kinetic energy and increase temperature and pressure of the core. Once pressure is high enough to support against the gravitational collapse of the core, it will slow down the collapsing of the core until it reaches a balance of
gravitational collapsing force and pressure (Figure 1.2b). Bipolar outflows and jets are also developed material in the envelope fall into the central core forming an optically thick disk as a result of angular momentum conservation. This stage, referred as Class 0/I YSOs, denotes the earliest stages of formation of a star and the time scale of this stage is less than 0.1 Myrs (Figure 1.2c). Once envelope infall ends, YSOs are classified as Class II YSOs with its timescale of 3-5 Myrs old. Relatively low mass stars, about less than $2M_\odot$, at the end of this Class II stage are called T Tauri stars and high mass stars greater than $2M_\odot$ at the end of this Class II stage are called Herbig Ae/Be stars (Figure 1.2d). As the disk dissipates due to process like photoevaporation or the planet formation, the central star remains with very little amount of circumstellar material and evolve as main sequence star along with associated planet system (Figure 1.2e and 1.2f).

To identify and classify the YSOs, we have to investigate the spectral energy distribution (SED) of each YSO. An SED is a graph of the energy emitted by an object as a function of different wavelengths. The different stages of YSOs have different SEDs. Figure 1.3 shows the spectral energy distribution of each evolutionary stage of YSO along with the corresponding geometry of each stage. Figure 1.4 shows how each component of disk contributes the spectral energy distribution for class II YSOs.

There are two main methods for investigating the SED of YSOs. First, color-color diagrams of mid-infrared observations are excellent tools for identifying YSOs (Allen et al. 2004). Based on the telescope such as Spitzer or WISE measurements of flux from each band, we can make color-color plot of each observation (i.e., [3.6] − [4.5] vs [5.8] − [8.0] in Spitzer and [3.4] − [4.6] vs [4.6] − [12] in WISE).

YSOs are also traditionally categorized based on the spectral index $\alpha = (d \log(\lambda F(\lambda))/d \log(\lambda))$ of their near- to mid-infrared SEDs (Lada, 1987). The youngest Class 0 YSOs are only visible in far-IR to submm wavelength due to an optically thick infalling envelope. Class I YSOs ($\alpha \geq 0.3$) are characterized by rising mid-IR SEDs due to the optically thick envelope and accumulated disk and bipolar outflows. Class II YSOs ($-1.6 \leq \alpha < -0.3$) have
SEDs that peak at near-infrared wavelengths and decrease at longer wavelengths that is much gradual than what expected for a stellar photosphere, and they agree well with pre-main sequence stars with a circumstellar accretion disk. Class III YSOs ($\alpha < -1.6$) have little or no infrared excess because they are thought to be in the disk dissipated stage with very little or no circumstellar material. Flat spectrum class also can be defined with spectral index ($-0.3 \leq \alpha < 0.3$) between Class I and Class II YSOs (Greene et al., 1994)

Figure 1.3 The formation of a single star and the evolution of the circumstellar material. The left panels show the spectral energy distribution (SED) of each evolutionary stage of YSO and right panels show the corresponding geometry of each stage. Figure from Isella (2006).
A spectral index ($\alpha$) can be directly derived from the equation using the magnitude of each band mid-infrared observations based on how we define the spectral index ($\alpha$) as $\alpha = (d \log(\lambda F(\lambda))/d \log(\lambda))$. The details of these methodologies will be discussed in Chapter 3.

In addition to this, we also present an analysis of HCO$^+$ ($J = 3 \rightarrow 2$) and H$^{13}$CO$^+$ ($J = 3 \rightarrow 2$) observations of the massive (M~20 M$_\odot$) submm/infrared sources IRAS 01202+6133 located on the periphery of one of four target H II region KR 120 (Sh 2-187). The HCO$^+$ line profile has a classic blue-asymmetric shape with the optically thin H$^{13}$CO$^+$ line peaking at the position expected if the HCO$^+$ line arises from a combination
of self-absorption and infall motion. There are 1-D radiative transfer models previously studied. However, these models are not able to fit both self-absorption features and optically thin wing shapes. Thus modified 1-D radiative transfer models need to be introduced in order to investigate the parameters of environment such as optical depth, infall velocity, and excitation temperature.

The main focus of this dissertation is an observational study of four small H II regions using YSO classification to examine various star-formation scenarios. Chapter 2 describes how four small H II regions are selected as targets and their characteristics. Chapter 3 presents the methods used to identify the young stellar objects in the star formation regions. Chapter 4 describes the analysis of YSO classification and star-formation scenarios in each H II regions. Chapter 5 illustrates a modified version of existing 1-D radiative transfer models and shows how well it can fit the observed submm spectrum. Finally, Chapter 6 summarizes this research and describes the directions of future work. Portions of the material in this dissertation have been modified from work published in the Astrophysical Journal (Kang and Kerton, 2012)
CHAPTER 2. CHARACTERISTICS OF GALACTIC RING-SHAPED H II REGIONS

2.1 Introduction

Young stellar objects (YSOs) are usually observed at the peripheries of H II regions. H II regions are partially ionized gas clouds in which star formation has recently taken place. Famous star-forming regions such as W3/W4/W5 and the Orion Trapezium Cluster are huge and complicated systems involving multiple massive stars and convoluted effects and feedbacks related to star-formation. However, our four samples of H II regions – KR 7, KR 81, KR 120 and KR 140 – are pretty isolated from giant molecular clouds and these H II regions are ionized only by a single massive star (late O-type or early B-type stars). This minimizes the effects of feedback from multiple massive stars and makes it easy to identify and classify the YSO population and to study various star-formation scenarios. In this chapter, the detailed characteristics of the four small H II regions are explained.

2.2 Target Selection and Observation

Our sample of four small H II regions (KR 7, KR 81, KR 120 and KR 140) are compact (2–3 pc radius) and ring-like shaped H II regions. Ultraviolet (UV) radiation and stellar wind from the exciting star is the power engine of expanding ionization front of H II region. This ionization front keeps expanding during the lifetime of the exciting star, thus the physical radius of the H II region increases in general as it gets older. However,
these samples of H II regions are compact, which means they are young, implying that there is active star-formation. If there are multiple massive stars ionizing the molecular cloud, the shape of an H II region will be irregular, but in our case there is only one single exciting star in each region, thus these H II regions have a circular, ring-like photodissociated region (PDR) as seen in MSX 8.3 μm and WISE 12 μm images. These PDRs are bright in these particular wavelengths due to the emission line from polycyclic aromatic hydrocarbons (PAHs) in the interface between the ionizing zone in the H II region and molecular cloud surrounding it. Inside of these H II regions, ultraviolet (UV) light coming from the exciting star is energetic enough to destroy all the PAHs. Just outside of the PAH free zone, UV light excites PAHs but does not destroy them so we can observe the infrared line emission from excited PAHs in the PDR. Outside of PDR, the UV flux is less energetic and neither excites nor destroys them.

These four compact H II regions were selected utilizing the data set of the Canadian Galactic Plane Survey (CGPS; Taylor et al. (2003)) and the Midcourse Space Experiment (MSX; Price et al. (2001)). These four galactic small H II regions are located in the outer galaxy in the 2nd quadrant (90° ≤ l ≤ 180°) of our Galaxy (see Figure 2.1). The properties of these four small H II regions, such as coordinates and distance, are in Table 2.1.

<table>
<thead>
<tr>
<th>Region</th>
<th>R.A.(h m s)</th>
<th>Dec. (° ± ′ ± ″)</th>
<th>l(°)</th>
<th>b(°)</th>
<th>Distance (kpc)</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KR 7</td>
<td>21 38 17.0</td>
<td>+50 19 78</td>
<td>94.461</td>
<td>-1.549</td>
<td>2.8±0.4</td>
<td>Sh2-124</td>
</tr>
<tr>
<td>KR 81</td>
<td>23 39 43.7</td>
<td>+61 54 48</td>
<td>114.6</td>
<td>0.210</td>
<td>1.9±0.4</td>
<td>Sh2-165</td>
</tr>
<tr>
<td>KR 120</td>
<td>01 22 58.0</td>
<td>+61 48 16</td>
<td>126.647</td>
<td>-0.840</td>
<td>1.44±0.26</td>
<td>Sh2-187</td>
</tr>
<tr>
<td>KR 140</td>
<td>02 20 05.7</td>
<td>+61 07 18</td>
<td>133.425</td>
<td>0.054</td>
<td>2.3±0.3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

These regions are chosen as samples of H II regions because they are pretty isolated from other giant molecular clouds and are single-star powered (late O type or early B type stars) H II regions in order to minimize the effects of feedback from multiple massive stars. In addition to this, these regions are also selected based on their appearance in
Figure 2.1 Artist concept of top-view of Milky Way Galaxy. A line from the Sun to the Galactic center is the line where galactic longitude ($l = 0$). 1st quadrant is $0^\circ \leq l \leq 90^\circ$, 2nd quadrant is $90^\circ \leq l \leq 180^\circ$, 3rd quadrant is $180^\circ \leq l \leq 270^\circ$, and 4th quadrant is $270^\circ \leq l \leq 360^\circ(0^\circ)$ Image credit: NASA

the MSX images, displaying that they have a roughly circular radio morphology and a ring-like infrared morphology with a small angular size.

2.2.1 KR 7

KR 7 (Sh 2-124) is a compact H II region with the distance of $2.8 \pm 0.4$ kpc (Foster and Routledge, 2003). Based on CGPS 1420 MHz observation, flux density is $F_{1420} = 2690 \pm 81$ mJy (Kerton, 2006) and angular diameter is $\sim 6$ pc (Figure 2.2). To identify the exciting star of each H II region, the ionizing photon luminosity ($N_L$) can be derived from the observed radio flux density; the derived $N_L$ value can then be compared with the spectral type-temperature calibration for Galactic O and early B stars from Crowther (2005) (see Table 2.2).

$$N_L \geq 7.5 \times 10^{43} F_{\nu} d^2 \nu^{0.1} T_e^{-0.45} \text{s}^{-1}$$  \hspace{1cm} (2.1)
Table 2.2  Spectral Type-Temperature Calibration for Galactic O and Early B Stars. Data taken from Crowther (2005).

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>( T_{\text{eff}} ) (K)</th>
<th>( \log g )</th>
<th>( R / R_{\odot} )</th>
<th>( \log L / L_{\odot} )</th>
<th>( M / M_{\odot} )</th>
<th>( M_v ) (mag)</th>
<th>( \log Q_0 )</th>
<th>( \log Q_1 )</th>
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<tbody>
<tr>
<td>O5</td>
<td>41</td>
<td>11.1</td>
<td>5.50</td>
<td>48</td>
<td>-5.2</td>
<td>49.2</td>
<td>48.5</td>
<td></td>
</tr>
<tr>
<td>O6</td>
<td>39</td>
<td>4.05</td>
<td>10.0</td>
<td>5.32</td>
<td>41</td>
<td>-4.9</td>
<td>49.0</td>
<td>48.3</td>
</tr>
<tr>
<td>O7</td>
<td>37</td>
<td>9.4</td>
<td>5.17</td>
<td>37</td>
<td>-4.7</td>
<td>48.8</td>
<td>47.9</td>
<td></td>
</tr>
<tr>
<td>O8</td>
<td>35</td>
<td>8.9</td>
<td>5.03</td>
<td>34</td>
<td>-4.5</td>
<td>48.5</td>
<td>47.4</td>
<td></td>
</tr>
<tr>
<td>O9</td>
<td>33</td>
<td>8.4</td>
<td>4.88</td>
<td>32</td>
<td>-4.3</td>
<td>48.1</td>
<td>46.3</td>
<td></td>
</tr>
<tr>
<td>O9.5</td>
<td>31.5</td>
<td>4.1</td>
<td>8.3</td>
<td>30</td>
<td>-4.1</td>
<td>47.9</td>
<td>45.8</td>
<td></td>
</tr>
<tr>
<td>B0</td>
<td>29.5</td>
<td>7.8</td>
<td>4.65</td>
<td>28</td>
<td>-4.0</td>
<td>47.4</td>
<td>45.2</td>
<td></td>
</tr>
<tr>
<td>B0.5</td>
<td>28</td>
<td>7.4</td>
<td>4.48</td>
<td>26</td>
<td>-3.7</td>
<td>46.8</td>
<td>44.3</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>26</td>
<td>6.6</td>
<td>4.26</td>
<td>22</td>
<td>-3.3</td>
<td>46.3</td>
<td>43.9</td>
<td></td>
</tr>
<tr>
<td>B1.5</td>
<td>24</td>
<td>4.15</td>
<td>5.7</td>
<td>3.98</td>
<td>17</td>
<td>-2.8</td>
<td>46.0</td>
<td>43.6</td>
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<tr>
<td>B2</td>
<td>21</td>
<td>5.3</td>
<td>3.69</td>
<td>15</td>
<td>-2.4</td>
<td>45.3</td>
<td>42.5</td>
<td></td>
</tr>
<tr>
<td>B2.5</td>
<td>19</td>
<td>4.2</td>
<td>4.8</td>
<td>3.43</td>
<td>13</td>
<td>-2.0</td>
<td>44.7</td>
<td>41.5</td>
</tr>
<tr>
<td>B3</td>
<td>17.5</td>
<td>4.1</td>
<td>3.15</td>
<td>10</td>
<td>-1.5</td>
<td>44.1</td>
<td>40.4</td>
<td></td>
</tr>
</tbody>
</table>

where \( \nu \) is the frequency in GHz, \( F_\nu \) is the flux density measured at frequency \( \nu \) with mJy, \( d \) is the distance to the source in kpc, and \( T_e \) is the electron temperature in units of \( 10^4 \) K (Rudolph et al., 1996).

