Catalog of High Protostellar Surface Density Regions in Nearby Embedded Clusters

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Received 2018 September 20; revised 2018 December 2; accepted 2018 December 3; published 2019 January 29

Abstract

We analyze high-quality stellar catalogs for 24 young and nearby (within 1 kpc) embedded clusters and present a catalog of 32 groups which have a high concentration of protostars. The median effective radius of these groups is 0.17 pc. The median protostellar and pre-main-sequence star surface densities are $46 M_\odot \text{pc}^{-2}$ and $11 M_\odot \text{pc}^{-2}$, respectively. We estimate the age of these groups using a model of constant birthrate and random accretion stopping and find a median value of 0.25 Myr. Some groups in Aquila, Serpens, Corona Australia, and Ophiuchus L1688 show high protostellar surface density and high molecular gas surface density, and seem to be undergoing vigorous star formation. These groups provide an excellent opportunity to study the initial conditions of clustered star formation. Comparisons of protostellar and pre-main-sequence stellar surface densities reveal continuous low-mass star formation of these groups over several Myr in some clouds. For groups with typical protostellar separations of less than 0.4 pc, we find that these separations agree well with the thermal Jeans fragmentation scale. On the other hand, for groups with typical protostellar separations larger than 0.4 pc, these separations are always larger than the associated Jeans length.

Key words: infrared: stars — stars: formation — stars: low-mass — stars: pre-main sequence — stars: protostars

1. Introduction

It is now commonly accepted that most stars form in clusters of hundreds of stars (Lada & Lada 2003; Reipurth et al. 2014). Understanding the process of stars forming in clusters is of considerable importance. Although we have an increasingly detailed picture of relatively isolated star formation in nearby dark clouds, such as those in the Taurus complex, many gaps remain in our understanding of clustered star formation, such as the elusive initial conditions (Myers 2010), as well as the dominant fragmentation process (e.g., Zhang et al. 2015; Busquet et al. 2016; Pokhrel et al. 2018).

Embedded clusters, in which their mass is dominated by that of their natal molecular clouds, are the primary laboratory for research into the question of the physical origin of stellar clusters (Gutermuth et al. 2009; Lada 2010; Friesen et al. 2016; Megeath et al. 2016). In particular, regions with high protostellar (PS) surface density and PS fraction are very young, and therefore they could be useful objects for understanding star formation and evolution in star clusters. Through observations of gas associated with these regions, the initial conditions for clustered star formation can be constrained.

Our understanding of the formation and early evolution of young stellar clusters has been greatly hindered by observational challenges, including their distance, their spatial density, and their association with high column density molecular clouds (Gutermuth et al. 2005). High angular resolution and high sensitivity are required to resolve individual stars, detect embedded sources, and identify members against a field of background stars. With the generation of mid-IR telescopes, especially the Spitzer Space Telescope (Werner et al. 2004), observations can finally probe nearby young clusters with the sensitivity to detect objects well below the hydrogen-burning limit, and the angular resolution to resolve high-density groupings of stars (Allen et al. 2007). Furthermore, Spitzer has been providing detailed images of young clusters in the mid-IR, which for the first time allows us to identify young stars with disks (pre-main-sequence (PMS) objects) and infalling envelopes (PS objects) efficiently in clusters out to 1 kpc and beyond (e.g., Evans et al. 2009; Gutermuth et al. 2009; Kryukova et al. 2012; Dunham et al. 2015). In addition, the Herschel Space Observatory (Pilbratt et al. 2010) also provides dust column density maps for nearby star-forming regions with high sensitivity and angular resolution (Harvey et al. 2013; Pokhrel et al. 2016), making it possible to study the relationship between young stellar clusters and their natal gas in detail. Extensive studies have been carried out of the relation between the surface density of young stellar objects (YSOs) and gas density with the Spitzer and Herschel data, and power-law correlation has been reported (e.g., Evans et al. 2009; Gutermuth et al. 2009, 2011; Heiderman et al. 2010; Harvey et al. 2013).

