1. INTRODUCTION

A full census of the young stellar object (YSO) population in star-forming regions is essential for accurately calculating statistical properties such as the star formation rate (SFR) and lifetimes of YSOs in different evolutionary stages, which are fundamental parameters for assessing the physical mechanism of global star formation. The idea that SFR should be related to gas surface density was first proposed by Schmidt (1959) and the relation is measured in a galaxy sample by Kennicutt (1998), which is known as the Kennicutt–Schmidt relation. To examine this relation in our galaxy, Evans et al. (2009) count the numbers of YSOs in giant molecular clouds (GMCs) and assume a mean mass and formation timescale for these YSOs. They find that their measured SFRs are higher than that indicated by the Kennicutt–Schmidt relation and claim that this is because the SFR decreases exponentially versus the viral parameter for a magnetic-field-dominated scenario while the SFR decreases exponentially versus the viral parameter for a turbulence-dominated scenario. Here we attempt to obtain an accurate SFR as possible by developing a new YSO census method. In addition, a better census method will provide better estimates in the lifetimes of YSOs in different evolutionary stages, which are usually estimated by comparing the fractions of YSOs in each stage, and successful theories should be able to explain the observed SFR scales.

The Spitzer Space Telescope (Werner et al. 2004) provides high-sensitivity surveys with the Infrared Array Camera (IRAC) at 3.6, 4.5, 5.8, and 8.0 μm (Fazio et al. 2004) and the Multiband Imaging Photometer (MIPS) at 24, 70, and 160 μm (Rieke et al. 2004), which allow us to search for YSOs in star-forming regions. Identifying YSOs is usually achieved by removing stars and background galaxies from the data (Young et al. 2005; Harvey et al. 2007a; Rebull et al. 2007, 2010). Stars can be easily selected by fitting spectral energy distributions (SEDs) with a reddened stellar atmosphere. However, the SED morphologies of galaxies are very similar to those of YSOs at infrared wavelengths (Harvey et al. 2006), and Spitzer can detect a substantial amount of background galaxies because of its high sensitivity. Therefore, separating background galaxies and YSOs becomes a difficult problem. Several methods have been developed to identify YSOs from molecular clouds (Harvey et al. 2007a; Gutermuth et al. 2005; Rebull et al. 2010) using Spitzer data. These methods identify YSOs by eliminating background galaxies based on comparing the distributions of the observed data with galaxy data in color–color diagrams (CCDs) and color–magnitude diagrams (CMDs). However, there are no obvious boundaries between YSOs and galaxies in CCDs and CMDs. Hence, based on different considerations, different
works use different sets of CCDs and CMDs and set their own boundaries in CCDs and CMDs to identify YSOs. Therefore, sources located close to the boundaries are possibly classified as different objects using different methods.

A large YSO survey of five nearby molecular clouds has been conducted by the Spitzer Legacy Project “From Molecular Cores to Planet Forming Disk” (c2d; Evans et al. 2003). The c2d project used an un-normalized galaxy probability (Harvey et al. 2007a) to eliminate possible galaxies and identify YSO candidates (YSOc) from the five clouds. (In this paper, YSOc is used for sources selected by our method or the c2d project, which may or may not be confirmed as true YSOs by other studies.) This galaxy probability is primarily calculated from the locations of sources in three CMDs by comparing them to the Spitzer Wide-Area Infrared Extragalactic Survey (SWIRE) data (Lonsdale et al. 2003), which contain a negligible amount of YSOs because the observations were taken at a high galactic latitude. Since this galaxy probability was calculated only for sources detected in all IRAC bands and MIPS1 (24 μm), the c2d YSO catalog may miss faint YSOs, which are undetected in one or more of the five bands. In this paper, we develop a new YSO identification method and apply it to the five c2d surveyed molecular clouds, providing a more complete YSO catalog in these clouds.

With a relatively complete YSO sample, we will be able to identify more very low luminosity objects (VeLLOs), which are defined as protostars with an internal luminosity, $L_{\text{int}}$, smaller than 0.1 $L_\odot$. The first VeLLO, L1014-IRS, was observed by Young et al. (2004). Dunham et al. (2008) then designed a set of color criteria and also used the c2d galaxy probability to select faint Class 0 and early Class I sources as VeLLO candidates. The faint nature of VeLLOs suggests that they could be either very young protostars or very low mass protostars, but recent works have shown that the low luminosity can be explained by protostars in the quiescent phase of episodic accretion processes (Dunham et al. 2010). To identify more VeLLOs, Dunham et al. (2008) use the galaxy probability from the c2d project and adopt a higher cutoff, which allows them to find more faint sources; the galaxy probability is calculated based on the general fact that the galaxies are faint (Dunham et al. 2008; Harvey et al. 2007a). However, the change in cutoff may result in higher galaxy contamination and more analyses are essential for confirming those VeLLOs of Dunham et al. (2008). Therefore, a method that identifies faint YSOc naturally may help to reduce galaxy contamination.

We develop a new method, the multi-dimensional (multi-D) method, to identify YSOs naturally. While a CMD (magA, magB-magC) contains only information from the three consisting magnitudes, the multi-D magnitude space contains all the information of the consisting magnitudes. We treat the number distribution of our galaxy sample in the multi-D magnitude space as galaxy probability distribution, and sources located in the region without galaxies are classified as YSOc. We apply this method to the five c2d surveyed clouds, and the number of YSOc sampled is increased by a factor of 28%. Therefore, the SFRs we calculated in this work are 28% larger than that calculated by Evans et al. (2009) due to the increased number of YSOc, but the lifetimes of YSOs in different evolutionary stages remain unchanged due to the similar ratios between different stages of newly found YSOc. We describe the data we used in Section 2 and our YSO identification method in Section 3. In Section 4, we discuss how reliable our new YSOc are. The statistical analysis and discussion are presented in Section 5 and the conclusions are summarized in Section 6.

### 2. DATA

The data we used in this paper are from two Spitzer Legacy Projects, c2d and SWIRE. The c2d project observed five nearby molecular clouds and the SWIRE project observed extragalactic fields that contain a negligible amount of YSOs. Our aim is to identify YSOs from the c2d data by comparing them to the SWIRE data in the multi-D magnitude space.

#### 2.1. c2d Data

Perseus, Serpens, Ophiuchus, Lupus (I, III, and IV), and Chamaeleon II have been observed by the c2d project in the IRAC1–4 (3.6, 4.5, 5.8, and 8.0 μm) and MIPS1–3 (24, 70, and 160 μm) bands. Hereafter, we use IR and MP to represent IRAC and MIPS, e.g., IR1 as IRAC1. All data are processed with the c2d standard pipeline and these processes are described in the c2d data delivery document in detail (Evans et al. 2007). The pipeline extracts point sources from images at all bands and performs photometric measurements. The Spitzer photometry data are merged with Two Micron All Sky Survey (2MASS) data (J, H, Ks bands) into source catalogs using a 2′′ matching radius. These source catalogs and images are released in the Spitzer Heritage Archive. Detailed studies of individual clouds using these catalogs have been presented in several papers (e.g., Perseus: Jørgensen et al. 2006; Serpens: Harvey et al. 2007a; Ophiuchus: Padgett et al. 2008; Lupus: Merín et al. 2008; Chamaeleon II: Porras et al. 2007). Two kinds of catalogs, FULL and HREL (high reliability), are provided by the c2d project. FULL catalogs include all detected sources, but some of them could be false detections misidentified by the automated photometry processes. Sources in HREL catalogs have to be detected in one band with S/N $> 7$ accompanied by a detection in another band with S/N $> 5$. In this paper, we select YSOc only from HREL catalogs in order to avoid false sources.

We adopt the photometry results from the c2d catalogs for our analysis. Source fluxes in the c2d catalogs are measured with a point-spread function (PSF) fitting. An important factor, image type (imtype), is used to indicate the quality of the PSF fitting. Sources that can be well fitted with the PSF are assigned imtype $= 1$ and sources with imtype $\neq 1$ have high uncertainty in photometry resulting from a low signal-to-noise ratio (S/N), extended size, or non-circular shape, etc. (Evans et al. 2007). For example, imtype $= 7$ indicates that the S/N is too low to be tested for shape, and we found that it is mostly due to confusion from the surrounding cloud structure. Therefore, we will check the images that have sources with imtype $\neq 1$ to determine whether they are real sources (see Section 3).