For KR 7, the ionizing photon flux, \( \log N_L = 48.2 \) which corresponds to an exciting star of O9V star (Crowther, 2005) For KR 7, the 850 \( \mu \)m image is also shown in figure 2.2 (right). From figure 2.2 (right), one prominent 850\( \mu \)m source \((S/N > 6)\) located at the south rim of KR 7 also can be seen in the MSX image in figure 2.2 (left). Faint sub-mm emission corresponds to the rim of MSX image and WISE band 3 \((12\mu m)\) image (red colors in figure 2.4). Figure 2.3 is a WISE 3-band \((3.4, 4.6,\) and \(12\ \mu m)\) color image of KR 7 and Figure 2.4 is a close-up view of WISE 3 band color images of KR 7 with galactic coordinates and flux contour levels.
Figure 2.2  
*left*) MSX 8.3 µm image of KR 7 (Sh2-124). The white contours correspond to CGPS 1420 MHz continuum brightness temperature levels of 11, 13, and 15K. 
*right*) James Clerk Maxwell Telescope (JCMT) 850µm SCUBA image of KR 7. There is a prominent 850µm source (inside circle), which is at the periphery of KR 7. Images from Arvidsson and Kerton (2011)
Figure 2.3  *WISE* view of KR 7. The red channel shows the 12 $\mu$m band 3 data that indicates the PAH emission from the rim of H II regions. The green channel is the 4.6 $\mu$m band 2 data, and the blue channel is the 3.4 $\mu$m band 1 data.
Figure 2.4  *WISE* view of KR 7 with galactic coordinate and flux contour of density of 12 $\mu$m band. This 12 $\mu$m flux contour shows the outer shape of KR 7 and red circle in the south rim is the 850 $\mu$m source.
2.2.2 KR 81

KR 81 (Sh 2-165) is a small compact H II region with a distance of $1.9 \pm 0.4$ kpc and a diameter is $\sim 4$ pc with a flux density of $CGPS$ 1420 MHz radio continuum emission, $F_{1420} = 607 \pm 40$ mJy (Kerton, 2006). The estimated flux of ionizing photons from the exciting star, $\log N_L = 47.2$ corresponds to a single B0V star (Table 2.2). This ionizing flux and estimation agrees with observations of the exciting star of KR 81, BD +61 2494, listed as a B0.5V star in Hunter and Massey (1990).

For KR 81, the 850 $\mu$m SCUBA image also shows a prominent 850 $\mu$m source at the periphery of KR 81 (red circle in Figure 2.5 (right)) also seen in the MSX 8.3 $\mu$m image (Figure 2.5 (left)).

A WISE view of KR 81 is also shown in figure 2.6 and 2.7 with coordinates grid and flux contour levels of WISE 12 $\mu$m image which indicates the shape of KR 81.
Figure 2.6  WISE view of KR 81. The red channel shows the 12 $\mu$m band 3 data that indicates the PAH emission from the rim of H II regions. The green channel is the 4.6 $\mu$m band 2 data, and the blue channel is the 3.4 $\mu$m band 1 data.
Figure 2.7  WISE view of KR 81 with galactic coordinate and flux contour of density of 12 µm band. This 12 µm flux contour shows the outer shape of KR 81 and white circle in the north rim is the 850 µm source.
2.2.3 KR 120

Figure 2.8  
(left) MSX 8.3 µm image of KR 120 (Sh2-187). The white contours correspond to CGPS 1420 MHz continuum brightness temperature levels of 10, 12, and 14K.  
(right) James Clerk Maxwell Telescope (JCMT) 850 µm SCUBA image of KR 120. There is an prominent 850µm source (inside red circle) where is at the southwest of periphery of KR 120. Images from Arvidsson and Kerton (2011)

KR 120 (Sh 2-187) is a very compact H II region with a distance of 1.44±0.26 kpc with angular diameter of about 2 pc. Based on its size alone, it is likely that KR 120 is the youngest H II region among the four target H II regions. Its flux density of CGPS 1420 MHz radio continuum emission is $F_{1420} = 928 \pm 28$ mJy (Kerton, 2006). The estimated ionizing photon flux, $\log N_L = 47.2$ corresponds to B0 V star (Table 2.2). Russeil et al. (2007) suggest that a B2.5V star could be the possible exciting star for KR 120 however, ionizing flux estimated using equation 2.1 matches O9V ∼ B0V stars rather than a B2.5V star.

For KR 120, the 850 µm image is shown in figure 2.8 (right). As with KR 7 and KR 81, KR 120 also has prominent 850µm source at the southeast of the rim of the KR 120 (red circle in figure 2.8). This submm source (IRAS 01202+6133) which is located on
the periphery of the KR 120 region will be studied in more detail in Chapter 5 where the infall motion of the source is examined using a modified 1-D radiative transfer model. Figure 2.9 is the 3 color \textit{WISE} with coordinate grid and Figure 2.10 is the same 3 color image with the associated flux density contour and coordinate grid.

Figure 2.9 \textit{WISE} view of KR 120. The red channel shows the 12 \mu m band 3 data that indicates the PAH emission from the rim of H II regions. The green channel is the 4.6 \mu m band 2 data, and the blue channel is the 3.4 \mu m band 1 data.
Figure 2.10  WISE view of KR 120 with galactic coordinate and flux contour of density of 12 µm band. This 12 µm flux contour shows the outer shape of KR 120 and red circle in the southeast rim is the 850 µm source.
2.2.4 KR 140

KR 140 is also a small H II region with a distance of $2.3 \pm 0.3$ kpc (Kerton et al., 1999) and $\sim 5.7$ pc diameter based on its distance and angular size. KR 140 is close to the giant star formation complex W3/W4/W5 regions, however, it is apparently isolated from all those regions. The exciting star of KR 140 is well studied and known as VES 735, O8.5V star (Kerton et al., 1999). Figure 2.11 (left) is a MSX 8.3 $\mu$m image and (right) is a 850 $\mu$m image. As you can see from 850 $\mu$m image, there are several submm clumps within few square arcmin; they suggest that enhanced active star-formation is on-going this region. All from KR 7, KR 81, KR 120 and KR 140 regions have at least one submm clumps at the periphery of the H II region (associated with PDR), which indicate that these sources may be induced star-forming region due to expansion of the H II region. There is an interesting filament feature east of the KR 140 region. As you can see from the figure 2.11 (left), there are many submm clumps also found along the
filament. However, these clumps are apparently not directly associated with KR 140 and its expansion. Figure 2.12 is a three-color WISE view of KR 140 and the filament feature can be seen in Figure 2.13 with flux contours.

![Figure 2.12 WISE view of KR 140. The red channel shows the 12 µm band 3 data that indicates the PAH emission from the rim of H II regions. The green channel is the 4.6 µm band 2 data, and the blue channel is the 3.4 µm band 1 data.](image)

2.3 Summary

Four small H II regions, KR 7, KR 81, KR 120 and KR 140 were selected for further study as they are spatially isolated from other giant molecular clouds and are single-
star powered H II regions in order to reduce the complex effects and feedbacks from multiple massive stars. MSX 8.3 $\mu$m images and WISE 12 $\mu$m images clearly show the circular ring-like shape of the photodissociated region. JCMT 850 $\mu$m SCUBA images show submm clumps that are candidates for early stages of young stellar objects (YSOs). These submm clumps, observed at the peripheries of these H II regions, suggest star-formation can be associated (or triggered) by the expansion of H II regions. We used WISE data to identify and classify YSOs and detailed analysis of the identification of these YSOs will be discussed in Chapter 3 and Chapter 4.
CHAPTER 3. METHODS OF YOUNG STELLAR OBJECTS IDENTIFICATION AND CLASSIFICATION

3.1 Introduction

The latest highly advanced near- and mid-infrared surveys such as the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) (Churchwell et al., 2009; Benjamin et al., 2003) with Spitzer telescope and the all-sky Wide-field Infrared Survey Explorer (WISE; Wright et al. (2010)) survey have led to the discovery of numerous stellar nurseries and young stellar objects (YSOs).

There are several ways to observe or detect YSOs such as X-ray, infrared survey or radio observations. However, we will focus on the infrared survey especially of the WISE data because WISE covers 99% of the sky at mid-infrared wavelengths and has available archival data to identify and classify YSOs in H II regions that allow us to investigate the stars and their disks through their natal phases. The light from a protostar will be absorbed by the dust surrounding it, causing the dust to warm up and radiates in the infrared. Since infrared studies of star-forming regions will give us important information about how stars are born and the interpretation of the components of YSOs such as disks, jets and envelopes, we used infrared as a primary observation.

As we discussed in the introduction, SEDs are used to classify and identify the classes of YSOs. Therefore, how we interpret or employ the SEDs from infrared observations is a crucial point of this research. In this chapter, we will introduce two main methods to identify and classify YSOs in H II regions.
In Section 3.2, we will show how we make and use color-color diagrams of WISE data to classify and find populations of YSOs. Allen et al. (2004) introduced a method using color-color diagrams to classify YSOs with Spitzer IRAC data. Later, Gutermuth et al. (2009) developed a more sophisticated way to classify YSOs based on IRAC color-color diagram ([3.6]-[4.5] vs [5.8]-[8.0]) in order to eliminate possible contaminations such as star-forming galaxies, AGNs and PAH-emissions which can be easily confused with YSOs. Koenig et al. (2012) established color-color criteria for WISE data derived from the Spitzer color-color criteria by Gutermuth et al. (2009). In Section 3.3, we introduce a method to find spectral index ($\alpha$) only by using WISE magnitude of each band to classify YSOs. Based on the fact that YSOs are obscured by circumstellar material that re-radiates stellar radiation in the infrared, we are able to measure the infrared spectral index ($\alpha$) that is a slope of SED which is defined as $d \log(\lambda F_{\lambda})/d \log(\lambda)$. Summary and discussion will be in Section 3.4.

### 3.2 YSO Classification by Color-Color Diagram

Color-color diagrams using infrared is a powerful tool for identifying and classifying of YSOs. We will focus on the procedure to make color-color diagram with WISE data using the criteria from Koenig et al. (2012). In this section, we will introduce how to select sources from AllWISE catalog, describe the contaminants eliminating procedure using colors, and finally show how we classify YSOs after eliminating all the contaminants.

#### 3.2.1 Sources Selection

The main data set we used in this research is from AllWISE catalog. The AllWISE catalog builds upon the work of WISE (Wright et al., 2010) by combining data from the WISE cryogenic and NEOWISE (Mainzer et al., 2011) post-cryogenic survey phases to form the most comprehensive view of the full mid-infrared sky currently available.
By combining the data from two complete sky coverage epochs using an advanced data processing system, AllWISE catalog has generated new products that have enhanced photometric sensitivity and accuracy, and improved astrometric precision compared to the WISE All-Sky Data Release released in 2012 (Koenig et al., 2012).

In order to extract legitimate WISE sources from AllWISE catalog, a number of constraints have to be employed. First, appropriate spatial constraints are applied in Galactic longitude and latitude (see Table 2.1) for each of the four H II regions. Next, we selected sources with signal-to-noise greater than 5 (or uncertainty < 0.2 mag) for all bands. Then we want to remove contamination and confusion flag from the photometric selection of the sources. We removed WISE objects with photometric contamination and confused flags “D”, “H”, “O” and “P” in any bands. These flags refer to the following: “D” – diffraction spike. Source may be a spurious detection or contaminated by a diffraction spike from a nearby bright star of the same age. “H” – sources may be a spurious detection or contaminated by the scattered halo light surrounding a nearby bright source. “O” – optical ghost. Source may be a spurious detection or contaminated by an optical ghost image caused by a nearby bright source and “P” – sources may be spurious or contaminated by a short-term latent image left by a bright source (Wright et al., 2010). After applying all these constraints to AllWISE catalog, we retrieved sources for each H II region.

3.2.2 Contamination Removal

Once WISE sources were retrieved from AllWISE catalog, we have to eliminate possible contamination arising from non-YSO sources. The original criteria of contamination was introduced by Gutermuth et al. (2009) using Spitzer photometry. Based on this criteria Koenig et al. (2012) modified criteria of Gutermuth et al. (2009) for WISE photometry. The figures included in this section are from Koenig et al. (2012) and similar figures of each four H II region are shown in Chapter 4.
The first objects removed are unresolved external star-forming galaxies. Galaxies with actively on-going star-formation exhibit increased PAH-features emission which gives them red colors in the Spitzer band 3 (5.8 μm) and band 4 (8 μm) that has similar characteristics observed in the WISE band [4.6] − [12] color. Equation 3.1 shows the inequalities that define the region shown with solid lines shown in Figure 3.1 and a magnitude cut to select only faint sources in WISE 4.6 μm band 2.

\[
\] (3.1)
Another possible contaminant is unresolved broad-line Active Galactic Nuclei (AGNs) which have very similar mid-infrared colors with YSOs. However, unresolved broad-line AGNs will be usually fainter than typical YSOs in the regions closer than $\sim 5$ kpc, such as the ones studied in this dissertation. Therefore, brightness cut in the WISE band 2 (4.6 $\mu$m) can be used as a primary discriminant. Figure 3.2 shows the cut of the AGNs. Below the dashed line in figure 3.2 is the cut of AGNs and the equation of the dashed line is shown in Equation 3.2 for 4.6 $\mu$m and 12 $\mu$m color-magnitude diagram or Equation 3.3 for 3.4 $\mu$m and 12 $\mu$m color-magnitude diagram.