Jeans fragmentation is known to be an important phenomenon in star-forming regions (Jeans 1929). The detailed fragmentation mechanism is a topic that is still under debate, with possibilities including purely thermal Jeans fragmentation, as well as where thermal and non-thermal motions play a role (e.g., Palau et al. 2015; Busquet et al. 2016). Some studies of massive infrared dark clouds (IRDCs) found that the fragments have masses much larger than the thermal Jeans mass and seem to be consistent with the non-thermal Jeans mass (e.g., Zhang et al. 2009, 2015; Pillai et al. 2011; Wang et al. 2014). In contrast, Palau et al. (2015) found that thermal Jeans fragmentation seems to be the dominant factor determining the fragmentation level of relatively nearby star-forming massive dense cores at a 0.1 pc scale. They proposed that the
inconsistency between mass and thermal Jeans mass in other studies could be caused by the low sensitivity and poor spatial resolution due to the large distance, e.g., the mass sensitivity is above the Jeans mass (>2 $M_\odot$), and the spatial resolution is >5000 au for most IRDCs. In Palau et al. (2015) the massive dense cores were observed with mass sensitivities <1 $M_\odot$, and spatial resolutions of about 1000 au. Busquet et al. (2016) assessed the fragmentation level in an IRDC with the SMA combined data, which is sensitive to structures of 3000–10,000 au, and also sensitive to flattened condensations. They also found that the observed fragmentation in the hub of an IRDC is more consistent with thermal Jeans fragmentation.

Recently Pokhrel et al. (2018) studied the hierarchical structure in the Perseus molecular cloud from the scale of the entire cloud to PS objects. This study was carried out over five scales of hierarchy: cloud, clumps, cores, envelopes, and PS objects. Their results provide clues that the thermal Jeans fragmentation begins to dominate at the scale of cores fragmenting into envelopes. More young stellar groups are needed for further investigate the fragmentation mechanism in the star formation process. In this paper we present a catalog of high PS fraction groups in nearby embedded clusters using a catalog of YSOs extracted from the Spitzer “cores to disks” (c2d) and Gould Belt (GB) Legacy surveys (Evans et al. 2009; R. A. Gutermuth et al. 2018, in preparation). In Section 2, we describe the YSO catalogs we use in our analysis, and our procedure for identifying groups with high PS surface densities and PS ratios. We analyze the properties of the groups identified in Section 3, discuss the implications in Section 4, and conclude in Section 5.

2. Sample and Methodologies

2.1. The Sample

The GB is a ring of nearby O-type stars inclined approximately 20° with respect to the Galactic Plane, in which most of the current star formation within 500 pc of the Sun occurs. All of the nearby, well-studied molecular clouds are located within this ring. The GB ring has been surveyed by the Spitzer c2d (Evans et al. 2003, 2009) and GB Legacy surveys (Dunham et al. 2015). The Spitzer c2d survey (PI: N.J. Evans) imaged five large, nearby molecular clouds in the GB, including Serpens, Perseus, Ophiuchus, Lupus, and Chamaeleon II, as well as approximately 100 isolated dense molecular cores (Evans et al. 2003, 2009). The Spitzer GB survey (PI: L.E. Allen) is a follow-up program that imaged the additional 11 molecular clouds in the GB, completing most of the remaining clouds in the GB except for the Taurus and Orion molecular clouds. Both surveys imaged molecular clouds at 3.6–8.0 μm with the Spitzer Infrared Array Camera (Fazio et al. 2004), and at 24–160 μm images with the Multiband Imaging Photometer (Rieke et al. 2004). Here we use YSOs cataloged classified by R. A. Gutermuth et al. (2018, in preparation), in which YSOs were identified following methods described in Gutermuth et al. (2008, 2009) with many improvements (Winston et al. 2018). The classifications of YSOs are identified based on the spectral index of their spectral energy distribution (R. A. Gutermuth et al. 2018, in preparation). These data provide a comprehensive sample of clusters in the solar neighborhood and a good opportunity to analyze regions with high PS surface density and fraction. In this paper, both