#### 2.2. SWIRE Data

The SWIRE data used in this work are the same data used by Harvey et al. (2007a), which were processed with a c2d pipeline to eliminate the systematic uncertainty introduced from different data reduction processes. Therefore, it can be used fairly as a comparison with the c2d data. The SWIRE data used here are from the observations toward the ELAIS N1 extragalactic field, which is at high latitudes ($b \sim 4^\circ$), and the observed field has a coverage of 5.3 deg$^2$ using both IRAC and MIPS. Since the YSOs are concentrated in the Galactic plane, there should be almost no YSOs in the SWIRE region. In order to acquire a galaxy sample as pure as possible, we removed the stars in...
the SWIRE data using the same method as that for c2d data (Section 3.2). Thus, it can be used to represent a full collection of the SED features of background galaxies.

3. YSO IDENTIFICATION

3.1. Selection Process

Our YSO identification procedure is shown in Figure 1 and described below. Basically, this process identifies YSOc by eliminating the non-YSO sources.

1. The main-sequence stars were first removed by SED fitting. The fitting process is the same as that in Harvey et al. (2007b) and Evans et al. (2007), which select stars with reddened stellar atmosphere SED templates. The extinction law with $R_V = 5.5$ from Weingartner & Draine (2001) is used to obtain the best fit extinction value, $A_V$. The Weingartner & Draine $R_V = 5.5$ model is suggested as a good description for dusts in dense molecular clouds (Chapman et al. 2009).

2. Giant stars were removed using a CCD, IR2 – IR3 versus IR3 – MP1 (Figure 2), as described in Section 3.3.

3. Since our galaxy sample (SWIRE) is observed from regions with negligible extinctions, we de-reddened the whole c2d catalog in order to compare it with our galaxy sample. We use the same computer program developed by the c2d project (Evans et al. 2007) to construct the extinction maps from the extinction of background stars. The average errors of all pixels in each extinction map are 0.03–0.05 mag for each cloud. Sources in the c2d catalog are then de-reddened according to the extinction value of their position in the map. We use the de-reddened fluxes in this paper except for the analysis with $\alpha$ (Section 5.3.2).

4. We found that some sources labeled as “U” (undetected) for MP1 in the c2d catalog are in fact saturated. Since bright MP1 flux makes the source move away from the galaxy-populated region in the multi-D array, we believe that these sources are very young YSOs rather than galaxies. Therefore, we classify these MP1-saturated sources as YSOc. To find the saturated sources, we search all sources labeled as “U” at MP1 with a pixel value larger than 800 MJy sr$^{-1}$ within the 7″66 radius. The cutoff of 800 MJy sr$^{-1}$ was determined from experience. By checking the pixel values around many saturated sources, we found that 800 MJy sr$^{-1}$ was small enough for us to pick up all saturated sources, but not too small for us to obtain too many false sources. The 7″66 radius is the 3σ radius of MP1 PSF. Then, we examine the images of selected sources by eye to confirm whether they are indeed saturated sources and the excess bright flux

Figure 1. YSO identification process. Sources consistent with the criteria in the block will enter the block connected by the “Y” arrow and those that are inconsistent will follow “N”.

### Diagram

```
    HREL catalog
         |   Y
    Star removal (Step 1)  |   N
          |   Y
    Extinction correction (Step 2)  |   N
          |   Y
    Giant star Removal (Step 3)  |   N
          |   Y
    MP1 saturate sources  |   N
          |   Y
    MP1 saturate (Step 4)  |   N
          |   Y
    Gal prob 1 > 1 and Gal prob 2 > 1 (Step 5)  |   N
          |   Y
    Gal prob 1p > 1 and Gal prob 2p > 1 (Step 6)  |   N
          |   Y
    IR 1 Image check (Step 7)  |   N
          |   Y
    YSO candidates (Step 8)  |   N
```

Problem objects  |   Y
              |   N
Image check (Step 6)  |   N
Gal prob 1 > 1 and Gal prob 2 > 1 (Step 5)  |   N
is indeed from a saturated source and not from a bad pixel. The typical images of saturated sources are PSF-like with saturated holes (no values or low values) in the center and bright rings around the center.

5. To eliminate background galaxies, many multi-D arrays are constructed by the SWIRE data to calculate the smoothed galaxy density. According to the location of the c2d sources in the multi-D arrays, we calculate four galaxy probabilities: Gal prob 1, Gal prob 2, Gal prob 1p, and Gal prob 2p, where Gal prob 1 and Gal prob 2 are the galaxy density in (J, K s, IR2, IR4, and MP1) and (IR1, IR2, IR3, IR4, and MP1) arrays or their subarrays (see Section 3.2 for details), and Gal prob 1p and Gal prob 2p are the galaxy density from the arrays discounting the bands with imtype $\neq 1$. Sources with both Gal prob 1 and 2 $\geq 1$ are classified as galaxy candidates and removed.

6. The remaining sources have Gal prob 1 $< 1$ or Gal prob 2 $< 1$, and thus are potential YSOs. Images of sources with Gal prob 1 (2) $< 1$ but Gal prob 1p (2p) $\geq 1$ (meaning an unreliable detection would affect its galaxy probability) are examined by eye. Sources with unreliable photometry such as jet knots or cloud structures are removed (see Section 3.2).

7. For all the remaining sources, we also check the IR1 images to eliminate nearby resolved galaxies, which can be bright and thus have a low galaxy probability. Eleven nearby galaxies are removed through this process.

8. The remaining sources are classified as YSOs.

3.2. Multi-D Array Construction and Galaxy Probability Calculation

The heart and soul of our new method is to use the galaxy density in the multi-D space as an indicator of the "galaxy probability"; anything outside of the galaxy populated region would have a galaxy density smaller than 1 and thus will be selected as YSOs. We assume that the SWIRE data are large enough to contain a complete set of galaxy samples. Note that our "galaxy probability" here is not a real probability for a source to be a galaxy; it is in fact an un-normalized number that indicates how many galaxies are near a specific position in the multi-D space. In this section, we describe the details for constructing the multi-D space and defining the galaxy probabilities.

The data we used contain 10 bands ($J, H, K_s, IR1, IR2, IR3, IR4, MP1, MP2$, and MP3). Although a high-dimensional array includes more information than that of a low-dimensional array, the maximum dimension of the data array we can handle is limited by our computing resource. If we want to calculate the galaxy probability from all 10 band data using a ten-dimensional array, our computer will need a random access memory of $\sim 10^8$ GB (with the cell sizes we choose, see below), which largely exceeds the limitation of our computer. Therefore, we choose to analyze our data with two five-dimensional main arrays constructed from bands that can represent the main SED features; one contains $J, K_s, IR2, IR4$, and MP1 bands (corresponding to Gal prob 1) and the other contains all IR1–4 and MP1 bands (corresponding to Gal prob 2). MP2 and MP3 bands are excluded due to their low detection numbers and their poor angular resolutions ($18'$ and $40'$, respectively).

The J–MP1 array covers the widest range of wavelengths and the IR1–MP1 array is designed for selecting YSOs that have no 2MASS detections. The IR1–MP1 array is necessary for identifying young embedded YSOs since they are very faint at short wavelengths and are often undetected in 2MASS bands.

Because the galaxy locations are discrete in the multi-D arrays, we need to carefully choose the cell size and also employ a smoothing process to produce a smoothed galaxy distribution so that the galaxies that fall in between SWIRE sources will not be classified as YSOs. We find that using a cell size of 0.2 mag for all bands is adequate for our data. We smooth the data using multi-D Gaussian beams with a peak value of 1, a standard deviation of $\sigma = 2$ cells (0.4 mag) in every dimension, and an outer cutoff at a radius of 7 cells. The galaxy probability for a source located at $(x_1, x_2, x_3, x_4, x_5)$ is defined as the total number of galaxies, $A(x_1, x_2, x_3, x_4, x_5)$, after being smoothed with multi-D Gaussian beams,

$$
A_{\text{smooth}}(x_1, x_2, x_3, x_4, x_5) = \sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \sum_{\ell} A(x'_{1i}, x'_{2j}, x'_{3k}, x'_{4l}, x'_{5m}) e^{-\left(\frac{(x_1-x'_{1i})^2}{\sigma_1^2} + \frac{(x_2-x'_{2j})^2}{\sigma_2^2} + \frac{(x_3-x'_{3k})^2}{\sigma_3^2} + \frac{(x_4-x'_{4l})^2}{\sigma_4^2} + \frac{(x_5-x'_{5m})^2}{\sigma_5^2}\right)},
$$

$$
(x_1 - x'_{1i})^2 + (x_2 - x'_{2j})^2 + (x_3 - x'_{3k})^2 + (x_4 - x'_{4l})^2 + (x_5 - x'_{5m})^2 \leq 49,
$$

Therefore, Gal prob 1 = $A_{\text{smooth}}(J, K_s, IR2, IR4, and MP1)$ and Gal prob 2 = $A_{\text{smooth}}(IR1, IR2, IR3, IR4, and MP1)$. If a galaxy is surrounded by other galaxies, the galaxy’s probability should be larger than the peak value of the smoothing beam, which is 1, because the smoothing process will accumulate a number of galaxies from nearby cells. Therefore, the surface with galaxy probability $= 1$ is expected to enclose the galaxy-populated region in the multi-D magnitude space except for isolated galaxies. For an isolated galaxy, its galaxy probability will be 1. Out of 135,400 SWIRE galaxies, there are only three galaxies with a Gal prob 1 equal to 1 and no galaxies with a Gal prob 2 equal to 1, which indicates that the galaxy sample is well smoothed in the multi-D arrays. Therefore, sources located out of the smoothed galaxy distribution will have a galaxy probability $< 1$ and can be classified as YSOs.