Figure 3.2  A color-color diagram of WISE 3.4, 4.6 and 12 $\mu$m band. Gray points show all of the objects detected by WISE with declination $b > 88.2^\circ$ Colored data are taken from the Taurus compilation of Rebull et al. (2010) detected by WISE. Inside the dashed line is a cut of unresolved broad-line AGN. Figure from Koenig et al. (2012)
\[ [4.6] > 1.9 \times ([4.6] - [12] + 3.16) \] (3.2)
\[ [4.6] > -1.4 \times ([4.6] - [12] - 11.93) \]
\[ [4.6] > 13.5 \]

\[ [3.4] > 1.9 \times ([3.4] - [12] + 2.55) \] (3.3)
\[ [3.4] > 14.0 \]

After we eliminated both star-forming galaxies and AGNs, next we removed two classes of contaminants from the remaining sources. First one is resolved shock emission knots. These shock emission knots are prominent in the 4.5 \( \mu \text{m} \) band in Spitzer or the roughly equivalent WISE 4.6 \( \mu \text{m} \) band. The criterion of shock objects is described in Equation 3.4.

\[ [3.4] - [4.6] > 1.0 \] (3.4)
\[ [4.6] - [12] < 2.0 \]

Finally, objects with resolved structured PAH emission had to be eliminated. In WISE observation, these objects are mostly fake detections at 12 \( \mu \text{m} \) due to the comparable point source response function of WISE at 12 \( \mu \text{m} \) and size scale of structure in the extensive PAH emission that is common in star-forming regions. Resolved PAH emission objects required the criteria shown in equation 3.5.
3.2.3 Classifying Young Stellar Objects

After removing all the possible defined contaminants, the remaining sources were considered to be YSO candidates. The next step was classifying YSOs based on the color. The following classification criteria is done by Koenig et al. (2012) by comparing known Taurus region YSOs listed in Rebull et al. (2010), which are also detected by WISE. Class I YSOs are the reddest objects and were selected if their colors match following Equation 3.6.

\[
[3.4] - [4.6] > 1.0 \quad (3.6)
\]

\[
[4.6] - [12] > 2.0
\]

Class II YSOs (possible candidate T Tauri stars) are slightly less red objects then Class I YSOs and were selected with following colors as equation 3.7.

\[
[3.4] - [4.6] - \sigma_1 > 0.25 \quad (3.7)
\]

and

\[
[4.6] - [12] - \sigma_2 > 1.0
\]

where

\[
\sigma_1 = \sqrt{\sigma_{3.6}^2 + \sigma_{4.6}^2} \quad (3.8)
\]

and

\[
\sigma_2 = \sqrt{\sigma_{4.6}^2 + \sigma_{12}^2}
\]
Figure 3.3  *WISE* band 1, 2, and 3 color-color diagram showing the distribution of Class I (red), Class II (gold and yellow) and Class III (black) YSOs. These data taken from the Taurus compilation of Rebull et al. (2010) detected by *WISE*. Dashed lines indicate the boundaries by which classify Class I and Class II sources.

Figure 3.3 shows the distribution of Class I, Class II, and Class III YSOs. Class III YSOs (Diskless protostar) are simply classified as neither Class I, Class II nor Transition disks, which will be explained later, among YSO candidates. However, we cannot distinguish Class III YSOs from other stars because Class III YSOs are residue of other classification of YSOs not classified with specific criteria. Dashed lines indicate the boundaries of each class of YSOs. Among the YSOs, the absence or low level of 1 to 10 $\mu$m mid-infrared excess emission and large excess above 20 $\mu$m has been modeled as originating from a truncated optically thick outer disk and a dissipated inner disk or a radial gap of the inner disk. Photoevaporation by the central star or planet formation produces this clearing of the inner parts of the disk resulting in a so-called “Transition Disk” YSOs that exhibits excess mid-infrared emission only at wavelength $> 20 \mu$m.
(Gutermuth et al., 2009).

In the same way that Gutermuth et al. (2009) used Spitzer MIPS 24 µm data to identify transition disks, WISE 22 µm can be used to identify transition disks (same photospheric feature as diskless stars between 3.4 and 12 µm but an excess at 22µm). Transition disks can be classified with the following colors shown in equation 3.9, and figure 3.7 shows the scheme of classification of transition disk in the WISE color-color diagram.

\[
[4.6] - [22] > 2.5 \\
[3.4] - [4.6] < 0.25 \\
\text{and} \\
[3.4] < 14
\] (3.9)

3.2.4 Combining 2MASS data with WISE

Many objects visible in WISE 3.4 and 4.6 µm band lack reliable 12 and 24 µm band detection due to the bright background emission and low sensitivity. To make up for this, Two Micron All-Sky Survey (2MASS) (Skrutskie et al., 1997) data can be combined with WISE data. 2MASS is a survey of the whole sky in three mid-infrared wavelengths: J (1.2 µm), H (1.7µm) and Ks (2.2 µm). The AllWISE catalog already provides matched 2MASS JHK\text{}s point source photometry if they are available. We already selected sources with S/N > 5 to choose reliable sources for all band of WISE. Thus we use 2MASS to compare YSO classification result solely by WISE color-color diagram and by WISE + 2MASS color-color diagram. Equation 3.10 is a criteria for Class II YSOs with 2MASS Ks band combined with WISE band 1 and band 2.
Figure 3.4  WISE band 1, 2, and 4 color-color diagram showing the distribution of Class I (red), Class II (gold and yellow), and Transition Disks (blue and light blue) Class III (black) YSOs. These data were taken from the Taurus compilation of Rebull et al. (2010) detected by WISE. Dashed lines indicate the boundaries by which we classify Class I and Transition Disk sources. Figure from Koenig et al. (2012).

\[
[3.4] - [4.6] - \sigma_1 > 0.101 \tag{3.10}
\]

\[
K_s - [3.4] - \sigma_3 > 0.0
\]

\[
K_s - [3.4] - \sigma_3 > -2.85714 \times ([3.4] - [4.6] - 0.101) + 1.05 - \sigma_1
\]

and

\[
[3.4] < 13.8
\]

where $\sigma_1$ is written in equation 3.8 and $\sigma_3 = \sqrt{\sigma_{K_s}^2 + \sigma_{[3.4]}^2}$. 
Among these Class II objects classified with 2MASS and WISE band 1 and 2 data, the reddest objects classified as Class I with following criteria are described in Equation 3.11. Figure 3.5 shows the criteria of Class II and Class I YSOs and their distribution.

\[
K_s - [3.4] - \sigma_3 > -2.85714 \times ([3.4] - [4.6] - 0.401 - \sigma_1) + 1.9 \quad (3.11)
\]

Again, Class III YSOs (Diskless protostar) are simply classified neither Class I, Class II and Transition disks among YSO candidates as we discussed earlier. Figure 3.6 is a flowchart of classifying YSOs using color-color diagram using WISE data. All the results of identification and classification of YSOs for four H II regions will be discussed in Chapter 4.
Figure 3.6 A summary flowchart of the YSO identification and classification process explained in section 3.2.3
3.3 Spectral Index ($\alpha$)

YSOs class distribution can also be examined by fitting slope of the SED in the mid-infrared (infrared spectral index ($\alpha$)). The class identification of YSOs for the slope of $\alpha$ is defined as log($\lambda F_\lambda$) vs. log($\lambda$) between 2–20 µm from Lada (1987) (see Figure 3.7). Table 3.1 is a classification of YSOs based on the spectral index ($\alpha$) value.

![Figure 3.7 SEDs for Each Classification of YSOs. YSO can be classified as spectral index ($\alpha$) which is the slope of the mid-infrared wavelength and contribution of each component of YSOs to SEDs.](image)

Table 3.1 The Class Identification of the Spectral Index ($\alpha$)

<table>
<thead>
<tr>
<th>Spectral Index ($\alpha$)</th>
<th>YSO Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.3 \geq \alpha$</td>
<td>Class I</td>
</tr>
<tr>
<td>$-0.3 \leq \alpha &lt; 0.3$</td>
<td>Flat Spectrum</td>
</tr>
<tr>
<td>$-1.6 \leq \alpha &lt; -0.3$</td>
<td>Class II</td>
</tr>
<tr>
<td>$\alpha &lt; -1.6$</td>
<td>Class III</td>
</tr>
</tbody>
</table>

To determine the intrinsic slope of the SEDs of YSOs (spectral index $\alpha$) with the WISE magnitudes, we have to derive the equation to find spectral index ($\alpha$) from the
The definition of $\alpha$. The relationship between $\lambda F_{\lambda}$ and the magnitude in a particular band is given by Majaess et al. (2012) and shown in Equation 3.12.

$$\log(\lambda \times F_{\lambda}) = \log(\lambda \times 10^{-m_{\lambda}/2.5} F_{\lambda}(0)q c/\lambda^2) \quad (3.12)$$

where $\lambda$ is the wavelength of the passband in the unit of cm, $m_{\lambda}$ is the magnitude in the corresponding passband, $F_{\lambda}(0)$ is the zero-magnitude flux in Jy, $q$ is a conversion factor $q = 10^{-23}$erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ and $c$ is the speed of light (cm s$^{-1}$). Table 3.2 shows the wavelength of passbands and zero-magnitude flux of four WISE bands.

**Table 3.2 Instrumental Zero Point Magnitude for WISE Source Photometry**

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength(µm)</th>
<th>Magnitude</th>
<th>$F_{\lambda}(0)$(Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>3.4</td>
<td>20.730</td>
<td>309.540</td>
</tr>
<tr>
<td>W2</td>
<td>4.6</td>
<td>19.567</td>
<td>171.787</td>
</tr>
<tr>
<td>W3</td>
<td>12</td>
<td>17.600</td>
<td>31.674</td>
</tr>
<tr>
<td>W4</td>
<td>22</td>
<td>12.980</td>
<td>8.363</td>
</tr>
</tbody>
</table>

Based on this, Marton et al. (2013) suggest the equation for finding spectral index ($\alpha$) with all of four WISE bands in Equation 3.13

$$\alpha \approx 0.36(W_1 - W_2) + 0.58(W_2 - W_3) + 0.41(W_3 - W_4) - 2.90 \quad (3.13)$$

Equation 3.13 is obtained by averaging the slope of nearby WISE data points. However, Majaess et al. (2012) found spectral index using only $K_s$ and WISE 22 µm bands. Yet, the wavelength dependence of extinction usually biases the perceived slope. 2MASS $K_s$ band shows higher sensitivity of extinction than WISE passbands. The bias may be reduced by the determination of $\alpha$ solely from WISE photometry since the passbands display nearly equivalent extinction ratios ($A_{[3.4]} : A_{[4.5]} : A_{[12]} : A_{[22]} \sim 0.5A_{K_s}$). Based on this, Majaess et al. (2012) used two classification-defined YSOs for simulation to derive the equation of spectral index including $K_s$ band from WISE only data sets. With this simulation, Majaess et al. (2012) derived the equation for spectral index ($\alpha$) with $K_s$
band only from WISE data as follows: \( \alpha_{K_s + W} \sim 0.98 \times \alpha_W - 0.15 \). Therefore, if \( \alpha_W \) is calculated only with WISE data, \( \alpha_{K_s + W} \) also can be estimated. Using the definition of \( \alpha \) which is \( d \log(F_\lambda)/d \log(\lambda) \), \( \alpha_W \) can be derived as in Equation 3.14.

\[
\alpha_W = \frac{\log(\lambda_{W4} \times 10^{-W4/2.5} F_{W4}(0) q c / \lambda_{W4}^2) - \log(\lambda_{W1} \times 10^{-W1/2.5} F_{W1}(0) q c / \lambda_{W1}^2)}{\log(\lambda_{W4}) - \log(\lambda_{W1})} \tag{3.14}
\]

After substituting all the constants and values from Table 3.2, Equation 3.14 becomes;

\[
\alpha_W = 0.488 \times (W_1 - W_4) - 2.915 \tag{3.15}
\]

\[
\alpha_{K_s + W} = 0.478 \times (W_1 - W_4) - 3.0 \tag{3.16}
\]

Table 3.3 Four WISE Magnitudes and Fluxes for Eight YSOs from Liu et al. (2011)

<table>
<thead>
<tr>
<th>Designation</th>
<th>( F_{K_s} ) (mJy)</th>
<th>( K_s ) (mag)</th>
<th>( F_{W1} ) (mJy)</th>
<th>( W_1 ) (mag)</th>
<th>( F_{W2} ) (mJy)</th>
<th>( W_2 ) (mag)</th>
<th>( F_{W3} ) (mJy)</th>
<th>( W_3 ) (mag)</th>
<th>( F_{W4} ) (mJy)</th>
<th>( W_4 ) (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J150208.37-630332.6</td>
<td>11.2</td>
<td>11.248</td>
<td>8.3</td>
<td>11.429</td>
<td>4.8</td>
<td>11.384</td>
<td>2.0</td>
<td>10.499</td>
<td>14.3</td>
<td>6.918</td>
</tr>
<tr>
<td>J150030.57-631030.3</td>
<td>17.8</td>
<td>11.434</td>
<td>19.3</td>
<td>10.513</td>
<td>25.2</td>
<td>9.584</td>
<td>20.4</td>
<td>7.978</td>
<td>41.6</td>
<td>5.758</td>
</tr>
<tr>
<td>J150345.69-632341.2</td>
<td>12.3</td>
<td>11.835</td>
<td>10.8</td>
<td>11.143</td>
<td>12.6</td>
<td>10.337</td>
<td>28.6</td>
<td>7.611</td>
<td>43.6</td>
<td>5.707</td>
</tr>
<tr>
<td>J150332.29-632563.6</td>
<td>21.6</td>
<td>11.244</td>
<td>21.9</td>
<td>10.376</td>
<td>33.4</td>
<td>9.278</td>
<td>73.7</td>
<td>6.583</td>
<td>155.0</td>
<td>4.330</td>
</tr>
<tr>
<td>J150022.02-631241.9</td>
<td>29.5</td>
<td>10.885</td>
<td>87.4</td>
<td>8.873</td>
<td>167.0</td>
<td>7.531</td>
<td>202.0</td>
<td>5.488</td>
<td>406.0</td>
<td>3.285</td>
</tr>
<tr>
<td>J150215.35-632028.3</td>
<td>7.1</td>
<td>12.432</td>
<td>12.6</td>
<td>10.976</td>
<td>24.0</td>
<td>9.637</td>
<td>105.0</td>
<td>6.199</td>
<td>307.0</td>
<td>3.588</td>
</tr>
<tr>
<td>J145913.60-630005.5</td>
<td>15.1</td>
<td>11.612</td>
<td>15.7</td>
<td>10.737</td>
<td>25.1</td>
<td>9.588</td>
<td>212.0</td>
<td>5.436</td>
<td>675.0</td>
<td>2.733</td>
</tr>
</tbody>
</table>