| Source Name | R.A. (J2000) | Decl. (J2000) | D (pc) | Dist. References |
|-------------|--------------|--------------|-------|-----------------|
| Aquila-a     | 18:38:00     | 00:12:00     | 260   | 1               |
| Aquila-b     | 18:30:00     | -02:00:00    | 260   | 1               |
| Aquila-c     | 18:28:00     | -03:48:00    | 260   | 1               |
| Aquila-d     | 18:29:00     | -01:39:00    | 260   | 1               |
| Aquila-e     | 18:31:36     | -02:14:00    | 260   | 1               |
| Auriga/CMC   | 04:29:36     | 35:42:00     | 450   | 2               |
| Cepheus      | 21:02:00     | 68:12:00     | 288   | 3               |
| Chamaeleon I | 11:08:48     | -77:00:00    | 150   | 4               |
| Corona Australis | 19:02:00 | -36:57:00 | 130   | 5               |
| IC 5146      | 21:53:12     | 47:15:00     | 460   | 6               |
| Ophiuchus    | 16:29:12     | -24:30:00    | 125   | 7               |
| Perseus-a    | 03:43:36     | 32:00:00     | 250   | 8               |
| Perseus-b    | 03:29:12     | 30:48:00     | 250   | 8               |
| Serpens-a    | 18:30:24     | 01:14:24     | 429   | 9               |
| Serpens-b    | 18:29:24     | 00:36:00     | 429   | 9               |

Note. References for the distances quoted in this work: (1) Maury et al. (2011), (2) Lada et al. (2009), (3) Kirk et al. (2009), (4) Belloche et al. (2011), (5) Neuhäuser & Forbrich (2008), (6) Arzoumanian et al. (2011), (7) Wilking et al. (2005), (8) Enoch et al. (2006), (9) Dzib et al. (2010).

Class 0/I and Flat Class are referred to as PS stars, while Class II and transition disk (TD) are referred to as PMS stars.

2.2. The Methodologies

In order to select high PS fraction regions, an objective method is required to identify such regions. One simple method which does not rely on the definition of stellar groups is to use the local surface density, $\Sigma$ (Kirk & Myers 2011). If the projected separation from the star to its $n$th nearest neighbor is $r_n$, then the local stellar surface density is

$$\Sigma = \frac{n - 1}{\pi r_n^2}. \quad (1)$$

The fractional uncertainty in $\Sigma$ varies as $(n - 2)^{0.5}$; higher values of $n$ give a lower spatial resolution, but smaller fractional uncertainty (Casertano & Hut 1985, Gutermuth et al. 2005). We adopted $n = 4$ in this paper to give a good compromise between resolution and uncertainty. We calculate the PS surface density, $\Sigma_{PS}$, at every pixel in the map, using the distance to the fourth nearest protostar, $d_{PS}$, using Equation (1). The mean mass of YSOs is assumed to be 0.5 $M_\odot$ (Evans et al. 2009).

Since the survey areas are very large, we first identify regions with abundant PS objects visually for each cloud, then perform surface density analysis to identify groups with high PS fraction. Information for these groups is listed in Table 1.

3. Results

3.1. Identification of High PS Surface Density Groups

We analyzed the local surface density of PS and PMS objects toward the sample of R. A. Gutermuth et al. (2018, in preparation). Figures 1–17 present PS object surface density maps and PS surface density overlaid on the extinction map or
column density map. In all figures, the contours represent the surface density of the PS stars. The PS, Class II and TD stars are overlaid in red dots, blue dots, and yellow dots, respectively. We are interested in zones that have both a high PS fraction and a high concentration of protostars. Using the PS surface density map, we examine contours at 20%, 10%, 5%, and 2.5% of the peak value. The 20% contour is shown in red, while other contours are shown in green. Right: the Two Micron All Sky Survey $A_K$ extinction map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.