![Figure 2. Giant star selection criteria. Green points are the SWIRE data excluding stars, and red points are giant stars in Serpens identified by Oliveira et al. (2009). Sources located in the region below the dashed line are classified as YSOs.](Image)
Figure 3. Reducing beam size from two dimensions to one dimension. The two circles indicate the beam size in two dimensions and the two half-ellipses indicate the projected beam size in one dimension. The “galaxy probability” along the diagonal dashed line in two dimensions will be the same as that along the x-axis in one dimension if a reducing beam length of $\sqrt{3/2}\sigma$ is applied. (A color version of this figure is available in the online journal.)

Since a large number of sources are not detected in all five bands of these two five-dimensional arrays, for these sources, Gal prob 1 and Gal prob 2 are calculated from three- and four-dimensional subarrays instead. Thus, sources with detections in three to five of the five bands for Gal prob 1 are assigned Gal prob 1 calculated from three- to five-dimensional magnitude arrays, respectively, and the same for Gal prob 2 (the detection threshold is set to $S/N = 2$). As a result, 15 subarrays (5 four-dimensional and 10 three-dimensional subarrays) for each five-dimensional array are constructed. The array cell size and/or the smoothing lengths of the subarrays need to be modified because the galaxy distribution is condensed from five dimensions to three or four dimensions and thus the number of galaxies in a three-dimensional or a four-dimensional array cell is much larger than that in a five-dimensional array cell. However, it is very difficult to make the galaxy probability of each source the same in different dimensions and fairly compare them in different dimensions. Therefore, we modified the smoothing beam to make the threshold for the galaxy probability, 1, a reasonable number for separating YSOc and galaxies in arrays with different dimensions. Here we demonstrate the principle of beam size modification in the case of two dimensions to one dimension. We assume that there are very few galaxies close to the surface of the galaxy-populated region where the galaxy probability is $\sim 1$. Considering two galaxies located near the surface and along the diagonal direction, we find that the galaxy probability profile in one dimension is exactly the same as that in two dimensions along the diagonal direction if we reduce the standard deviation of the Gaussian beam in two dimensions by a factor of $\sqrt{1/2}$ (Figure 3). Therefore, we use the standard deviation $\sigma$ of $\sqrt{3/5} \times 2$ cells (the $\sigma$ in five-dimensional array is 2 cells) for the three-dimensional arrays and $\sqrt{4/5} \times 2$ cells for the four-dimensional arrays, and we keep the cell size unchanged. This modification will produce a similar galaxy probability distribution in the regions close to the boundary of galaxy-populated regions for arrays with different dimensions; thus, the same threshold for the galaxy probability (i.e., 1) can be used to identify YSOc.

We found that a lot of sources with PSF fitting flag “imtype $\neq 1$” (Section 2.1) have contaminated flux measurements due to jet knots, nearby bright sources, and an extended cloud structure, which may change the locations of the sources in the multi-D arrays. Thus, we define Gal prob 1p and Gal prob 2p, which are calculated from subarrays using only the detections with imtype = 1 (well fitted as a point source), and use them along with Gal prob 1 and Gal prob 2 to separate YSOs and galaxies. Since imtype = 1 indicates that the source has a more precise flux measurement, a source with Gal prob 1p (or 2p) $< 1$ implies that this source is located out of the galaxy-populated region in the multi-D space with high confidence. If a source has Gal prob 1 (or 2) $< 1$ but Gal prob 1p (or 2p) $> 1$, it is obvious that the bands with imtype $\neq 1$ cause the sources to deviate from the galaxy-populated region. For these sources, images of IR1–IR4 and MP1 bands are examined by eye. If a reliable point source is found in the images at bands with imtype $\neq 1$, the calculated Gal prob 1 (or 2) that contains these bands is reliable and the sources are classified as a YSOc. A large number of examined sources were found to have an unreliable photometry measurement (70%–90% for different clouds) due to jet knots, nearby bright sources, and an extended cloud structure, and are removed from our YSOc list.

### 3.3. Giant Star Contamination

Giant stars could be bright and have SEDs similar to Class II/III YSOs in the infrared (Oliveira et al. 2009), and thus are very difficult to identify using only IRAC and MIPS data. We are not able to exclude the giant stars by finding the natural boundary of them in the multi-D array because the giant star sample is too small to represent a full collection of the SED features. From the SWIRE data, we found that there are 30 bright sources that are not grouped with the majority of the SWIRE sources in the (IR2–IR3, IR3–MP1) CCD. Because we think that the SWIRE data only contain galaxies, main-sequence stars, and giant stars, we suspect that these 30 bright sources are giant stars. Therefore, we define three criteria to exclude the giant stars from the c2d data: IR3–MP1 $< 2$, IR2–IR3 $> IR3$–MP1, and IR2–IR3 $> 0$ (Figure 2). The numbers of giant stars selected from these criteria are 9, 8, 5, 2, and 1 in Serpens, Ophiuchus, Lupus, Perseus, and Chamaeleon II, respectively. However, these criteria do not remove 17 sources in Serpens, which have been identified as giant stars by Oliveira et al. (2009) based on the optical spectrum. Because the locations of these 17 sources in Figure 2 are closer to the SWIRE sources than our selected giant stars, we suspect that these spectroscopically identified giant stars may have a small disk or dusty envelopes that increase their IR3–MP1 color. We later removed these 17 sources from our YSOc list. Since we did not find any spectroscopic data for giant stars in Perseus, Ophiuchus, Lupus, and Chamaeleon II, we are not able to remove spectroscopically-identified giant stars in these clouds. However, because the Serpens molecular cloud is located in the direction close to the Galactic plane while other clouds are not, Serpens has the most serious giant star contamination among these clouds. Thus, the giant star contamination should be much smaller in the other four clouds.

### 3.4. Advantages of the Multi-D Method

Using the multi-D space as a whole instead of using limited numbers of selected CMDs to identify YSOs has the following advantages.
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Figure 4. All variations of MMDs consisting of any two bands of IR1, IR2, IR3, IR4, and MP1 for Perseus. Red, blue, and green points indicate the “same” YSOc, newly identified YSOc, and SWIRE galaxies, respectively. The arrows represent the diagonal direction, which is related to source brightness.

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

1. Avoidance of selecting specific CMDs. In order to identify YSOs in molecular clouds, previous works adopted different CMDs as their selection criteria. Although these CMDs are all selected with justifiable reasons, it is difficult to argue which CMD separates YSOs and galaxies best and how many CMDs are sufficient for the identification. The various selections of CMDs in use produce different YSO identification results by different works. Since the multi-D magnitude space includes information from all the possible variations of CMDs, we have no need to select specific CMDs. Therefore, the multi-D method is relatively complete and unbiased compared to CMD methods.

2. A natural boundary of the galaxy-populated region in the multi-D space. We use the natural boundary constructed from the number distribution of our galaxy sample. This boundary encloses a relatively accurate galaxy SED ensemble, which reduces the bias in identifying YSOc near the boundary.

3. Uncovering YSOs that cannot be found with all possible CMDs. A CMD is equal or equivalent to a projection in the multi-D magnitude space. However, even if all the possible variations of the CMDs are used, it is possible that some YSOs may not be found if they are located in a region without galaxies in the multi-D magnitude space but immersed in galaxy-populated regions in all CMDs; that is, some YSOs cannot be revealed in any projections from the multi-D magnitude space (see Figures 4–9).