Table 3.4 Comparison of Spectral Indices of Eight YSOs from Liu et al. (2011) Determined by Different Data Points.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Liu et al. (2011)</th>
<th>Marton et al. (2013)</th>
<th>( \alpha_W ) (Eqn 3.15)</th>
<th>( \alpha_{W + K_s} ) (Eqn 3.16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J150156.59-631728.2</td>
<td>-1.39 (II)</td>
<td>-1.22 (II)</td>
<td>-1.21 (II)</td>
<td>-1.39 (II)</td>
</tr>
<tr>
<td>J150208.37-630332.6</td>
<td>-0.89 (II)</td>
<td>-0.90 (II)</td>
<td>-0.71 (II)</td>
<td>-1.17 (II)</td>
</tr>
<tr>
<td>J150030.57-631030.3</td>
<td>-0.63 (II)</td>
<td>-0.72 (II)</td>
<td>-0.60 (II)</td>
<td>-0.63 (II)</td>
</tr>
<tr>
<td>J150345.69-632341.2</td>
<td>-0.46 (II)</td>
<td>-0.248 (F)</td>
<td>-0.26 (F)</td>
<td>-0.46 (II)</td>
</tr>
<tr>
<td>J150332.29-632356.3</td>
<td>-0.15 (F)</td>
<td>-0.02 (F)</td>
<td>0.04 (F)</td>
<td>-0.14 (F)</td>
</tr>
<tr>
<td>J150022.02-631241.9</td>
<td>0.13 (F)</td>
<td>-0.329 (II)</td>
<td>-0.19 (F)</td>
<td>0.13 (F)</td>
</tr>
<tr>
<td>J150215.35-632028.3</td>
<td>0.62 (I)</td>
<td>-0.65 (I)</td>
<td>0.69 (I)</td>
<td>0.62 (I)</td>
</tr>
<tr>
<td>J145913.60-630005.5</td>
<td>0.64 (I)</td>
<td>1.03 (I)</td>
<td>0.99 (I)</td>
<td>0.63 (I)</td>
</tr>
</tbody>
</table>

To test this derived formula, we compared data taken from Liu et al. (2011) (see Figure 3.8). They calculated spectral index (\( \alpha \)) using the 2MASS \( K_s \) and WISE 22 \( \mu m \) data points. Figure 3.1 shows the spectral index (\( \alpha \)) and classification of YSO candidates
based on spectral index ($\alpha$). Table 3.3 is four WISE magnitudes and fluxes for eight YSOs from Liu et al. (2011) and Table 3.4 shows the comparisons of the spectral index ($\alpha$) with equation 3.15 and equation 3.16 to the spectral index ($\alpha$) of Liu et al. (2011). Liu et al. (2011) calculated the spectral index, $\alpha = \Delta \log F_{\lambda} / \Delta \log \lambda$ with 2MASS K$_s$ band and WISE 22 $\mu$m data points. From Table 3.4, we compared the spectral index of 8 YSOs from Liu et al. (2011) with spectral index from Marton et al. (2013), Equation 3.15 and Equation 3.16. Spectral index ($\alpha$) from $K_s$ band to 22 $\mu$m band estimated from spectral index from WISE 3.4 $\mu$m band to 22 $\mu$m band is quite well matched with the spectral index from Liu et al. (2011). Therefore, spectral index calculated using Equation 3.16 is a fairly robust way to find spectral index of YSOs.

### 3.4 Summary

The young stellar objects (YSOs) evolve quickly, in just a few $\sim 10^6$ years. Therefore, identifying and classifying YSOs are crucial point to determine the relative age of H II region and associated star-formation scenarios. Making a color-color diagram based on the mid-infrared observations is a powerful tool for identifying a classification of YSO. With color-color diagram, we can eliminate possible contaminants which can be confused with YSOs and classify the YSOs easily with their colors. A spectral index($\alpha$) derived from the flux of mid-infrared observation provides a quick and easy way to classify YSOs. However, this method is less accurate then color-color diagrams because we cannot filter out the contaminants that we discussed earlier in section 3.2.2 only using the spectral index. Therefore, color-color diagrams can be used a primary methods to identify and classify YSOs. Finding the spectral index from the flux can be used as a secondary or subsidiary method to compare the YSO classification from color-color diagrams.
Figure 3.8 SEDs for eight YSOs in Circinus from Liu et al. (2011). The dotted lines represent the photospheric emission normalized to $K_s$ band. Four data points from right correspond to four WISE bands and three data points from left correspond to $J$, $H$, $K_s$ data points. First plot shows an example of typical star in the region with purely photospheric emission. Error bars are smaller than the symbols.
CHAPTER 4. AN ANALYSIS OF YSO CLASSIFICATION IN FOUR SMALL H II REGION

4.1 Introduction

To identify and classify YSOs in four compact H II regions – KR 7, KR 81, KR 120 and KR 140 discussed in section 2, we mainly used WISE 3.4 µm, 4.6 µm, 12 µm, and 22 µm data from AllWISE catalog. We first applied Koenig et al. (2012) criteria which modified for WISE data the original Gutermuth et al. (2009) criteria used for Spitzer. As a comparison, we then compared other methods discussed in section 3 to the classification devised by using spectral index (α).

4.2 Analysis

A detailed analysis and explanation of the YSO identification and classification methods will be introduced for KR 140 in section 4.2.1. The same analysis and methods will be applied for three other compact H II regions – KR 7, KR 81, KR 120— with the result summarized in section 4.2.2, 4.2.3, and 4.2.4, respectively.

4.2.1 KR 140

The first stage of YSO identification is the appropriate source selection from the AllWISE catalog via the catalog search tool on the IRSA website\(^1\). We applied spatial constraint 0.7° × 0.4° which corresponds to galactic longitude, 133.04° ≤ l ≤ 133.74°.

\(^1\)http://irsa.ipac.caltech.edu
and galactic latitude, $-0.16^\circ \leq b \leq 0.24^\circ$. Another constraint applied at the same time was signal-to-noise (S/N) $\geq 5$ in all four WISE bands and exclude contamination and confusion flags (cc_flags) containing “D”, “H”, “O”, and “P” as described in section 3.2.1. With all of these constraints, 758 sources are retrieved from the AllWISE catalog.

![Figure 4.1](image-url)

Figure 4.1  WISE band 1, 2, and 3 color-color diagram showing the distribution of 758 sources retrieved from AllWISE catalog with constraints of KR 140 H II regions. Inside of red dashed lines show the region from which we cut PAH/star-forming galaxies, inside of blue dashed lines show the region where we cut shock objects, and inside of green dashed lines where we cut resolved PAH emission line.

Next, we eliminate contaminants such as star-forming galaxies, unresolved broad-line AGNs, shock emission blobs, and resolved PAH emissions. In Figure 4.1, we plot a color-color diagram showing the 758 sources retrieved from AllWISE catalog of KR 140 using WISE band 1, 2 and 3. First step in extracting young stellar objects was to remove objects from the merged catalog that are most likely to be unresolved external
PAH/star-forming galaxies. The criteria for delimiting PAH/star-forming galaxies is the inside of the red dashed line boundary shown in Figure 4.1 whose criterion is described in Equation 3.15. Yet not all sources inside the red boundary will be eliminated. Only faint sources in band 2 ([4.6] > 12) will be eliminated and bright sources in band 2 are still considered as YSO candidates. With this PAH/star-forming galaxy contaminants process, 44 sources considered as PAH/star-forming galaxies out of 758 sources are eliminated.

Figure 4.2 WISE color-magnitude diagram showing the distribution of sources after elimination of PAH/star-forming galaxies. Dashed lines show the regions where we cut likely unresolved broad-line AGN contaminants.

Once you eliminate unresolved PAH/star-forming galaxies, the next step is removing unresolved broad-line AGNs. They possess mid-IR colors very similar to YSOs. However, on average they will be much fainter than a typical YSOs. Thus, brightness cut in WISE band 1 (3.4 µm) and band 2 (4.5 µm) treated as primary contaminants. All the criteria to eliminate unresolved broad-line AGNs from the retrieved sources are described in Equation 3.16. Figure 4.2 shows color-magnitude diagram of band 1 and band 2 against with their color using band 1 and band 3. Below the dashed line region is where we cut likely unresolved broad-line AGN contaminants. In total 155 sources are eliminated as unresolved broad-line AGNs.
Figure 4.3  *WISE* band 1, 2, and 3 color-color diagram showing the distribution of YSO candidates of KR 140 after all the contaminants were eliminated. Only 228 sources are selected as YSO candidates.

The next contaminants considered are shock emission knots. Shock emission knots are prominent in the 4.6 $\mu$m *WISE* band 2. The criteria of shock emission knots were discussed in Equation 3.4 and also shown in blue dashed line in Figure 4.1. After removing PAH/star-forming galaxies and AGNs, only 3 additional sources are eliminated from this criteria of shock emission knots.

Finally, resolved PAH emission is the last contaminant that we need to consider. These objects are mostly fake detections in *WISE* 12 $\mu$m due to the comparable point source-response function of *WISE* at 12 $\mu$m and size scale of structure in the extensive PAH nebulosity that is common in star-forming regions. The criteria of PAH emission is also discussed in Equation 3.5 and 228 sources are eliminated shown inside the green dashed line in Figure 4.1. After process of all the eliminating contaminants, a total of 228 sources are selected as YSO candidates out of 758 sources (see Table 4.1). Figure 4.3 is the color-color diagram showing the distribution of YSOs candidates after eliminating all the contaminants.
Table 4.1 Data Reduction Summary for KR 140

<table>
<thead>
<tr>
<th>Stage</th>
<th>Number of contaminants</th>
<th>YSO Candidate Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>−</td>
<td>758</td>
</tr>
<tr>
<td>Removal PAH/star-forming galaxy</td>
<td>44</td>
<td>714</td>
</tr>
<tr>
<td>Removal Broad-line AGNs</td>
<td>155</td>
<td>559</td>
</tr>
<tr>
<td>Removal Shock-emission knots</td>
<td>3</td>
<td>556</td>
</tr>
<tr>
<td>Removal Resolved PAH emission</td>
<td>328</td>
<td>228</td>
</tr>
<tr>
<td>Final YSO candidates</td>
<td>−</td>
<td>228</td>
</tr>
</tbody>
</table>

After rejecting all of the potential contaminated sources, next we identify YSOs using a *WISE* color-color diagram for *WISE* band 1, 2, and 3. Class I YSOs are the reddest objects and are selected if their colors match the criteria discussed in Equation 3.6. They are plotted as red symbols in Figure 4.4. Class II YSOs are slightly less red objects and are selected with color criteria given in Equation 3.7. They are plotted as green symbols in Figure 4.4.

Out of 228 sources, 12 sources are classified as Class I sources and 27 sources are selected as class II sources based on criteria illustrated in the *WISE* color-color diagram shown in Figure 4.4.

In the same way that Gutermuth et al. (2009) used *Spitzer* MIPS 24\( \mu \)m data to identify evolved Transition Disks —disks with photospheric colors between 3.4 \( \mu \)m and 12 \( \mu \)m but excess emission at 22 \( \mu \)m, Koenig et al. (2012) identified Transition Disks using *WISE* band 1 (3.4 \( \mu \)m), band 2 (4.6 \( \mu \)m) and band 4 (22 \( \mu \)m) using criteria discussed in Equation 3.9.

Table 4.2 Number of YSOs in Each Class Using *WISE* color-color diagram for KR 140

<table>
<thead>
<tr>
<th>YSO Class</th>
<th>Number of YSOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>12</td>
</tr>
<tr>
<td>Class II</td>
<td>27</td>
</tr>
<tr>
<td>Transition Disk</td>
<td>163</td>
</tr>
<tr>
<td>Class III</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
</tr>
</tbody>
</table>
Figure 4.4  *WISE* band 1, 2, and 3 color-color diagram showing distribution of 228 YSO candidates of KR 140 after all the contaminants eliminated. Out of 228 YSOs candidates, red diamonds indicate the Class I YSOs and green diamonds indicate the Class II YSOs. Dashed lines indicate the boundaries of classification of Class I and Class II sources.
Figure 4.5  *WISE* band 1, 2, and 4 color-color diagram showing the distribution of 228 YSO candidates of KR 140 after all the contaminants eliminated. Below the lower dashed line is the criteria of Transition Disk indicated with blue diamonds.
Figure 4.5 shows WISE color-color diagram with band 1, 2 and 4 and the location of the Class I criteria specified in Equation 3.6 and the region in which we find candidate Transition Disk objects specified in Equation 3.9. With this Transition Disk classification process, 163 YSO candidates are identified as Transition Disks. Compared to the number of Class I and Class II sources, we found too many Transition Disks. We suspect there are many spurious sources included when we retrieved the sources from the AllWISE catalog. Therefore, further processes are required to correct the number of Transition Disks. This further process will be referred to future work and will be discussed in Chapter 6.

After classifying Class I, II and Transition Disks, YSOs match none of these criteria are treated as candidate Class III diskless YSOs. These Class III sources are indicated as black diamonds in Figure 4.5 and 26 sources are classified as Class III YSOs. Note that we made no effort to separate true Class III YSOs from reddened stars. Table 4.2 shows the number breaks of classification of YSOs out of 228 YSO candidates.

As we discussed in Chapter 3, many objects visible in WISE band 1 and 2 will lack a reliable band 3 or 4 detections due to the bright background emission present at longer wavelengths such as 12 or 22 µm band. To make up for this drawback, we used 2MASS data sets from AllWISE catalog. AllWISE catalog also provides J, H, K_s data if they are matched with sources detected by WISE. Not all WISE sources are available in 2MASS data because resolution of WISE is much better than 2MASS and WISE detection bands stretch to the 22 µm band.