Figure 1. Maps of the Aquila-a region. Left: the $n = 4$ surface density of PS objects for the clusters with positions of PS (red dots), Class II (blue dots), and TD (cyan dots) objects overlaid. Contours represent the PS surface density, shown at 10%, 20%, 40%, and 80% of the peak value. The 20% contour is shown in red, while other contours are shown in green. Right: the Two Micron All Sky Survey $A_K$ extinction map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.

Figure 2. Maps of the Aquila-b region. Left: the $n = 4$ surface density of PS objects for the clusters with positions of PS (red dots), Class II (blue dots), and TD (yellow dots) objects overlaid. Contours represent the PS surface density, shown at 2.5%, 5%, 10%, 20%, 40%, and 80% of peak value. The 20% contour is shown in red, while other contours are shown in green. Right: the Herschel column density map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid. The color scale is given in units of cm$^{-2}$.

column density map. In all figures, the contours represent the surface density of the PS stars. The PS, Class II and TD stars are overlaid in red dots, blue dots, and yellow dots, respectively. We are interested in zones that have both a high PS fraction and a high concentration of protostars. Using the PS surface density map, we examine contours at 20%, 10%, 5%, and 2.5% of the peak PS surface density, and select clusters of interest using the smallest contour value (i.e., largest area) which visually encompasses only one local concentration of protostars. We then measure the area, number, and average surface density of PS and PMS objects, and the average surface density and mass of gas contained within the identified regions. We identify a total of 32 PS groups using this method. There are five groups that have only PS objects, including Aquila-b5, Musca, Perseus-b2, Serpens-a1, and Serpens-b2. These clusters should be very young.

In Table 2 we present a catalog of high PS groups, which stand for clusters with both high PS surface density and PS fraction. The location, the peak surface density of PS objects, the contour adopted, the effective radius, the number of PS
objects, the percentage of PS objects formed within high PS groups, and the number of PMS objects within high PS groups are presented. The values were measured as follows. The position of the density center was defined as the density-weighted average of the positions of the stars, in a similar way as von Hoerner (1963):

$$x_{d,j} = \frac{\sum_i x_i \Sigma_{j}^{(i)}}{\sum_j \Sigma_{j}^{(i)}}$$

where $\Sigma_{j}^{(i)}$ is the density estimator of order $j$ around the $i$th particle, and $x_i$ is the two-dimensional position vector of the $i$th star. The contour is the surface density fraction used to select the high PS surface density groups (i.e., 20%, 10%, 5%, or 2.5%). The effective radius of the high PS surface density groups, $r_{\text{eff}}$, is the square root of the area (divided by $\pi$) of the selected region. The effective radius of the groups ranges from 0.02 to 1.10 pc.

3.2. Relationship of the PS Surface Density with Gas

To investigate relationship of the PS groups and gas, we made use of the Herschel GB survey to derive the gas column density for most groups (André et al. 2010). The column densities and temperatures are derived on a pixel-by-pixel basis by fitting a graybody model to the resolved emission at 160, 250, 350, and 500 $\mu$m with a fixed power law (Pokhrel et al. 2016). The two exceptions are Auriga/CMC and Aquila-1. The Auriga/CMC data also come from the Herschel observations (Harvey et al. 2013). The Two Micron All Sky Survey

Figure 3. Maps of the Aquila-c region. Contours represent the PS surface density, shown at 5%, 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.