Therefore, the multi-D method provides the best opportunity to identify YSOs as complete as a photometric data set can offer.

4. RESULT: NEW YSOc LIST

We present our YSOc lists for the five c2d-surveyed clouds selected with the multi-D method. The total number of our YSOc and the difference between our YSOc numbers and the c2d numbers are listed in Table 1, which shows that we increase the total YSOc number by 28% (from 1024 to 1313). The YSOc we selected in Perseus, Serpens, Ophiuchus, Lupus, and Chamaeleon II, along with their galaxy probabilities, are listed in Table 2. Note that the smaller a galaxy probability is, the more distant the sources are from the galaxy-populated region. We discuss the properties of our newly selected YSOc in Section 4.1 and argue that they are likely to be real YSOs. In Section 4.2, we present the reasons for excluding some YSOc from the c2d list and retrieve three missed established YSOs. In Section 4.3, we further discuss the YSOc with a “polycyclic aromatic hydrocarbon (PAH) emission” feature and label them as less reliable YSOc, which composes less than 3% of all YSOc. Finally, in Section 4.4, we discuss the uncertainty resulting from our band selections for constructing two five-dimensional arrays.

4.1. Analysis of the Newly Identified YSOc

In order to examine whether our newly identified YSOc are likely to be real YSOs, we compare our list and the c2d list in the following three aspects. First, we show that the distributions of YSOc from the two lists are consistent in all magnitude–magnitude diagrams (MMDs) and that the two lists of YSOc have a similar luminosity function. Second, we show that our YSOc stellar surface density is more consistent...
Figure 5. Same as Figure 4 but for Serpens.

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

Figure 6. Same as Figure 4 but for Ophiuchus.

(A color version of this figure is available in the online journal.)
Figure 7. Same as Figure 4 but for Lupus.
(A color version of this figure is available in the online journal.)

Figure 8. Same as Figure 4 but for Chamaeleon II.
(A color version of this figure is available in the online journal.)
with the c2d’s YSOc stellar density than the galaxy surface density. Finally, we show that the distributions of the two YSOc lists are also consistent in the multi-D color space. Note that these analyses can only give us hints about whether the newly identified YSOc are likely to be real YSOs or not. Without other data, such as spectroscopy, we are not able to confirm whether they are real YSOs.

4.1.1. Newly Identified YSOc in The Magnitude–Magnitude Diagrams and Their Infrared Luminosity Functions

Because we are not able to plot a multi-D figure with more than three dimensions, we display the distribution of our newly identified YSOc in all possible MMDs in order to examine whether their distributions in the MMDs are similar to the previously identified YSOc. For the same type of sources with similar SEDs, their locations in the CCDs will be close to each other and their locations in the MMDs will be along the diagonal direction since the only difference between the sources is brightness (distance). Therefore, if the newly identified YSOc are real YSOs, they should align with the previously identified YSOc in the diagonal direction. Figures 4–8 show the populations of newly identified YSOc (blue), the galaxy sample (green), and YSOc identified by both c2d and our method (red) (hereafter we call these YSOc the “Same” YSOc) in all variations of MMDs consisting of any two bands of IR1, IR2, IR3, IR4, and MP1. As we expected, the newly identified YSOc are well aligned with the “Same” YSOc in the diagonal direction, but at fainter ends close to the galaxy-populated regions. Although in Figures 4–8, some faint YSOc appear to be mixed with galaxies, they are in fact separated in the multi-D space. Figure 9 shows an example of a three-dimensional space consisting of IR2, IR4, and MP1 magnitudes, in which YSOc and galaxies are better separated than in any two-dimensional space.

We also compare the infrared luminosity distribution of our YSOc list and the “Same” YSOc list (infrared luminosity is obtained from J to MP2) and find that most of the newly identified YSOc are at the faint end of the distribution (Figure 10(a)). The distribution of the newly identified YSOc is more like an extension of the YSOc sample at the low-luminosity end rather
th part of the galaxy distribution. Therefore, both the YSOc locations in MMDs and the luminosity distribution support that the multi-D method is able to identify fainter YSOc that were not found by previous works.

4.1.2. Stellar Surface Density

Since YSOs tend to form in clusters in molecular clouds and background galaxies have a relatively random distribution in the sky, the newly identified YSOc are expected to have a higher probability of being in regions with other YSOc if they are real YSOs. We use stellar surface density as the parameter to indicate whether a newly identified YSOc is located within YSO clusters. Stellar surface density is defined as

\[ \sigma_{i,j} = \frac{n - 1}{\pi r^2_{ij}}, \]

where \( n \) is the nth closed star and \( r_{ij} \) is the distance to the nth closed star (Gutermuth et al. 2005, 2009). Here we adopt \( n = 6 \), the same value as that used in Gutermuth et al. (2009), as a surface density reference. The stellar surface density for each source is calculated by its location with respect to the “Same” YSOc population, and the results are listed in Column 7 of Table 2. In Figure 11, we compare the stellar surface density for the “Same” YSOc sample, newly identified YSOc, and background galaxies for each cloud. We select background galaxies with both Gal prob 1 and Gal prob 2 larger than 10 as sources. We use the Kolmogorov–Smirnov test to determine whether the stellar surface density distributions of our newly identified YSOc are similar to that of the “Same” YSOc sample or galaxies. The results (P-value) of the Kolmogorov–Smirnov test are shown in Table 3. If the P-value is significantly larger than 0.05, we cannot reject the hypothesis that the distributions of the two samples are the same (SciPy Reference Guide 2012).

For Perseus, Serpens, and Ophiuchus, the \( P \)-values calculated from newly identified YSOc and the “Same” YSOc are larger than those from newly identified YSOc and galaxies. These results suggest that the stellar surface density distributions of our newly identified YSOc are similar to that of the “Same” YSOc rather than the background galaxies in Perseus, Serpens, and Ophiuchus. In Chamaeleon II and Lupus, the distributions of both the newly identified and the “Same” YSOc sample show low stellar surface density, therefore, the distributions have a low statistical significance in determining whether newly identified YSOc are similar to real YSOs or background galaxies.

4.1.3. YSO Probability

If YSOs have similar SEDs, they should be distributed continuously in a rather concentrated region in the multi-D color space (Figure 12). We examine this property by calculating a new parameter, the YSO probability, in the multi-D color space, which is calculated in a similar way to the galaxy probability in the multi-D magnitude space. Here we calculate the YSO probability from the number distribution of our identified YSOc in the multi-D color space constructed with four axes (IR1−IR2, IR1−IR3, IR1−IR4, and IR1−MP1). Similar to the galaxy probability calculation, the subarrays (two- and three-dimensional arrays) are also used for YSOc with detections only in three or four of the five bands. The cell size is 0.2 mag, the same as was used in the galaxy probability calculations, and the \( \sigma \) of the smoothing beam is 2, \( \sqrt{3/4} \times 2 \), and \( \sqrt{2/4} \times 2 \) cells for four-, three- and two-dimensional arrays, respectively. The YSO probability for each source is listed in Column 8 of Table 2. YSOc located closer to the center of the YSOc-populated region in the multi-D color space will have a higher YSO probability, and only isolated YSOc will have a YSO probability equal to 1.