We tested how well YSO classification by using 2MASS K_s band combined with WISE band 1 and band 2 well matched with YSO classification by using WISE bands. Out of a total of 758 sources, K_s magnitude is available for 457 sources. With these 457 sources, we eliminated contaminants as discussed earlier; 238 sources are eliminated and 219 sources remain as YSO candidates. The criteria for classifying Class I and Class II YSOs using 2MASS and WISE data is discussed earlier in Equation 3.10. Following this
criteria, 21 sources identified as Class I YSOs, shown with red diamonds in Figure 4.6, and 16 sources identified as Class II YSOs, shown with green diamonds in Figure 4.6.

Figure 4.6 2MASS $K_s$ and WISE band 1 and 2 color-color diagram showing the distribution of 233 YSO candidates detected by WISE. Class I YSOs are indicated as red diamonds and Class II YSOs are indicated as green diamonds. Dashed lines indicate the boundaries where we classify Class I and Class II sources.

Figure 4.7 shows the combined YSO distribution using WISE only color-color diagram and combined WISE and 2MASS data. Class I YSOs identified as red colors, Class II YSOs identified as green, Transition Disks in blue and Class III YSOs indicated in black. Diamonds indicate YSOs classified by using WISE only color-color diagram and plus signs indicate YSOs classified by using combined WISE and 2MASS. From Figure 4.7 we see that the classification of YSOs using only WISE data is generally well matched with the classification of YSOs with WISE and 2MASS data. Eleven Class I YSOs, classified by WISE and 2MASS data, do not agree with the Class II YSOs classified with WISE only data (green diamonds filled with red plus signs). However, a YSO
Figure 4.7  WISE band 1, 2, and 3 color-color diagram showing the distribution of Class I (red), Class II (green), Transition Disks (blue) and Class III (black) YSOs in KR 140 region. Diamonds indicate YSOs classified with WISE color-color diagram and plus signs indicate YSOs classified with combined 2MASS and WISE color-color diagram.

classification using 2MASS – WISE does not show same result with YSO classification only use of WISE. We think that could be due to the extinction effect of $K_s$ band and this can lead to redder $K_s$-[3,4] values (see Figure 4.8). In addition to that, YSO classification by WISE only data can give us a more accurate classification because WISE have longer wavelength data.

Spectral index ($\alpha$) also can be used to classify YSOs. A spectral index is the slope of the SED $\log(\lambda F_\lambda)$ vs. $\log(\lambda)$ between 2 and 20 $\mu$m in the mid-infrared from Lada (1987). To determine the intrinsic slope of the SED (spectral index $\alpha$) of YSOs, we used Equation 3.13 for shortest wavelength as WISE band 1 3.4 $\mu$m and Equation 3.14 for shortest wavelength as $K_s$ band derived from Equation 3.13 discussed in section 3.3.
YSO classification based on spectral index is shown in Table 4.3.

As you can see from Table 4.3, Class I sources are over-estimated based on the color-color diagrams that appear more likely to be Class II YSOs. This is likely caused by the high column density material in the area of KR 140 that contribute to cross-contamination of Class I YSOs by reddened Class II YSOs. Although determining the spectral index ($\alpha$) of the SED is a very rapid and conventional method to classifying potential YSO candidates, there are some flaws in this method. First, as we discussed earlier, we have to eliminate the contaminants to find appropriate YSO candidates. However, we cannot eliminate the contaminants with this simple equation. Next, this
method is even more sensitive to photometric errors and flux that can artificially increase the apparent redness of a source as we can see over-estimated Class I YSOs in Table 4.3. Thus, this method can only be used as a comparison along with color-color diagrams.

4.2.2 KR 7

For KR 7, we applied spatial constraints area of $0.4^\circ \times 0.4^\circ$ which corresponds to $94.28^\circ \leq l \leq 94.68^\circ$ and $-1.73^\circ \leq b \leq -1.33^\circ$ as galactic coordinates. In addition to this, the same constraints, $S/N > 5$ and cc_flags “D”, “H”, “O”, “P” were applied in the same way as for KR 140. With all these constraints applied to the AllWISE catalog, 487 sources were retrieved. Next, we eliminated all of the contaminants as discussed earlier for KR 140. In total, 279 sources were eliminated. Table 4.4 shows the number of contaminants for each part of contamination and Figure 4.9 shows the distribution of 487 sources of KR 7 and boundaries of contaminants.

Table 4.4 Data Reduction Summary for KR 7

<table>
<thead>
<tr>
<th>Stage</th>
<th>Number of contaminants</th>
<th>YSO Candidate Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>–</td>
<td>487</td>
</tr>
<tr>
<td>Removal PAH/star-forming galaxy</td>
<td>17</td>
<td>470</td>
</tr>
<tr>
<td>Removal Broad-line AGNs</td>
<td>100</td>
<td>370</td>
</tr>
<tr>
<td>Removal Shock-emission knots</td>
<td>0</td>
<td>370</td>
</tr>
<tr>
<td>Removal Resolved PAH emission</td>
<td>162</td>
<td>208</td>
</tr>
<tr>
<td>Final YSO candidates</td>
<td>–</td>
<td>208</td>
</tr>
</tbody>
</table>

After we removed 279 sources out of 487 sources, 208 sources were selected as YSO candidates. Then, we applied color-color criteria for Class I (Equation 3.6) and Class II
WISE band 1, 2, and 3 color-color diagram showing the distribution of 487 sources retrieved from AllWISE catalog with constraints of KR 7 H II regions. Inside of red dashed lines show the region from which we cut PAH/star-forming galaxies, inside of blue dashed lines show the region where we cut shock objects, and inside of green dashed lines where we cut resolved PAH emission line.

(Equation 3.7) using WISE band 1, 2 and 3. Out of 208 sources, 5 YSOs are classified as Class I and 11 YSOs are classified as Class II. Figure 4.10 is the WISE color-color criteria for identifying Class I and Class II using WISE band 1, 2 and 3. Red diamonds indicate the Class I YSOs and green diamonds represent Class II YSOs. 158 YSOs are classified as Transition Disks with WISE band 1, 2 and 4 following criteria in Equation 3.9.

<table>
<thead>
<tr>
<th>YSO Class</th>
<th>Number of YSOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>5</td>
</tr>
<tr>
<td>Class II</td>
<td>11</td>
</tr>
<tr>
<td>Transition Disk</td>
<td>158</td>
</tr>
<tr>
<td>Class III</td>
<td>34</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>208</strong></td>
</tr>
</tbody>
</table>

We also used 2MASS data along with WISE data. After eliminating all the contaminants discussed earlier, 196 sources remained as YSO candidates. Following the criteria
Figure 4.10  *WISE* band 1, 2, and 3 color-color diagram showing distribution of 208 YSO candidates of KR 7 after all the contaminants eliminated. Class I (red) and Class II (green) YSOs were classified using *WISE* band 1, 2 and 3 showed in Equation 3.10, and 3.11, 10 sources are classified as Class I YSOs and 3 sources as Class II YSOs. Figure 4.12 shows the combined color-color plot of both *WISE* only classification and *WISE*+2MASS classification.

Table 4.6  Number of YSO Candidates Identified using spectral index (α) in KR 7

<table>
<thead>
<tr>
<th>Shortest Wavelength</th>
<th>Total YSOs</th>
<th>Class I</th>
<th>Flat Spectrum</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>208</td>
<td>29</td>
<td>69</td>
<td>74</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.9%</td>
<td>33.2%</td>
<td>35.6%</td>
<td>17.3%</td>
</tr>
<tr>
<td>3.4$\mu$m</td>
<td>208</td>
<td>49</td>
<td>59</td>
<td>65</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.6%</td>
<td>28.4%</td>
<td>31.3%</td>
<td>16.8%</td>
</tr>
</tbody>
</table>

A spectral index (α) also used for classify YSOs in KR 7. In the same way we discussed in KR 140, Equation 3.13 used for shortest wavelength as *WISE* band 1 and Equation 3.14 used for shortest wavelength as $K_s$ band. Table 4.6 shows the YSO classification by spectral index (α) in KR 7.
Figure 4.11  *WISE* band 1, 2, and 4 color-color diagram showing distribution of 208 YSO candidates of KR 7 after all the contaminants eliminated. Class I, Class II, and Class III were classified earlier in 4.10 and Transition Disks (blue) YSOs are classified using *WISE* band 1, 2 and 4.

### 4.2.3 KR 81

A searching area of KR 81 is $114.4^\circ \leq l \leq 114.8^\circ$ and $0.01^\circ \leq b \leq 0.41^\circ$ in galactic coordinates, corresponding to $0.4^\circ \times 0.4^\circ$. In addition to these spatial coordinates, S/N > 5 and cc_flags are applied as another constraint in AllWISE catalog for KR 81. After all these constraints were applied, a total of 491 sources were retrieved from the AllWISE catalog. Then, after eliminating contaminants, 182 sources were selected as YSO candidates. Table 4.7 shows the number of contaminants by each type of contaminant.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Number of contaminants</th>
<th>YSO Candidate Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>–</td>
<td>491</td>
</tr>
<tr>
<td>Removal PAH/star-forming galaxy</td>
<td>18</td>
<td>473</td>
</tr>
<tr>
<td>Removal Broad-line AGNs</td>
<td>80</td>
<td>393</td>
</tr>
<tr>
<td>Removal Shock-emission knots</td>
<td>0</td>
<td>393</td>
</tr>
<tr>
<td>Removal Resolved PAH emission</td>
<td>211</td>
<td>182</td>
</tr>
<tr>
<td>Final YSO candidates</td>
<td>–</td>
<td>182</td>
</tr>
</tbody>
</table>
Following the color-color criteria (Equation 3.6 and 3.7) we found 2 Class I YSO candidates and 22 Class II YSO candidates. Figure 4.13 shows the WISE color-color diagram classification of Class I (red) and Class II (green) in KR 81. With WISE band 1, 2 and 4 color-color diagram, 138 YSO candidates were classified as Transition Disks (Figure 4.13). Adding 2MASS data with WISE data sets, 8 YSO candidates are classified Class I YSOs and 16 YSOs candidates were classified as Class II YSOs. Figure 4.15 shows the combined color-color diagram of both WISE and WISE+2MASS classification.

A spectral index ($\alpha$) classification is shown in Table 4.9 with $K_s$ band as the shortest wavelength and WISE band 1 3.4 $\mu$m band as the shortest wavelength. Same as for the KR 140 and KR 7 regions, Class I YSOs still over-estimated as expected.
Figure 4.13  *WISE* band 1, 2, and 3 color-color diagram showing distribution of 182 YSO candidates of KR 81 after all the contaminants eliminated. Class I (red) and Class II (green) YSOs were classified using *WISE* band 1, 2 and 3.

Table 4.8  Number of YSOs in Each Class Using *WISE* color-color diagram in KR 81

<table>
<thead>
<tr>
<th>YSO Class</th>
<th>Number of YSOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>2</td>
</tr>
<tr>
<td>Class II</td>
<td>22</td>
</tr>
<tr>
<td>Transition Disk</td>
<td>138</td>
</tr>
<tr>
<td>Class II</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>182</td>
</tr>
</tbody>
</table>

Table 4.9  Number of YSO Candidates Identified using spectral index ($\alpha$) in KR 81

<table>
<thead>
<tr>
<th>Shortest Wavelength</th>
<th>Total YSOs</th>
<th>Class I</th>
<th>Flat Spectrum</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>182</td>
<td>18</td>
<td>58</td>
<td>82</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9%</td>
<td>31.9%</td>
<td>45.1%</td>
<td>13.2%</td>
</tr>
<tr>
<td>3.4$\mu$m</td>
<td>182</td>
<td>30</td>
<td>58</td>
<td>74</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.4%</td>
<td>31.9%</td>
<td>40.7%</td>
<td>10.4%</td>
</tr>
</tbody>
</table>
Figure 4.14  WISE band 1, 2, and 4 a color-color diagram showing distribution of 182 YSO candidates of KR 81 after all the contaminants eliminated. The Transition Disks (blue) YSOs are classified using WISE band 1, 2 and 4.
Figure 4.15  *WISE* band 1, 2, and 3 color-color diagram showing the distribution Class I (red), Class II (green), Transition Disks (blue) and Class III (black) YSOs in KR 81 region. Diamonds indicate YSOs classified with *WISE* color-color diagram and plus signs indicate YSOs classified with combined 2MASS and *WISE* color-color diagram.
4.2.4 KR 120

KR 120 is smaller than the other three regions, thus its searching area is $0.3^\circ \times 0.3^\circ$ which corresponds to $114.4^\circ \leq l \leq 114.8^\circ$ and $0.01^\circ \leq b \leq 0.41^\circ$ in galactic coordinates. With the same procedure used to select sources from the AllWISE catalog, S/N > 5 and cc_flags are applied as well along with spatial constraints. After all these constraints were applied, a total of 218 sources were retrieved from the AllWISE catalog, which is a much smaller sample than any of the other three regions. Then after eliminating contaminants, only 65 sources were selected as YSO candidates. Table 4.10 shows the number of contaminants by each type of contaminant.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Number of contaminants</th>
<th>YSO Candidate Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>–</td>
<td>218</td>
</tr>
<tr>
<td>Removal PAH/star-forming galaxy</td>
<td>4</td>
<td>214</td>
</tr>
<tr>
<td>Removal Broad-line AGNs</td>
<td>10</td>
<td>204</td>
</tr>
<tr>
<td>Removal Shock-emission knots</td>
<td>0</td>
<td>204</td>
</tr>
<tr>
<td>Removal Resolved PAH emission</td>
<td>139</td>
<td>65</td>
</tr>
<tr>
<td>Final YSO candidates</td>
<td>–</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 4.11 Number of YSOs in Each Class Using WISE color-color diagram in KR 120

<table>
<thead>
<tr>
<th>YSO Class</th>
<th>Number of YSOs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>7</td>
</tr>
<tr>
<td>Class II</td>
<td>19</td>
</tr>
<tr>
<td>Transition Disk</td>
<td>37</td>
</tr>
<tr>
<td>Class II</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>65</td>
</tr>
</tbody>
</table>

Following the color-color criteria (Equation 3.6 and 3.7), we found 7 Class I YSO candidates and 19 Class II YSO candidates. Figure 4.15 shows the WISE color-color diagram classification of Class I (red) and Class II (green) in KR 120. With WISE band 1, 2 and 4 color-color diagram, 37 YSO candidates were classified as Transition Disks (Figure 4.13). Adding 2MASS data with WISE data sets, 13 YSO candidates
Table 4.12 Number of YSO Candidates Identified using spectral index ($\alpha$) in KR 120

<table>
<thead>
<tr>
<th>Shortest Wavelength</th>
<th>Total Class I</th>
<th>Flat Spectrum II</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>65</td>
<td>27</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>41.5%</td>
<td>29.2%</td>
<td>26.2%</td>
<td>3.1%</td>
</tr>
<tr>
<td>3.4$\mu$m</td>
<td>65</td>
<td>19</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>29.2%</td>
<td>32.3%</td>
<td>20%</td>
<td>3.1%</td>
</tr>
</tbody>
</table>

Figure 4.16 WISE band 1, 2, and 3 color-color diagram showing distribution of 182 YSO candidates of KR 120 after all the contaminants eliminated. Class I (red) and Class II (green) YSOs were classified using WISE band 1, 2 and 3. Were classified as Class I YSOs and 8 YSOs candidates were classified as Class II YSOs. Figure 4.18 shows the combined color-color diagram of both WISE and WISE+2MASS classifications. KR 120 is a very young H II region based on the color-color diagram because out of about half sample size than KR 7 or KR 81 regions, their number of Class I YSOs are higher than KR 7 and KR 81 and fewer number of Class II and Class III YSOs. This indicates that star-formation in KR 120 is very recent and young. More details will be discussed in section 4.3

A spectral index ($\alpha$) classification is shown in Table 4.9 with $K_s$ band as the shortest wavelength and WISE band 1 3.4 $\mu$m band as the shortest wavelength. Same as for
Figure 4.17  WISE band band 1, 2, and 4 color-color diagram showing distribution of 182 YSO candidates of KR 120 after all the contaminants eliminated. Class I (red) and Class II (green) YSOs were classified from 4.16 and the Transition Disks (blue) YSOs are classified using WISE band 1, 2 and 4.

the other KR regions, Class I YSOs are over-estimated a lot more than any other KR regions. Very high percentage of Class I YSOs also agrees well with what we found from color-color diagram and that this region is very young and star-formation began recently.
Figure 4.18  *WISE* band 1, 2, and 3 color-color diagram showing the distribution Class I (red), Class II (green), Transition Disks (blue) and Class III (black) YSOs in KR 120 region. Diamonds indicate YSOs classified with *WISE* color-color diagram and plus signs indicate YSOs classified with combined *2MASS* and *WISE* color-color diagram.
4.3 Discussion

There are two main categories of star formation scenarios in the study of star-formation. First, spontaneous star formation is one that occurs without any intervention of outer effects such as stellar winds, supernova shocks or the expansion of H II regions. The other category of the star-formation is triggered or sequential star-formation scenarios, which mainly occur by the presence and expansion of H II regions or stellar winds from massive stars. If there is a massive star, its ultraviolet (UV) light ionizes and excites near by molecular cloud and form a H II region. Due to the high pressure of the relatively warm ionized gas that surrounds cold neutral material, the H II region will be expanding. During this expansion, the ionized front of the H II region sweeps and compresses the material so the neutral materials in the molecular clouds may become dynamically unstable and begin to collapse. Star-formation can also occur in regions within molecular clouds but far from H II regions. Therefore, the spatial distribution of the YSOs can be related with the star-formation scenarios in each H II region. Figures 4.19, 4.20, 4.21 and 4.22 shows a spatial distribution of the YSOs along with WISE band 3, 12 $\mu$m image of KR 7, 81, 120 and 140 respectively.

As shown in figure 4.19, 4.20, and 4.21, all of the class I YSOs (red circles) are located at the periphery of each KR region and Class II YSOs are located at the center of the KR regions along with the periphery of the H II regions. This means that Class II YSOs located at the center of the H II region formed and evolved as the H II region expanded. Class I YSOs are just formed at the photodissociated region (PDR), where the region directly influenced by the expansion of the H II region and UV flux of the H II region clearly can be seen directly by PAH emission. Therefore, the spatial distribution of Class I and Class II YSOs can give us evidence that the expansion of the H II region has swept up material that has subsequently collapsed to form the submm clumps that support triggered star formation scenarios. The submm clumps we could see in 850 $\mu$m images
Figure 4.19  Class I and Class II YSO distribution of the KR 7 with WISE band 3 12\(\mu\)m image. Class I YSOs are indicated as red circles and Class II YSOs are indicated as green circles.

in each region (Figure 2.2, 2.5, and 2.8), are classified as Class I sources and associated with the PDR. These sources may also represent the youngest star formation sites in the molecular cloud.
Figure 4.20 Class I and Class II YSO distribution of the KR 81 with WISE band 3 12µm image. Class I YSOs are indicated as red circles and Class II YSOs are indicated as green circles.
Figure 4.21  Class I and Class II YSO distribution of the KR 120 with WISE band 3 12µm image. Class I YSOs are indicated as red circles and Class II YSOs are indicated as green circles.
Figure 4.22  Class I and Class II YSO distribution of the KR 140 with WISE band 3 12µm image. Class I YSOs are indicated as red circles and Class II YSOs are indicated as green circles.
Figure 4.22 is a YSO class distribution of KR 140. The exciting star of the KR 140 H II region is about 2 Myrs old (Kerton et al., 1999) and kinematic models of the H II region set the expansion time-scale of 1−2 Myrs (Ballantyne et al., 2000). Spatial distribution of YSOs in the region of KR 140 is consistent with swept-up material a triggered by the expansion of the H II region. As you can see from Figure 4.22, there is a very interesting filamentary feature in the west area of KR 140. This elongated morphology of the densest portion of the molecular cloud also shows very active on-going star-formation. However, this very dense region is for away from the influence of the KR 140 region (∼2 pc), thus we cannot say that this active star-forming region is associated with KR 140. Based on the number of Class I YSOs in this filamentary morphology, this star-formation activity is very recent on the time scale of ∼ 10^5 yrs which is about the timescale of Class I YSOs. Thus, we can say that the star-formation scenario of this filamentary feature is spontaneous star-formation scenario coincidentally associated with triggered star-formation in the KR 140.
CHAPTER 5. IRAS 01202+6133: A POSSIBLE CASE OF PROTOPSTELLAR COLLAPSE TRIGGERED BY A SMALL H II REGION KR 120

\[ \text{5.1 Introduction} \]

The molecular gas surrounding a H II region is thought to be a place where star formation can be induced. Such triggered star formation can arise from the overpressurization of existing density enhancements (Thompson et al., 2004) or through the collapse of swept-up layers of material (Elmegreen, 1998; Deharveng et al., 2003). This chapter will present an analysis of submm spectroscopic observations of the Class I young stellar object (YSO) IRAS 01202+6133, which is located on the periphery of the relatively close \((d = 1.44 \pm 0.26 \text{ kpc})\) H II region KR 120 (Sh 2-187; (Arvidsson and Kerton, 2011; Sharpless, 1959; Kallas and Reich, 1980)). As shown in Figure 5.1, the proximity alone of this massive \((M = 21 \pm 9 M_\odot)\), luminous \((L \sim 5600 L_\odot)\) YSO to the H II region makes it a strong candidate for an example of triggered star formation. The submm spectra presented here strengthen this scenario as they clearly show that infall is occurring as would be expected for a very young YSO. We believe that IRAS 01202+6133 is one of the clearest examples to date of an HII region triggering the formation of another massive star.

Our observations are described in section 5.2. In section 5.3 we review the analytical models of Myers et al. (1996) and De Vries and Myers (2005) and develop new varieties
Figure 5.1 The H II Region KR 120 (Sh 2-187). This Midcourse Space Experiment (MSX; Price et al. (2001)) 8.3 μm image traces emission from the photodissociation region within the molecular cloud surrounding KR 120. The red contours correspond to Canadian Galactic Plane Survey (CGPS; Taylor et al. (2003)) 1420 MHz continuum emission at $T_B = 8, 10, 12$ and $14$ K. The elongated radio source seen at the bottom of the main H II region is extragalactic source. The blue contours represent SCUBA 850 μm continuum with levels of $1.2 \times 10^{-3}$, $2 \times 10^{-3}$, $3 \times 10^{-3}$, $6 \times 10^{-3}$ Jy beam$^{-1}$. Note the location of the Class I YSO IRAS 01202+6133 on the periphery of the H II region.

of these models that allow for both infall and outflow motions. Physical properties of the YSO derived using these models are presented and discussed in section 5.4 followed by our conclusions in section 5.5.

5.2 Observations and Infall Motion of the Molecular Core

In order to explore the kinematics of IRAS 01202+6133 we obtained observations of the commonly used (e.g., Sun and Gao (2009)) optically thick infall tracer molecule
HCO$^+$ ($J = 3 \rightarrow 2; 267.6$ GHz) and its optically thin isotopologue H$^{13}$CO$^+$ ($J = 3 \rightarrow 2; 260.3$ GHz) at the James Clerk Maxwell Telescope (JCMT) in the 06B semester. Single pointing observations (beamsize $\sim 20''$ FWHM) were made using the A3 receiver and ACSIS backend with a frequency resolution of 61 kHz ($0.068$ km s$^{-1}$) and an integration time of $\sim 40$ minutes for each line. The reduced spectra are shown in Figure 5.2. Both have a noise level of $\sim 0.1$ K resulting in a peak S/N $\sim 30$ for the HCO$^+$ spectrum and $\sim 3$ for the weaker H$^{13}$CO$^+$ spectrum.

![Figure 5.2 HCO$^+$ spectra of IRAS 01202+6133. The HCO$^+$ ($J = 3 \rightarrow 2; 267.2$ GHz) line has a classical blue asymmetric line profile. The optically thin H$^{13}$CO$^+$ ($J = 3 \rightarrow 2; 260.3$ GHz) line (with Gaussian fit shown as dashed line) peaks at the minimum between two peaks of HCO$^+$ line confirming that blue asymmetric line shape comes from the infall motion.](image)

If there was no infall motion associated with IRAS 01202+6133 we would expect the HCO$^+$ spectrum to be a single self-absorbed profile with symmetric red and blue peaks...
around a local minimum at some systematic velocity. Following Myers et al. (1996), in
the simplest model, two uniform layers approach each other. If the approach speed is less
than the velocity dispersion, the absorption dip appears between the brighter blue peak
and fainter red peak. If there is infall, there will be density and excitation temperature
\( T_{ex} \) differences between the central regions and the outer parts of the molecular core.

![Figure 5.3](image)

**Figure 5.3**  *WISE* three color image of KR 120 and IRAS 01202+6133 (red circle). Red
color represent *WISE* band 3, green color represent *WISE* band 2, and blue
color represent *WISE* band 1.

Blue-shifted emission from the rear of the core is not strongly absorbed because it
passes through the central (high \( T_{ex} \) region, then through a high Doppler shifted front
portion of the core. In contrast, the red-shifted emission from the front of the core is
absorbed by surrounding gas that is at both a comparable velocity and similar low \( T_{ex} \).
The overall effect of the infall motion is to create a “blue-asymmetric” line profile where the self-absorption line is asymmetric with a stronger blue peak. Such a line profile could also form from multiple unrelated emission components being aligned along the line of sight or from rotational motion, but in both cases we would expect to see a similar profile in the optically thin line. The fact that our H$^{13}$CO$^+$ spectrum peaks up at the same velocity as the minimum in the HCO$^+$ spectrum makes us confident that we are looking at a single self-absorbed line profile with the asymmetry arising from infall motions (Figure 5.2).

5.3 Analytical Radiative Transfer Modeling

Myers et al. (1996) and De Vries and Myers (2005) developed basic one-dimensional (1-D) analytic radiative transfer models to derive kinematic data from mm/submm spectra of star-forming molecular cores. In this section, we first review these models and then present modified versions that better model cases where there is simultaneous infall and outflow motions.

All of the models are based on the general solution to the 1-D radiative transfer equation for a homogeneous medium with total optical depth $\tau_0$

$$T_B = T_i e^{-\tau_0} \int_0^{\tau_0} J(T) e^{-\tau} d\tau$$  \hspace{1cm} (5.1)

where $T_B$ is the brightness temperature of the outgoing radiation, $T_i$ is the brightness temperature of any incoming radiation, $J(T) \equiv T_0/\exp(T_0/T) - 1$ and $T_0 \equiv h\nu/k$, where $\nu$ is the frequency of the transition and $T$ is the temperature.

If $J(T)$ is a linear function of $\tau$ then equation 5.1 can be integrated to obtain,

$$T_B = T_i e^{-\tau_0} + (J_2 - J_1) \frac{1 - e^{-\tau_0}}{\tau_0} + J_1 - J_2 e^{-\tau_0}$$  \hspace{1cm} (5.2)
Where $J_1$ and $J_2$ are the values of $J(T)$ at the two ends of the path with optical depth $\tau_0$. All of the models presented in this section are based on equation 5.2 with variations due to how $J(T)$ varies with $\tau$ in detail.

### 5.3.1 Two-Layer Model

Myers et al. (1996) introduced the simplest model, two uniform “front” and “rear” layers approaching each other with constant $T_{ex}$ and infall velocity $V_{in}$ (Figure 5.4). As an optical depth ($\tau_0$) of the collapsing core increases, you will see more distinct blue-asymmetric infall line profile. If the speed of each layer is less than the velocity dispersion, the absorption feature appears as a dip between blue and red peaks. As the infall speed $V_{in}$ increases, more of the red peak is absorbed by the foreground layer, and the blue peak becomes more intense while the red peak is dissipated into a wing of shoulder (Figure 5.5).