| R.A. (deg) | Decl. (deg) | Gal prob 1 log(num) | Gal prob 2 log(num) | Gal prob 1p log(num) | Gal prob 2p log(num) | Ste den log(pc^-2) | YSO prob log(num) | c2d Classification^a |
|-----------|-------------|---------------------|---------------------|---------------------|---------------------|---------------------|-------------------|---------------------|
| Perseus    |             |                     |                     |                     |                     |                     |                   |                     |
| 51.1968071 | 30.4656086  | −1.99               | 2.44                | −1.99               | 2.44                | −0.06               | 1.03              | −                   |
| 51.3304656 | 30.7577636  | −0.06               | −                   | −0.36               | 0.47                | 0.46                | −                   |
| 51.3313375 | 30.5737384  | −1.36               | −∞                  | −                   | 0.43                | 0.95                | YSOc_star+dust(IR1) |
| 51.3400184 | 30.7536686  | −∞                  | −∞                  | −                   | 0.49                | 0.00                | YSOc_red           |
| 51.4009155 | 30.7543631  | −∞                  | −∞                  | −∞                  | 0.44                | 0.23                | YSOc_red           |
| 51.4202445 | 30.7561528  | −∞                  | −∞                  | −∞                  | 0.43                | 0.00                | YSOc_red           |
| 51.4092048 | 30.4527241  | −0.46               | 1.14                | 0.38                | 1.86                | 0.04                | 0.01              |
| 51.4117940 | 30.7350532  | −∞                  | −∞                  | −                   | 0.51                | 0.03                | YSOc_red           |
| 51.4130155 | 30.7328223  | −∞                  | −∞                  | −                   | 0.52                | 0.01                | YSOc_red           |
| 51.6561277 | 30.2578016  | −∞                  | −∞                  | −                   | 0.17                | 0.06                | YSOc_red           |
| 51.8292253 | 30.2883997  | −0.32               | −0.44               | −                   | 0.63                | 0.14                | −                   |
| 51.8393548 | 30.8312253  | −2.22               | −∞                  | −                   | −0.16               | 0.00                | −                   |
| 51.9093741 | 30.2329495  | −∞                  | −∞                  | −                   | 0.87                | 0.87                | YSOc_star+dust(IR4) |
| 51.9109468 | 30.2267923  | −1.37               | −0.31               | −1.19               | 0.47                | 0.91                | 1.50              |
| 51.9117155 | 30.2235869  | −1.24               | −0.24               | −0.34               | 0.81                | 0.88                | 1.09              |
| 51.9128437 | 30.2175414  | −∞                  | −∞                  | −                   | 0.89                | 0.89                | 0.00              |
| 51.9228069 | 30.3379885  | −∞                  | −∞                  | −                   | 0.43                | 1.64                | YSOc_star+dust(IR2) |
| 51.9301209 | 30.2080268  | −∞                  | −∞                  | −                   | 1.03                | 0.00                | YSOc_red           |
| 51.9486420 | 30.2012577  | −∞                  | −∞                  | −                   | 1.18                | 0.62                | YSOc_star+dust(IR1) |
| 52.0003793 | 30.1463963  | −∞                  | −∞                  | −                   | 0.87                | 1.36                | YSOc_star+dust(IR2) |

Note. ^a If the c2d source type does not contain “YSO,” the source is added to the YSOc list by Evans et al. (2009) based on ancillary data from the literature. Sources without a classification are added to the YSOc list by Gutermuth et al. (2009). The Astrophysical Journal Supplement Series, 205:5 (18pp), 2013 March Hsieh & Lai

This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.
which is the minimum value for YSO probability. Out of 1313 identified YSOc, only 49 YSOc have a YSO probability \(= 1\) and 18 of them are newly identified YSOc. The chance that these “isolated” YSOc in the multi-D color space are not real YSOs is higher; however, it is still possible that small numbers of YSOc contain unusual SED features. Since the SEDs of YSOs are not exactly identical, a lower YSO probability suggests that the type of SEDs are less common if they are indeed YSOs. Note that the YSO probability cannot be used to identify YSOc because galaxies occupy similar color space.

4.2. Missed or Excluded YSOc from the c2d Lists

In this section, we discuss the c2d-identified YSOc that were missed in our selection processes. There are 36 sources that were missed in total. We add only three of them back into our YSOc candidate list (Table 2) because they were previously identified as well-known sources. These three sources were not identified in our identification process because they are not HREL sources (Table 4); DK Cha is saturated at several Spitzer bands, and VLA1623 and IRAS 16293 are only detected at MP1. The remaining 33 sources are separated into two groups: 23 sources are identified by Harvey et al. (2007a) using several CMD criteria (“c2d classification” starting with “YSOc” in Column 4 of Table 5) and 10 sources are added by Evans et al. (2009) with additional observations from other literature (Dunham et al. 2008; Enoch et al. 2009; Jørgensen et al. 2007, 2008). Here we justify why they are not likely true YSOs, and the exact reasons for the removal of each source are listed in Table 5.

First, for the 23 YSOc identified by Harvey et al. (2007a).

1. Eleven sources may be giant stars: seven sources are classified as giant stars in this work including giant star GY232 independently identified by Luhman & Rieke (1999) with

| Table 3 |
|---|
| K-S Test Results for Stellar Surface Density—P Value |
| Perseus | Serpens | Ophiuchus | Lupus | Chamaeleon |
| Newly identified YSOc and “Same” YSOc | 0.88 | 0.08 | 0.21 | 0.01 | 0.07 |
| Newly identified YSOc and galaxies | 0.00 | 0.00 | 0.00 | 0.06 | 0.37 |
Figure 11. Histograms of stellar (YSOc) surface density for sources in all clouds. The histograms indicate the “Same” YSOc (red), newly identified YSOc without PAH_em features (blue), and newly identified YSOc with PAH_em YSOc (green), respectively. The black dashed line is the background galaxy found in the direction of the cloud and the number is multiplied by a factor of 0.2.

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

Table 4
True YSO Missed by our Selection Method

| R.A. (deg) | Decl. (deg) | Reason Description |
|-----------|-------------|---------------------|
| 193.3217719 | −77.1196340 | DK Cha. This source saturates at IR2, IR4, and MP1 bands and is not an HREL source. We consider only HREL sources (see Section 2.1). |
| 246.6100815 | −24.4083265 | VLA1623. Since it has only been detected at MP1 and longer wavelength, lack of data excludes it from our selection process. |
| 248.0942748 | −24.4755023 | IRAS 16293−2422. IRAS 16293−2422A and B are not resolved at MP1. IRAS 16293−2422A is not detected in IRAC bands, while IRAS 16293−2422B is barely detected from IR2 to IR4. These sources are not HREL sources. |

spectroscopic data, and four sources are identified as giants by Oliveira et al. (2009).

2. Ten sources are removed by the image checking process: seven sources have flux contamination from nearby sources or cloud emission, one source is elongated like a galaxy, and two sources are jet knots from HH211.

3. One source is not an HREL object. It is also very distant from the cluster regions with a low stellar surface density in Perseus and slightly extends; thus we suggest it is a background galaxy.

4. One source has Gal Prob >1 (1.07).

Second, for the 10 c2d YSOc added by Evans et al. (2009) but removed from our work.

1. Three sources were identified as jet knots in the HH211 system by image checking. Note that HH211 itself also cannot be identified through our procedure since it has only been detected at MP2 and longer wavelengths.

2. Two sources are very close to selected YSOc, and their flux appears to be contaminated by these YSOc.

3. Five sources were not considered in our identification process. Three of them are not HREL sources, and they all appear to be extended and seem to be part of the cloud structure. The remaining two are located at the edge of the survey regions without IR1 and IR3 observations, which were not considered in our analysis.

4.4. PAH Emission

From the SWIRE data, we find that the galaxies with a peak at IR4 in SEDs (PAH emission) are usually bright and are thus much more difficult to eliminate. The PAH emission is usually seen in star-forming galaxies (Evans et al. 2009);
Table 5
YSOc Excluded from the c2d Lists