The line brightness temperature of the two-layer model is

$$
\Delta T_B = J(T_f)[1 - e^{-\tau_f}] + J(T_r)[1 - e^{-\tau_r}]e^{-\tau_f} - J(T_b)[1 - e^{-\tau_f - \tau_r}] 
$$

(5.3)

where $T_f$ and $T_r$ are the front and rear excitation temperatures and $T_b$ is the background temperature. The optical depths of each layer, $\tau_f$ and $\tau_r$ are given by

$$
\tau_f = \tau_0 \exp \left[ - (v - v_{LSR} - v_{in})^2 / 2\sigma^2 \right], 
$$

(5.4)

$$
\tau_r = \tau_0 \exp \left[ - (v - v_{LSR} + v_{in})^2 / 2\sigma^2 \right] 
$$

(5.5)

where $\tau_0$ is the optical depth line center, $v_{LSR}$ is an average line-of-sight velocity of the system, and $\sigma$ is the velocity dispersion of the observed molecule.

Infall velocity $v_{in}$ can be obtained from the equation 5.3, 5.4 and 5.5:

$$
v_{in} \approx \frac{\sigma^2}{v_{red} - v_{blue}} \ln \left( \frac{1 + \epsilon T_{BD}/T_D}{1 + \epsilon T_{RD}/T_D} \right) 
$$

(5.6)
For a given choice of $T_b$ (usually $T_b = 2.7$ K) the two-layer model has six adjustable parameters: $T_f, T_r, \tau_0, v_{LSR}, v_{in}$ and velocity dispersion $\sigma$. Infall velocity $v_{in}$ from equation 5.6 is a good starting point for two-layer model yet it is still considered as a free parameter along with other parameters above. By making some assumptions about the expected density and temperature structure in an infalling core, Myers et al. (1996) were able to reduce the number of parameters in the two-layer model to five, replacing $T_r$ and $T_f$ by a kinetic temperature, $T_k$. This version of the model also used the non-thermal velocity dispersion as an input, $\sigma_{NT} \equiv (\sigma^2 - kT_k/m_{obs})^{1/2}$ where $m_{obs}$ is the mass of the observed molecule. Here we present the formulas used to calculate the model parameters and refer the readers to Myers et al. (1996) for their derivation.
Figure 5.5  Line profile variation with optical depth (a), infall velocity (b). Increasing peak optical depth $\tau_0$ shows distinct blue-asymmetric features of infall line profile. $V_{in}$ also affect the features of infall line profile. For slow infall velocity $V_{in} (V_{in} \ll \sigma)$, as optical depth increases, the line brightens until it develops a self-absorption dip between a brighter blue peak and a fainter red peak. As $V_{in}$ increases, the degree of asymmetry increases, from two equally bright peaks to a blue peak brighter than the red peak, to a blue peak and a red shoulder. (c) shows the definition of parameters $T_D$, $T_{BD}$, $T_{RD}$, and $v_{red} - v_{blue}$ for use with equation 5.7, Figure from Myers et al. (1996).

The excitation temperature of each layer is determined using the following equations,

$$\frac{T_f}{T_k} = \frac{T_b + (4T_0/\beta)\langle n_f \rangle/n_{max}}{T_k + (4T_0/\beta)\langle n_f \rangle/n_{max}}, \quad (5.7)$$

$$\frac{T_r}{T_k} = \frac{T_b + (4T_0/\beta)\langle n_r \rangle/n_{max}}{T_k + (4T_0/\beta)\langle n_r \rangle/n_{max}}, \quad (5.8)$$

where $\beta = [1 - \exp(-\tau_0)]/\tau_0$, and $\langle n_f \rangle/n_{max}$ and $\langle n_r \rangle/n_{max}$ are given by,

$$\frac{\langle n_f \rangle}{n_{max}} = (1 - e^{-\tau_0})^{-1}\left[\frac{6}{\tau_0^3} - e^{-\tau_0}(1 + \frac{3}{\tau_0} + \frac{6}{\tau_0^2} + \frac{6}{\tau_0^3})\right], \quad (5.9)$$

$$\frac{\langle n_r \rangle}{n_{max}} = (1 - e^{-\tau_0})^{-1}\left[1 - \frac{3}{\tau_0} + \frac{6}{\tau_0^2} - \frac{6}{\tau_0^3}(1 - e^{-\tau_0})\right]. \quad (5.10)$$
5.3.2 Hill Model

In the “hill” model of De Vries and Myers (2005), \( J(T) \) increases linearly from the \( T_0 \) to \( T_p \) over a front optical depth (\( \tau_f \)), and then decreases from \( T_p \) to \( T_0 \) over a rear optical depth (\( \tau_r \)). The shape of a \( J(T) \) plot against \( \tau \) gives the model its name (Figure 5.6). As with the two-layer model, the front and rear sections, each with a line center optical depth (\( \tau_0 \)), are moving toward each other with an infall velocity \( v_{in} \), and have a velocity dispersion \( \sigma \).

![Figure 5.6](image_url)

Figure 5.6 A schematic demonstration of the Hill 1-D transfer model, which has an optional envelope of constant excitation temperature \( T_0 \) with an optical depth of \( \tau_F \) on the side close to the observer, and optical depth \( \tau_R \) on the far side of the observer. In the core of the hill model, \( J(T) \) rises linearly from \( J(T_0) \) to \( J(T_{pk}) \) over an optical depth \( \tau_f \) and linearly falls down from \( J(T_{pk}) \) to \( J(T_0) \) over an optical depth \( \tau_r \).

The line brightness temperature of the hill model is given by

\[
\Delta T_B = [J(T_p) - J(T_0)] \left[ \frac{1 - e^{-\tau_f}}{\tau_f} - \frac{e^{-\tau_f}(1 - e^{-\tau_r})}{\tau_r} \right] + [J(T_0) - J(T_b)](1 - e^{-\tau_f - \tau_r}) \tag{5.11}
\]

For a given choice of \( T_b \), the hill model has six adjustable free parameters: \( T_0, T_p, \tau_0, v_{LSR}, v_{in} \) and \( \sigma \). Equations 5.4 and 5.5 are used to determine \( \tau_f \) and \( \tau_r \).
5.3.3 Analytical Models with Outflow

While the two-layer and the hill models are able to reproduce the central portion of the observed blue-asymmetric line profile, they are not able to model the extended wings of the line profile observed beyond $\sim \pm 2\text{ km s}^{-1}$ (see Figure 5.7 and 5.8). In order to correctly model the entire line, we follow the approach used in the Myers et al. (1996) analysis of L1527 and incorporate a central outflow region into both the two-layer and hill models. The resulting variation of $T_{ex}$ with $\tau$ is shown schematically in Figure 5.10 and 5.11. The values of free parameters used in two-layer model and hill model is shown in Table 5.1 and 5.2

![Graph](image)

Figure 5.7 Best fit of IRAS 01202+6133 with two-layer model. Simple two-layer model is able to show the feature of blue-asymmetric infall line profile. However this model was not able to fit the width of two peaks and extended wings seen in the HCO$^+$ spectrum. The values of free parameters used in this two-layer model fit are shown in Table 5.1

<table>
<thead>
<tr>
<th>$\tau_0$</th>
<th>$T_k$ (K)</th>
<th>$V_{LSR}$ (km s$^{-1}$)</th>
<th>$V_{in}$ (km s$^{-1}$)</th>
<th>$\sigma$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>9</td>
<td>$-13.74$</td>
<td>0.02</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Figure 5.8  Best fit of IRAS 01202+6133 with Hill model. Hill model produces a better fit than the two-layer model with width of peaks and sharp absorption features. However hill model is not able to fit the extended wings seen in the HCO$^+$ spectrum either. To fit the extended wings, we needed to modify the two-layer and hill model. The values of free parameters used in this fit of the hill model are shown in Table 5.2

Table 5.2  Values of Best-fit Free Parameters of IRAS 01202+6133 with Hill Model

<table>
<thead>
<tr>
<th>$\tau_c$</th>
<th>$T_0$ (K)</th>
<th>$T_p$ (K)</th>
<th>$V_{LSR}$ (km s$^{-1}$)</th>
<th>$V_{in}$ (km s$^{-1}$)</th>
<th>$\sigma$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>4.4</td>
<td>10</td>
<td>$-13.74$</td>
<td>0.08</td>
<td>0.5</td>
</tr>
</tbody>
</table>

5.3.3.1 Two-layer Model with Central Outflow (2L-O Model)

With the addition of a central outflow region to the two-layer model the line brightness temperature (Equation 5.3) becomes,

$$\Delta T_B = J(T_f)[1-e^{-\tau_f}] + J(T_{out})[1-e^{-\tau_{out}}]e^{-\tau_f} + J(T_p)[1-e^{-\tau_p}]e^{-\tau_f-\tau_{out}} - J(T_b)[1-e^{-\tau_f-\tau_{out}-\tau_p}]$$

(5.12)

where $\tau_{out}$ and $T_{out}$ are the optical depth and excitation temperature of the outflow.

The only additional parameters needed in the 2L-O model are $\tau_{0,\text{out}}$ and $\sigma_{\text{out}}$, the line center optical depth and the velocity dispersion of the outflow region. Both are used to calculate $\tau_{out}$ using...
Figure 5.9  A schematic demonstration of the modified two-layer analytical transfer model(2L-O model). Along the line of sight, central “outflow” region added over optical depth $\tau_{out}$ to the existing two-layer. The temperature of the outflow region is assumed as the average of the temperature of rear-layer $T_r$ and front layer $T_f$.

\[
\tau_{out} = \tau_{0, out} \exp\left[-(v - v_{\text{LSR}})^2/2\sigma_{out}^2\right] \quad (5.13)
\]

In our model, we set $T_{out}$ equatl to the average of $T_r$ and $T_f$ calculated using $\tau_{0, out}$ in Equations 5.7, 5.8, 5.9, and 5.10 as appropriate.

As a test of our version of the 2L-O model, we were able to exactly match the model H$_2$CO ($J = 2 \rightarrow 1$) profile of L1527 shown in Figure 5.9 from Myers et al. (1996) using the outflow and model parameters given in the figure caption.

5.3.3.2  Hill Model with Central Outflow (Hill-O Model)

The brightness temperature of the hill model with a central outflow is

\[
\Delta T_B = (J_p - J_0) \left[ \frac{1 - e^{-\tau_f}}{\tau_f} - \frac{(1 - e^{-\tau_r})e^{-\tau_r-\tau_{out}}}{\tau_r} \right] + (J_0 - J_b)(1 - e^{-\tau_f-\tau_{out}-\tau_r}) \quad (5.14)
\]
Figure 5.10  A schematic demonstration of the modified hill analytical transfer model (Hill-O model). Along the line of sight, central “outflow” region added over optical depth $\tau_\text{out}$ between two linear $J(T)$. The temperature of the central outflow region is set to temperature $T_p$.

where $\tau_\text{out}$ is the optical depth of outflow. Since we set the excitation temperature of the outflow equal to $T_p$ (Figure 5.10). The only additional parameters are $\tau_0,\text{out}$ and $\sigma_\text{out}$. As in the 2L-O model, $\tau_\text{out}$ is calculated using Equation 5.14.

5.4 Results and Discussion

5.4.1 YSO Properties

We applied the 2L-O and the Hill-O models to our observed HCO$^+$ spectrum (Figures 5.11, 5.12 respectively). The best fit parameters are given in Tables 5.3 and 5.4. Uncertainties were derived using a Monte Carlo method; an initial best fit of the model was obtained, then random noise at the same level as the observed line profile was added to the best fit and the resulting simulated line profile was then fit, generating a new set of parameters.

The standard deviation of spectral line parameters after 1000 repeats was combined with the mean fit uncertainties to produce the final error estimates.
Figure 5.11  Best-fit of 2L-O model of IRAS 01202+6133. The model is able to fit the extended wings of the HCO$^+$ line, but as expected for a two-layer model, it has some trouble matching the line widths and the trough structure. The best-fit parameters are given in Table 5.3 and the systematic velocity of the YSO has been removed from this plot.

Table 5.3  The Values of Best-fit Free Parameters of 2L-O Model of IRAS 01202+6133

<table>
<thead>
<tr>
<th>$\tau_0$</th>
<th>$T_K$ (K)</th>
<th>$V_{LSR}$ (km s$^{-1}$)</th>
<th>$V_{in}$ (km s$^{-1}$)</th>
<th>$\sigma_{NT}$ (km s$^{-1}$)</th>
<th>$\tau_{out}$</th>
<th>$\sigma_{out}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11$\pm$0.2</td>
<td>9.5$\pm$0.15</td>
<td>-13.74$\pm$0.01</td>
<td>0.02$\pm$0.003</td>
<td>0.4$\pm$0.01</td>
<td>0.35$\pm$0.01</td>
<td>2.3$\pm$0.03</td>
</tr>
</tbody>
</table>

As noted by Myers et al. (1996), the two-layer model tends to output profiles that have narrower peaks and flatter central troughs than observations, and both of these characteristics can be seen in the 2L-O best-fit model shown in Figure 5.11. In contrast, the Hill-O model does a much better job in fitting the observed peak widths and the structure of the central absorption trough (Figure 5.12).

De Vries and Myers (2005) showed that hill-style models were able to obtain accurate estimates of infall velocities (rms error 0.01 km s$^{-1}$) from two-peak profiles, in contrast with two-layer models, which tended to underestimate the infall velocity by factors of $\sim$2. Consistent with this finding, we see that the best-fit 2L-O $V_{in}$ is a factor of 3.5 lower than the Hill-O value. While we adopt the numerical results of the Hill-O model for
Figure 5.12  Best-fit Hill-O model. The model is able to fit the extended wings of the 
HCO$^+$ line and has a better fit to the central portions of the line profile 
compared to the 2L-O model. The best-fit parameters are given in Table 5.4 
and the systematic velocity of the YSO has been removed from this plot.