| Number | R.A. (deg) | Decl. (deg) | c2d Classification\(^a\) | Type\(^b\) | Reason/Description |
|--------|------------|-------------|-------------------------|-----------|--------------------|
| Perseus |            |             |                         |           |                    |
| 1      | 51.9117838 | 30.2169053  | YSOc_red                | B         | This source is not observed at IR1 and IR3 because it is in the edge of the c2d map. |
| 2      | 52.2383644 | 31.2386438  | YSOc_star+dust(MP1)     | B         | Its MP1 flux is band-filled and its location is within the PSF of “Same” YSOc (51.9128437, +30.2175414) at 6 arcsec away. |
| 3      | 52.2578166 | 31.2814344  | YSOc_star+dust(IR2)     | B         | MP1 locates in the diffraction spike of an extremely bright source and thus possibly has a wrong flux measurement. |
| 4      | 52.2693214 | 31.3682561  | Red1                    | C         | This is not an HREL source. It is only detected in MP1 and the MP1 flux appears to be affected by the cloud emission. |
| 5      | 52.2957986 | 31.3072254  | YSOc_red                | B         | Its IR2, IR3, IR4, and MP1 flux are band-filled, and its location is between two “Same” YSOc (52.2944829, 31.3057251) and (52.2969172, 31.3087350). |
| 6      | 52.3229380 | 31.4634218  | YSOc_red                | B         | It appears like a jet knot 5 arcsec from a “Same” YSOc (52.3215278 31.4629087). |
| 7      | 53.1734652 | 31.1789357  | YSOc                    | B         | Its MP1 flux is band-filled and its location is within the PSF of a “Same” YSOc (51.9128437, 30.2175414) at 2 arcsec away. |
| 8      | 55.9791799 | 32.0175333  | YSOc_star+dust(IR2)     | B         | This is a jet knot of HH211 close to the driven source. HH211 has only been detected at MP2 or longer wavelength, thus is not identified by our work. |
| 9      | 55.9854925 | 32.0146713  | Red                     | B         | This is a jet knot of HH211 close to the driven source. HH211 has only been detected at MP2 or longer wavelength, thus is not identified by our work. |
| 10     | 55.9886063 | 32.0131886  | Red                     | B         | This is a jet knot of HH211 close to the driven source. HH211 has only been detected at MP2 or longer wavelength, thus is not identified by our work. |
| 11     | 55.9901535 | 32.0124525  | Galc                    | B         | This is a jet knot of HH211 close to the driven source. HH211 has only been detected at MP2 or longer wavelength, thus is not identified by our work. |
| 12     | 55.9909120 | 32.0534315  | Red                     | C         | This is not an HREL source. Although this source has detections with S/N = 3, 2, and >7 at IR2, IR3, and MP1, we think it is not a real source due to the contamination from cloud emission. |
| 13     | 55.9975507 | 32.009032   | YSOc_red                | B         | This is a jet knot of HH211 close to the driven source. HH211 has only been detected at MP2 or longer wavelength, thus is not identified by our work. |
| 14     | 56.0793373 | 32.2883878  | YSOc                    | A         | Giant star in this work (Section 3.3). |
| 15     | 56.1498481 | 32.1567564  | YSOc_star+dust(IR2)     | B         | IR4 and MP1 detections seem to be part of the clouds. The source appears to be star-like at shorter wavelengths. |
| 16     | 56.4473566 | 31.7198486  | YSOc_star+dust(IR4)     | C         | This is not an HREL source. |
| Lupus  |            |             |                         |           |                    |
| 17     | 234.7014819 | -34.6772876 | YSOc_PAH-em             | B         | This source is elongated in the IR1 image, thus we identified it as a galaxy. |
| 18     | 242.2427972 | -39.1265213 | YSOc                   | A         | Giant star in this work (Section 3.3). |
| 19     | 242.3921400 | -39.2283528 | YSOc                   | A         | Giant star in this work (Section 3.3). |
| Ophiuchus |          |             |                         |           |                    |
| 20     | 246.5609716 | -24.4187556 | Red1                   | C         | This is not an HREL source. It is only detected in MP1 and we think the MP1 flux is contributed from a cloud. |
| 21     | 246.7462569 | -24.5842515 | Red                    | B         | Its MP1 flux is band filled and its location is within the PSF of a newly identified YSOc (246.7464700, -24.5829609) at 6 arcsec away. |
| 22     | 246.8052355 | -24.6926085 | YSOc                   | A         | Giant star in this work (Giant star GY 232 identified by Luhman & Rieke 1999). |
| 23     | 246.8746731 | -24.5601135 | YSOc                   | A         | Giant star in this work (Section 3.3). |
| 24     | 246.9323892 | -24.7188227 | YSOc                   | A         | Giant star in this work (Section 3.3). |
| Serpens |            |             |                         |           |                    |
| 25     | 277.0458600 | -0.0276004  | YSOc_star+dust(MP1)     | A         | Giant star identified by Oliveira et al. (2009). |
| 26     | 277.1140203 | -0.1972144  | YSOc_star+dust(MP1)     | A         | Giant star identified by Oliveira et al. (2009). |
| 27     | 277.2270870 | 0.4812201   | YSOc                   | A         | Giant star in this work (Section 3.3). |
| 28     | 277.2837039 | -0.1269813  | YSOc_star+dust(MP1)     | A         | Giant star identified by Oliveira et al. (2009). |
| 29     | 277.2876881 | 0.5244498   | Galc                   | B         | This is a jet knot of “Same” source (277.2877868, 0.5256632) close to the driven source. |
| 30     | 277.3858779 | -0.2231446  | YSOc_star+dust(MP1)     | A         | Giant star identified by Oliveira et al. (2009). |
| 31     | 277.5219079 | 0.6846068   | Red                    | E         | This source locates in the edge of the mapping area of c2d, thus is not observed in IR1 and IR3. We do not consider such sources in our analysis. |
| 32     | 277.5237366 | 0.6588334   | Rising                 | E         | This source locates in the edge of the mapping area of c2d, thus is not observed in IR1 and IR3. We do not consider such sources in our analysis. |
| 33     | 277.5451572 | 0.7835665   | YSOc_star+dust(IR4)     | D         | We identify this source as a galaxy due to its galaxy probability (Gal prob1 = 1.07 and Gal prob2 = 1.04). |

Notes.
\(^a\) If the c2d source type does not contain “YSO,” the source is added to the YSOc list by Evans et al. (2009) based on ancillary data from the literature.
\(^b\) Reasons for excluding the source from our YSOc list.
A: This source is classified as a giant star by either this work or Oliveira et al. (2009).
B: This source is excluded in the image checking process.
C: This source is not considered in our identification process. It has detections at fewer than three bands or is not an HREL source (see Section 2.1).
D: This source has both galaxy probabilities, Gal prob 1 and Gal prob 2, larger than 1.
E: This source is not observed at IR1 and IR3 because it is in the edge of the c2d map.
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5. DISCUSSION

5.1. New YSO Identification Method and Results

We develop the multi-D method for separating two kinds of sources, which have similar SEDs and are indistinguishable in CMDs and CCDs. In this paper, we use the multi-D method to identify YSOc in molecular clouds with Spitzer data by comparing it to a galaxy sample from SWIRE. A large number of new YSOc are identified and our analysis indicates that they are much like faint YSOs that were not selected before (Figure 10). This result suggests that the multi-D method is very powerful in identifying faint YSOs that have been detected. However, there are several caveats in the multi-D method.

1. The SWIRE data may not represent a complete collection of galaxy SEDs. In addition, in the direction of the observed clouds, the brightest galaxies may be brighter than all the SWIRE galaxies due to their proximity. Thus, if the SWIRE data are incomplete galaxy samples, some true galaxies will not be removed and will be identified as YSOc.

2. Some YSOs may have similar SEDs and brightness to those of galaxies. If a YSO has an SED and brightness similar to galaxies in the comparison galaxy sample in the analysis wavelengths, it will have a galaxy probability larger than 1 and will be removed from the YSOc list. We found that our YSOc and galaxy sample are continuously distributed in MMDs and three-dimensional plotting (Figures 4–9), which implies that there may be faint YSOs located in the galaxy-populated region and cannot be identified with Spitzer data only. However, no available methods can identify such sources with only photometry data.

3. Some sources may have high uncertainty in photometry, which will affect the YSO identification process. Sources with incorrect flux measurements will have peculiar SED structures, which makes their location far from the galaxy-populated region in the multi-D space and thus classifies them as YSOc. We have designed an image checking process to reduce such cases (Section 3.4).

Although the multi-D method has these caveats, such problems are unavoidable and also exist in those methods using CCD and CMD criteria. The multi-D method does allow us to obtain the most complete YSOc list from the provided data set.

5.2. Newly Identified VeLLO Candidates

VeLLOs are faint embedded protostars ($L_{\text{int}} < 0.1 L_\odot$), and therefore they are difficult to identify. Recent works suggest that VeLLOs are likely to be protostars in the quiescent accreting phase (Dunham et al. 2010). However, this does not exclude the possibility that some VeLLOs could be faint protostars at early evolutionary stages or even “first cores,” which is the transition phase between starless cores and Class 0 sources. Since our method discovers more faint protostars compared to previous works, we examine here whether we can identify more VeLLOs.

The most thorough survey of VeLLOs was carried out by Dunham et al. (2008) using c2d data. Several other sources were thought to be VeLLOs in recent years (Pineda et al. 2011; Kauffmann et al. 2011). Since a large number of faint YSOc are identified using the multi-D method in this work, we are in a good position to add reliable VeLLO candidates to the collection. Figure 10(b) shows that some newly identified Class 0 and Class I YSOc (with MP2 detections) have lower infrared luminosity (luminosity between 1.25–70 μm) than that of the more reliable VeLLO candidates (group 1–3) identified.
Figure 13. SEDs of VeLLO candidates identified from our YSOc list (see Section 5.2 for selection criteria). Number 3 is newly identified from our work, and the rest of the VeLLOs have been identified by Dunham et al. (2008) but were classified as less confident VeLLOs.