Table 5.4  The Values of Best-fit Free Parameters of Hill-O Model of IRAS 01202+6133

<table>
<thead>
<tr>
<th>$\tau_r$</th>
<th>$T_0$</th>
<th>$T_p$</th>
<th>$V_{LSR}$</th>
<th>$V_{in}$</th>
<th>$\sigma$</th>
<th>$\tau_{out}$</th>
<th>$\sigma_{out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>3.2</td>
<td>7.7</td>
<td>-13.74</td>
<td>0.07</td>
<td>0.47</td>
<td>0.32</td>
<td>2</td>
</tr>
<tr>
<td>±0.1</td>
<td>±0.22</td>
<td>±0.13</td>
<td>±0.01</td>
<td>±0.012</td>
<td>±0.02</td>
<td>±0.03</td>
<td>±0.06</td>
</tr>
</tbody>
</table>

IRAS 01202+6133, we note that regardless of the exact numeric values, both the 2L-O 
and Hill-O results are consistent with an object with a substantial envelope ($\tau_0 \sim 10$) 
undergoing slow infall ($V_{in} \ll \sigma$).

5.4.2 Formation Scenarios

There are two basic scenarios for the formation of IRAS 01202+6133; either its forma-
tion was triggered by the action of the expanding H II region, or it formed spontaneously 
and its proximity to the H II region is coincidental.

To gauge the likelihood of the first scenario, we can first look at the various time 
scales associated with the YSO–H II region system. The canonical duration of the Class
I stage of YSO evolution is of the order of $10^5$ years (Ward-Thompson, 2002). The fact that IRAS 01202+6133 still has a substantial envelope and exhibits slow infall suggests that it is still a fairly young Class I YSO. The presence of outflow motions does not constrain the age as they are known to be associated with even the very earliest stages of YSO evolution (Andre et al., 1993). Assuming that any Class 0 stage would be very rapid ($\sim 10^4$ years), we conclude that the age of the YSO is $\tau_{YSO} \leq 10^5$ years. KR 120 is a fairly young H II region; Joncas et al. (1992) estimated an age of $\tau_{HII} \approx 1 - 2 \times 10^5$ years based on kinematic and photodissociation region models for the region. So it appears that a necessary condition for triggered formation, that $\tau_{YSO} < \tau_{HII}$, is satisfied in this case.

As mentioned in section 5.1, triggered star formation around H II regions can arise from the overpressurization of existing cores or through the collapse of swept up layers of material. To investigate the latter “Collect and Collapse” scenario, we used the equation from Whitworth et al. (1994) giving the timescale at which fragmentation and collapse will occur in a swept-up shell around an expanding H II region:

$$t_{\text{fragment}} \approx 1.56 \text{ Myr} \left[ \frac{a_s}{0.2 \text{ km s}^{-1}} \right]^{7/11} \left[ \frac{Q_0}{10^{49} \text{ photons s}^{-1}} \right]^{-1/11} \left[ \frac{n_0}{1000 \text{ cm}^{-3}} \right]^{-5/11} \quad (5.15)$$

where $a_s$ is the sound speed of the molecular cloud, $Q_0$ is the H I ionizing flux, and $n_0$ is the density of the molecular cloud. The exciting star of KR 120 is B0 V (Arvidsson and Kerton, 2011) corresponding to $Q_0 = 10^{47.4}$ photons s$^{-1}$ using the Crowther (2005) calibration. For $n_0$, we use the value $n_0 = 1000 \text{ cm}^{-3}$ from Joncas et al. (1992). A fragmentation collapse timescale is approximately between 2 Myr with sound speed $a_s = 0.2 \text{ km s}^{-1}$ (for very cold molecular clouds) and up to a 6 Myr as a upper limit with $a_s = 1 \text{ km s}^{-1}$ (for warm molecular/neutral clouds). Since this fragmentation timescale is 10 times longer than $\tau_{HII}$, we can eliminate the “collect and collapse” triggered star formation scenario.

The morphology of the molecular cloud surrounding KR120 (see Figure 5.4.2) is consistent with the alternative scenario of the triggered collapse of pre-exsiting molecular
Figure 5.13 Molecular cloud of KR 120. The image is $^{12}\text{CO} \ (J = 1 \rightarrow 0)$ emission from the Outer Galaxy Survey (Heyer et al., 1998) integrated between $-20.4 < V_{\text{LSR}} < -5.6 \ \text{km s}^{-1}$ (contours at 20, 30, 40, 50, and 60 K km s$^{-1}$). The position of KR 120 is shown by the red contour at $T_{1420} = 8 \ \text{K}$, and the position of IRAS 01202+6133 is indicated by the cross.

core. The highest column density gas (e.g., $T_B > 50 \ \text{K km s}^{-1}$), where one would expect to find molecular cloud cores, lies in a ridge to one side of the H II region. In this picture, a shock front being driven into this gas by the expanding H II region has overrun and compressed a pre-existing core initiating the star formation process (Bertoldi, 1989; Thompson et al., 2004).

We cannot rule out a spontaneous star formation scenario; it is possible that the YSO happened to form at the correct distance from the exciting star of KR 120 that now lies on the edge of the expanding H II region. On balance, though, we prefer the triggered scenario as it naturally explains the close spatial association of the H II region and the very young Class I YSO.
5.5 Conclusion

1. Our analysis of the HCO$^+$ ($J = 3 \rightarrow 2; 267.6$ GHz) and H$^{13}$CO$^+$ ($J = 3 \rightarrow 2; 260.3$ GHz) spectra of the submillimeter/IR source IRAS 01202+6133 shows that the blue-asymmetric HCO$^+$ line profile is almost certainly due to infall motions.

2. We have modified the analytic radiative transfer models of Myers et al. (1996) and De Vries and Myers (2005) to allow for fitting of submillimeter/millimeter line profiles that have both selfabsorption features and optically thin wings. We applied these models to our HCO$^+$ submillimeter spectrum of IRAS 01202+6133 and conclude that it is a young Class I YSO with a substantial envelope undergoing slow infall.

3. Based on its young evolutionary state ($\tau_{\text{YSO}} < \tau_{\text{HII}}$) and its proximity to the H II region KR 120 (Sh 2-187), we think that the formation of IRAS 01202+6133 was triggered by the expansion of the H II region. However, due to the young age of the H II region, a “collect and collapse” scenario is ruled out.
CHAPTER 6. SUMMARY AND FUTURE WORK

6.1 Summary

A main topic of this dissertation is identifying and classifying YSOs in the four small galactic H II regions and trying to figure out star-formation scenarios based on their spatial distribution and population ratios between classes of YSOs. These small H II regions have common properties in order to we choose them as samples; they are isolated from giant molecular cloud and single-star powered H II regions, thus the effects and complexity of feedback from multiple massive O or B type stars are minimized. In addition to this, these are quite young H II regions based on their size and morphology. Thus, these are excellent regions where to study the interaction of H II regions with surrounding molecular gas.

By combining multiwavelength observations such as near-infrared from 2MASS, mid-infrared from WISE, and submm observation from JCMT, we are able to identify hundreds of young stellar objects in each small H II region. We analyzed spectral energy distribution to identify the class of YSOs with two different methods – analyzing color-color diagram and spectral index ($\alpha$).

We obtained archival WISE data from AllWISE catalog of four small H II regions in near- and mid-infrared wavelength ($K_s$, 3.4 $\mu$m, 4.5 $\mu$m, 12 $\mu$m and 24 $\mu$m). Using a newly developed YSO classification scheme for WISE observation introduced by Koenig et al. (2012), modified from Gutermuth et al. (2009) for Spitzer observation, to identify YSOs and remove all the extragalactic contamination, we have studied the distribution
of YSOs within each region. These distributions lead us to conclude that in almost every case, a small H II region will have multiple stages of star formation within it. The latter generations that began to form recently are YSOs classified as Class I. These YSOs may have spontaneously formed or triggered by the expansion of the H II region. We argue from the averaged distribution of the YSOs that the triggered star-formation mode is more strongly supported, but in the KR 140 region there could be a mix of triggered star-formation around the photodissociated region and spontaneous star-formation along the filament located to the east of KR 140.

We also have developed existing 1-D radiative transfer model to reproduce the line profiles having infall asymmetry features, that have blue-shifted shape of infall motion indicative of contracting motion of YSOs. With the optically thick HCO$^+$ ($J = 3 \rightarrow 2$) and optically thin H$^{13}$CO$^+$ ($J = 3 \rightarrow 2$) line observations from JCMT 850 $\mu$m of the massive submm/IR source IRAS 01202+6133 located in the periphery of KR 120, we confirm that this submm/IR source has a self-absorption and infall motion as optically thin H$^{13}$CO$^+$ peak at the position where optically thick HCO$^+$ self-absorption feature arises. Existing 1-D radiative transfer models — Two layer model and Hill model,— were not able to fit both the self-absorption feature and optically thin wings at the same time. Thus, by introducing the parameter of central outflow, we have modified those existing 1-D analytic radiative transfer models — 2L-O and Hill-O model—to allow for the fitting of self-absorption features and optically thin wings at the same time. We conclude that this submm/IR source is a young Class I YSO with a substantial envelope undergoing slow infall and having some outflow motions. The young age of the H II region rules out a “collect and collapse” mode of triggered star formation and suggests instead that subsequent generation of YSOs formed spontaneously, or was triggered by the expansion of the H II region. While we cannot eliminate the possibility that this submm/IR source formed spontaneously at its current location, considering its early evolutionary state and
its proximity to the H II region, we think that the star formation of IRAS 01202+6133 was triggered by the expansion of KR 120 (Sh 2-187).

6.2 Future Work

6.2.1 Transition Disk Problems

From the results described in Chapter 4, we found many more Transition Disks than we expected for each region. We suspect that many of these Transition Disks could be fake sources due to the contamination of the AllWISE point-source catalog itself. The original science mission of WISE is to study infrared-bright galaxies, to find brown dwarfs, and to study near-Earth asteroids, and was not designed to study star formation. The Spitzer IRAC 3.6 and 4.5 μm and MIPS 24 μm images are a close match to WISE bands 1, 2 and 4. The IRAC 8μm band is not an exact match to WISE band 3 at 12 μm, but is close enough in wavelength that bright point sources in these Spitzer images are similarly evident in WISE 12 μm images, allowing us a determination if an apparent WISE band 3 point source is in fact a nebular emission knot when seen at the higher resolution and sensitivity of Spitzer.

In the Galactic plane, star-forming regions contain bright, structured emissions from PAH molecules and dust grains excited and heated by radiation from nearby and embedded YSOs (Li and Draine, 2001), and extinction features like infrared dark clouds. Even though WISE is very useful because it is a survey of 99% of all the sky, AllWISE catalog still contains many fake sources because of the reasons we discussed earlier. Therefore, to maximize usage and increase the accuracy of the AllWISE catalog to study star-formation, we need to find methods to eliminate or minimize the fake sources from the AllWISE catalog. Koenig and Leisawitz (2014) tried to deblend fake sources from the AllWISE catalog using $\chi^2$ value and signal to noise of each band. Figure 6.1 shows their process to filter spurious or fake sources using $\chi^2$ value and signal to noise of each band.
However, in band 3 and band 4 from Figure 6.1, many real sources (red dots) are still eliminated for low $\chi^2$ values with decent signal to noise ($5 < S/N < 10$). Thus, we need to modify and find a method to minimize the elimination of real sources in order to make maximize use of AllWISE catalog for studying star formation. We believe if we can get more completeness from the AllWISE catalog, it will dramatically reduce the number of Transition Disks in each H II regions and will increase the accuracy of WISE color-color diagram becomes a powerful tool for classifying YSO.
6.2.2 1-D Radiative Transfer Model for all Submm/IR source in Four H II Regions.

In Chapter 5 we used only one submm source IRAS 01202+6133 from KR 120 for modifying 1-D radiative transfer model. We have chosen this source for modeling because it has a very clear blue asymmetric classical infall line of HCO\(^+\) \((J = 3 \rightarrow 2)\) along with an optically thin wing shape. We also have available HCO\(^+\) \((J = 3 \rightarrow 2)\) data for submm sources in other KR regions from James Clerk Maxwell Telescope (JCMT). HCO\(^+\) \((J = 3 \rightarrow 2)\) line profile from those submm sources didn’t have the clear feature of a line profile with infall motion so they were not appropriate for developing new 1-D radiative transfer model. Since we developed an existing 1-D radiative transfer model using IRAS 01202+6133, we can apply this new model to other submm line profiles in order to get good fits from the relevant parameter values. In addition to that, we are going to get new data of the submm sources in KR regions with the Submillimeter Array (SMA) or Taeduk Radio Astronomy Observatoru (TRAO) in South Korea so we can compare the line profile from JCMT.

6.2.3 Color-Color Diagram with CFHT data

The 3.6 meter Canada France Hawaii Telescope (CFHT) deep \(J, H, K_s\) band photometry has been obtained for the regions KR 7, KR 81, KR 120 and KR 140. CFHT data are much higher resolution than 2MASS and better photometry is available as deep as \(K_s\) band magnitude 18 which is two magnitudes over 2MASS. When we analyzed KR regions in Chapter 4, we used 2MASS data set to cross check with a WISE only data set. However, if we can use CFHT data rather than 2MASS, we might be able to find additional or deeply embedded class I sources that might not be classified with WISE color-color diagram.

Other than CFHT, better photometry will be obtained for all four KR H II regions and their surrounding molecular cloud. GLIMPSE360 will be available for those KR regions.
GLIMPSE360 is a survey part of Spitzer “Warm Mission”, which will be available for 3.6 μm and 4.5 μm only. Combining CFHT $J, H, K_s$ and GLIMPSE360 3.6 μm and 4.5 μm photometry can give us a better tool for identifying and classifying YSOs from KR regions.
BIBLIOGRAPHY