![Figure 13](image)

Table 6

VeLLO Candidates

| R.A. (deg) | Decl. (deg) | \( L_{\text{IR}} \) \( (L_\odot) \) | \( L_{\nu,70} \) \( (L_\odot) \) | c2d Classification | \( A_V \) (mag) |
|-----------|-------------|-----------------|-----------------|-------------------|-----------------|
| 52.2752091 | 30.5108863  | 0.017 (0.007)   | 0.023 (0.006)   | YSOc_star+dust(IR2) | 2.4             |
| 52.3348374 | 31.2139919  | 0.016 (0.006)   | 0.034 (0.008)   | ···                | 9.5             |
| 52.7512777 | 30.9360812  | 0.009 (0.004)   | 0.011 (0.003)   | ···                | 0.9             |
| 53.2410000 | 31.022931   | 0.010 (0.004)   | 0.016 (0.004)   | YSOc_red           | 13.7            |
| 56.3075775 | 32.027786   | 0.050 (0.02)    | 0.054 (0.013)   | YSOc_star+dust(IR2) | 3.0             |
| 194.2566223 | −76.8097467 | 0.028 (0.007)   | 0.049 (0.009)   | ···                | 2.4             |
| 277.2287724 | 0.3090777   | 0.034 (0.003)   | 0.038 (0.005)   | YSOc_red           | 15.9            |

by Dunham et al. (2008). Dunham et al. (2008) use a relation to translate the MP2 flux into the internal luminosity:

\[
L_{\text{int}} = 3.3 \times 10^8 F_{70}^{0.94} L_\odot
\]

where \( F_{70} \) is MP2 flux in cgs units (erg cm\(^{-2}\) s\(^{-1}\)) based on the SED model from the Monte Carlo dust radiative transfer code RADMC (Dullemond & Dominik 2004). We adopt this relation to estimate \( L_{\text{int}} \) for our Class 0 and I candidates and find 32 sources with \( L_{\text{int}} < 0.1 L_\odot \) in addition to the VeLLOs found in Dunham et al. (2008). In order to make sure the selected VeLLOs are young YSOs, two more criteria from Dunham et al. (2008) are adopted to ensure that the SEDs rise (1) from the longest detected IRAC wavelength to MP1 and (2) from MP1 to MP2, which reduces the number of VeLLO candidates to seven (Table 6). Their SEDs are shown in Figure 13. Among these seven candidates, only one is newly identified by us. The other six candidates have been identified by Dunham et al. (2008), but they are in a less confident group 4–7 that corresponds to sources not obviously associated with high column density regions. Since one possible nature of VeLLOs is proto-brown-dwarfs, which could be ejected from their parent cores during the formation process, VeLLOs may not necessarily be embedded in high-density regions. Therefore, we do not exclude these sources from our VeLLO candidate list. In short, with the multi-D method, faint protostar candidates can be selected naturally.

5.3. Statistical Properties

The significant increase of YSOc numbers in molecular clouds can alter statistical properties such as SFR and the lifetime of YSOs in different evolutionary stages. The variations of these two properties are analyzed in this section.

5.3.1. Comparing Star-forming Rate with Theoretical Models

The accuracy of SFR is critical in distinguishing whether the star formation in GMCs is dominated by turbulence or magnetic fields. Without any support, typical GMCs should collapse on a free-fall timescale, which results in an SFR of roughly 250 \( M_\odot \) yr\(^{-1}\) (Krumholz & McKee 2005). However, the SFR in the Milky Way is measured as \( \sim 3 M_\odot \) yr\(^{-1}\) (McKee & Williams 1997). Thus, supporting forces, such as turbulence and/or magnetic fields, are required to reconcile the difference between theory and observations. To study how the turbulence affects the SFR, Krumholz & McKee (2005) define the dimensionless SFR per unit free-fall time, \( \text{SFR}_{\text{ff}} \),

\[
\text{SFR}_{\text{ff}} = \frac{\text{SFR} \times t_{\text{ff}}}{M(\text{cloud})},
\]

where \( t_{\text{ff}} \) is the free-fall time of the cloud and \( M(\text{cloud}) \) is the mass of the cloud, and derive an analytic expression for \( \text{SFR}_{\text{ff}} \) in a supersonic turbulent median,

\[
\text{SFR}_{\text{ff}} \approx 0.014 \left( \frac{\alpha_{\text{vir}}}{1.3} \right)^{-0.68} \left( \frac{M}{100} \right)^{-0.32},
\]

where \( \alpha_{\text{vir}} \) is the virial parameter defined by Bertoldi & McKee (1992) measuring the ratio of kinetic energy and gravitational
energy of a clumpy, and $M$ is the Mach number. The definition of $\alpha_{\text{vir}}$ is $\alpha_{\text{vir}} = 5\sigma_{\text{tot}}^2R/(GM)$, where $\sigma_{\text{tot}}$ is velocity dispersion from thermal and turbulent velocities over the entire cloud, and $R$ and $M$ are the radius and mass of the cloud, respectively. The turbulence-dominated model suggests that a small $\alpha_{\text{vir}}$ can result in a large SFR$_{\text{ff}}$. However, magnetic-field-dominated models predict that the SFR$_{\text{ff}}$ is proportional to $\alpha_{\text{vir}}$ (Krumholz & Tan 2007), which is

$$\text{SFR}_{\text{ff}} \approx 0.01\alpha_{\text{vir}}. \quad (5)$$

The parameter values (Krumholz & Tan 2007) used to derive this relation could vary more than an order of magnitude, resulting in a wide range of possible values for the coefficient. Nevertheless, the linear proportionality of SFR$_{\text{ff}}$ and $\alpha_{\text{vir}}$ should be unaffected. Hence, comparing the relation of SFR$_{\text{ff}}$ and $\alpha_{\text{vir}}$ may provide us with a hint to which mechanism dominates in molecular clouds.

The c2d data and our new YSOc catalogs provide necessary information to compare SFR$_{\text{ff}}$ and $\alpha_{\text{vir}}$. SFR$_{\text{ff}}$ is estimated following the same analysis method in Evans et al. (2009). Assuming that the mean mass of a YSO is $M_\star = 0.5 M_\odot$ and the period of star formation is $T = 2$ Myr, the SFR can be estimated from

$$\text{SFR} = \frac{N(\text{YSO}) \times M_\star}{T} \quad (6)$$

and

$$t_{\text{ff}} = 34 \text{ Myr}/\sqrt{n}, \quad (7)$$

where $N(\text{YSO})$, $M_\star$, $T$, and $n$ are the number of YSO, the mean mass of YSO, the period of star formation, and the number density of the cloud, respectively. Inserting Equations (6) and (7) into Equation (3), we are able to obtain the SFR$_{\text{ff}}$ from $N(\text{YSO})$, $M(\text{cloud})$, and $n$. We calculated $n$ from the cloud mass and surface area by assuming a spherical cloud and the cloud mass was obtained from Table 1 in Evans et al. (2009). The cloud mass and the surface area of the clouds are both obtained from the c2d extinction maps in area with $A_V > 2$. We use the mass of the clouds from Table 1 in Evans et al. (2009) and calculated the surface area of the clouds, which are both from the c2d extinction maps in area with the $A_V > 2$ region. The errors of SFR$_{\text{ff}}$ are from error propagating and the only uncertainty considered here is the uncertainty in cloud distances.

We calculate $\alpha_{\text{vir}}$ using $\alpha_{\text{vir}} = 5\sigma_{\text{tot}}^2R/(GM)$. $R$ and $M$ are the same as that used in SFR$_{\text{ff}}$ calculations. The $\sigma_{\text{tot}}$ are velocity dispersions from $^{13}\text{CO}$ $J = 1 \rightarrow 0$ observations and are averaged over a full map of the cloud. For Perseus, Serpens, and Ophiuchus, we use the $\sigma_{\text{tot}}$ from Evans et al. (2009) who obtained the values from the COMPLETE project (Ridge et al. 2006). For Lupus and Chamaeleon, we use the $\sigma_{\text{tot}}$ from Tachihara et al. (1996) and Vilas-Boas et al. (1994), respectively, who also use $^{13}\text{CO}$ $J = 1 \rightarrow 0$ as the tracer. The calculated $\alpha_{\text{vir}}$ for all clouds are shown in Table 7 and the propagating errors are from the errors of distance and $\sigma_{\text{tot}}$ in the cloud.

Figure 14 shows the relations between $\alpha_{\text{vir}}$ and SFR$_{\text{ff}}$ for all clouds in this paper. We fit the data with the predictions for the turbulence model and the magnetic field model, i.e., Equations (4) and (5), respectively, derived by Krumholz & Tan (2007). For the magnetic field model, we set the coefficient to be a variable in Equation (5). The reduced $\chi^2$ are 3.0 and 5.6 for the turbulence model and the magnetic field model, respectively, which implies that the data are more consistent with the turbulence model than the magnetic field model. Our result hints that turbulence dominates the star formation in large scales, such as GMCs. In addition, in Figure 14, the SFR$_{\text{ff}}$ of Lupus are all larger than that of the best fitting curve of the turbulence model, especially for Lupus III. This could result from our assumption of a mean mass of $0.5 M_\odot$ for YSOs in all clouds, but the mean stellar mass in Lupus may be closer to 0.2 $M_\odot$ (Merín et al. 2008). The mean stellar mass is 0.6 or 0.8 $M_\odot$ for different evolutionary tracks in Serpens (Oliveira et al. 2009) and is $0.52 \pm 0.11 M_\odot$ in Chamaeleon II (Spizzi et al. 2008). Better estimates of the mean stellar mass in all clouds will provide a more accurate SFR$_{\text{ff}}$ and a stronger conclusion.

5.3.2. Lifetimes of YSOs in Different Evolutionary Stages

The lifetimes of YSOs in different evolutionary stages are estimated from the numbers of YSOs in each stage, and thus the variation of the YSOc sample may result in different lifetime estimations. YSOs are commonly classified into four evolutionary stages: Class 0/I, Flat, Class II, and Class III from young to old using the spectral slope, $\alpha$, which is the best fit slope from the $K$ to MP1 band of the SED. The definition of $\alpha$ and the classification criteria are from Greene et al. (1994):

$$\alpha = \frac{d\log(\lambda S(\lambda))}{d\log(\lambda)} \quad (8)$$
Figure 15. Populations of all sources with age indicator, $\alpha$, in the five clouds. Blue and red lines indicate our YSOc and the “Same” YSOc, respectively.

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

### Table 7

| Cloud      | Distance $^a$ (pc) | N(YSO) $^b$ | M(cloud) $^c$ ($M_\odot$) | Area $^c$ (pc$^2$) | $\Delta v$ $^a$ (km s$^{-1}$) | SFR$_{ff}$ | $\alpha_{vir}$ |
|------------|-------------------|-------------|----------------------------|--------------------|-----------------------------|------------|----------------|
| Perseus    | 250 (50)          | 452         | 4814 (1925)                | 62.0 (24.8)        | 1.54 (0.11)                 | 0.050 (0.034) | 0.46 (0.21) |
| Serpens    | 260 (50)          | 295         | 2016 (775)                 | 17.5 (6.7)         | 2.16 (0.01)                 | 0.047 (0.030) | 1.14 (0.49) |
| Ophiuchus  | 125 (25)          | 343         | 2182 (873)                 | 27.3 (10.9)        | 0.94 (0.11)                 | 0.068 (0.045) | 0.25 (0.13) |
| Lupus I    | 150 (20)          | 20          | 250 (58)                   | 4.5 (1.2)          | 1.9 (0.19)                  | 0.026 (0.012) | 3.62 (1.30) |
| Lupus III  | 200 (20)          | 60          | 443 (102)                  | 8.5 (1.7)          | 1.7 (0.17)                  | 0.054 (0.018) | 2.25 (0.68) |
| Lupus IV   | 150 (20)          | 13          | 119 (28)                   | 1.7 (0.5)          | 1.7 (0.17)                  | 0.025 (0.011) | 3.74 (1.34) |
| Chamaeleon II | 178 (18)       | 27          | 426 (86)                   | 7.4 (1.5)          | 1.2 (0.4)                   | 0.023 (0.008) | 1.09 (0.77) |

Notes.

- $^a$ The area and $\Delta v$ of clouds are from Evans et al. (2009).
- $^b$ The YSOc numbers are counted with YSOc located in the region with $A_V > 2$ magnitude.
- $^c$ The area is calculated from the extinction map with the $A_V > 2$ magnitude area.
- $^d$ We use the distance uncertainty of Serpens with a wide range to cover the distance measurement mentioned in Evans et al. (2009), i.e., Straizys et al. (1996), Eiroa et al. (2008).
- $^e$ The extinction map of Serpens has all pixel with $A_V > 2$ magnitude, thus the area is from the Spitzer observing region.
- $^f$ The $\Delta v$ in Lupus is from Tachihara et al. (1996).
- $^g$ The $\Delta v$ in Chamaeleon is from Vilas-Boas et al. (1994).

### Table 8

| Cloud          | 1/0 | Flat | II | III | 1/0 | Flat | II | III |
|----------------|-----|------|----|-----|-----|------|----|-----|
| This Work      |     |      |    |     |     |      |    |     |
| Perseus        | 99  | 49   | 272 | 49  | 87  | 42   | 225| 31  |
| Serpens        | 55  | 36   | 170 | 35  | 36  | 23   | 140| 28  |
| Ophiuchus      | 72  | 60   | 191 | 58  | 35  | 47   | 176| 34  |
| Lupus          | 12  | 12   | 64  | 41  | 5   | 10   | 52 | 27  |
| Chamaeleon II  | 7   | 3    | 21  | 7   | 2   | 1    | 19 | 4   |
| Total          | 245 (19%) | 160 (12%) | 718 (55%) | 190 (14%) | 165 (16%) | 123 (12%) | 612 (60%) | 124 (12%) |
and Class 0/I: $0.3 \leq \alpha$
Flat: $-0.3 \leq \alpha < 0.3$
Class II: $-1.6 \leq \alpha < -0.3$
Class III: $\alpha < -1.6$

Although it has been demonstrated that the SED morphologies of YSOs are affected by geometry, such as the inclination angle with radiative transfer codes (Whitney et al. 2003a, 2003b; Robitaille et al. 2006; Crapsi et al. 2008), here we still use $\alpha$ as a rough age indicator as there are no better alternatives. Our large YSO sample size may mitigate the geometry effect.

Figure 15 shows the distributions of $\alpha$ in each cloud and the fractions of YSOc in different evolutionary stages. The latter numbers are almost the same as the results in Evans et al. (2009) in both individual clouds and the whole data set, implying that the estimates of the lifetimes of each evolutionary stage are not changed (Table 8). Figure 15 also shows that the distributions of $\alpha$ in different clouds are different, which indicates that those clouds may be in different evolutionary stages. Because the Perseus molecular cloud consists of two major YSO clusters, NGC 1333 and IC348, we separated it into two regions, western and eastern Perseus, by R.A. = 54:3: Our results suggest that western Perseus (NGC 1333) has the highest fraction of Class 0/I YSOc, while Lupus has the highest fraction of Class III YSOc. Therefore, western Perseus is the youngest cloud and Lupus is the oldest cloud among c2d-surveyed regions, while the other clouds are at similar evolutionary stages.

6. SUMMARY
We have developed the “multi-D method” to identify YSOc from star-forming regions with reliable photometry measurements from multiple bands. Main-sequence and giant stars are first eliminated from the observed sources, and the rest of the sources are compared to a galaxy sample, such as the Spitzer’s SWIRE data set, in the multi-D magnitude space. We demonstrate that this multi-D method, which uses simultaneous multi-band photometry, can identify all possible YSOc above the galaxy confusion limit and recover those that have been missed by using a certain set of color–magnitude or color–color criteria. We identify 1313 YSOc from Spitzer’s c2d high reliability (HREL) catalogs, which is 28% more than what have been identified by the c2d project (Evans et al. 2009). The increased amount of YSOc suggests the following results.

1. The increased amount of YSOc directly increases the SFR estimated in each region by the same percentage. We further compare the relation between $\alpha_{vir}$ and SFR$_{ff}$ to theoretical models, and our results are more consistent with the prediction of a supersonic turbulence-dominated model than that of a magnetic field-dominated model.
2. Although we identify 28% more YSOc than those listed in the c2d catalogs, the lifetimes of YSOs in different evolutionary stages are unchanged since the fractions of YSOc in different Classes are almost the same.
3. Our multi-D method allows us to reliably identify more faint YSOc, which can be used to select VeLLOs. Using the 70 $\mu$m flux in the internal luminosity relation suggested by Dunham et al. (2008), we are able to find seven new VeLLO candidates.

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