Figure 4. Maps of the Aquila-d region. Contours represent the PS surface density, shown at 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.
(2MASS) derived extinction map of Lombardi (2009) and Lombardi & Alves (2001) is used to derive the column density of molecular gas for Aquila-1. The average column density of molecular gas within selected regions, $\Sigma_{\text{gas}}$, is calculated using $\Sigma_{\text{gas}} = \frac{A_K}{2.5} \times 8.5 \times 4.40 \times 10^{-3} \text{ g cm}^{-2}$ (Kirk et al. 2009; Boogert et al. 2013). Pokhrel et al. (2016) compared 2MASS $A_V$ maps with the Hershel column density and found good agreement over $A_V = 1 \sim 8$ mag. We only used 2MASS for Aquila-1 (where Herschel data were not available), in which $A_K = 0.81$, and $A_V \sim 6.88$, so the column densities in this regime should be reasonably well probed by both the 2MASS and Herschel observations (Pokhrel et al. 2016). For the remaining regions, Herschel data are better because of their unprecedented angular resolution and sensitivity in the far-IR (Andrè et al. 2010). In addition, Herschel is much better at tracing higher column densities where $A_V$ maps saturate. We computed the position of nearby gas column density peak, average extinction, and average molecular gas column density of the identified groups and present them in Table 3. All of these parameters are obtained in Starlink (Currie et al. 2014). The uncertainty in average column density is the statistical standard deviation obtained using the Starlink and GAIA software. The gas and dust tend to be distributed in filaments, which are much more compact than the selected region, therefore the standard deviations in the column density values are large.

We can see from the column density maps that the PS groups are always aligned with dense filaments. However, the PS surface density peaks do not coincide with the gas column density peaks in most cases. We measure the angular separation...
between the PS surface density peak and its nearest-neighbor gas column density peak, and present the results in Table 3. The uncertainty of the separation listed is the pixel size of the PS surface density map. The largest separation between PS surface density peaks and their nearby gas column density peaks comes from Chamaeleon I, in which the separation is up to $\sim 12$ arcmin. The separation between two peaks is larger than twice the uncertainty for most PS clusters. From visual inspection, we note that the regions with a high PS fraction are overdense in stars relative to the molecular gas density. Such a phenomenon has been noted by Gutermuth et al. (2011) and Kirk & Myers (2011). They proposed that the immediate environments of the YSOs have finished the star formation process, but there are still reservoirs of material nearby which are capable of forming a significant number of new stars.

3.3. Properties of High PS Surface Density Groups

We compute the average PS and PMS surface density, PS ratio, age, freefall time, and present them in Table 4. The value of the average PS surface density, $\Sigma_{PS}$, is simply the number of PS objects divided by the area of the selected region ($N_{PS} \times 0.5/\pi r_{eff}^2$, $M_\odot$ pc$^{-2}$), where the mean PS mass is assumed to be 0.5 $M_\odot$. $\Sigma_{PS}$ ranges from $2.24 \times 10^{19}$ to $1.07 \times 10^{23}$ cm$^{-2}$ with the highest PS surface density being associated with Aquila and Serpens. Similarly, the average PMS surface density, $\Sigma_{PMS}$, is the number of PMS stars divided by the area of the selected region. The relative uncertainty for the $n = 4$ surface density map is $\frac{1}{\sqrt{n}} = 0.7$ (Casertano & Hut 1985). The fraction of PS objects, $f_{PS}$, is the number of PS objects divided by the total number of YSOs.
The age of the groups, \( t \), is derived using the model of Myers (2012):

\[
f_{PS} = \frac{1 - \exp(-t/a)}{t/a},
\]

where \( a = 0.2 \) Myr. Myers (2012) developed a cluster evolution model for cluster age estimation. It assumed a constant PS birthrate, core–clump accretion, and equally likely accretion stopping in the model. The cluster ages can be obtained from the observed numbers of PS and PMS objects. This method of age estimation is simpler than optical spectroscopy, which is derived from stars’ luminosities, spectral types, and evolutionary tracks on the color–magnitude diagram (Da Rio et al. 2009; Reggiani et al. 2011). In addition, the Myers (2012) age estimation method can be applied to young embedded clusters where optical spectroscopy is not possible.

Six of the groups studied here have also been analyzed by Gutermuth et al. (2009), including Auriga/CMC-3, Ophiuchus L1688, Corona Australis, Chameleon I, NGC 1333, and Serpens-a, corresponding to LkHα101, L1688, CrA, Cha I, NGC 1333, and Serpens in that work. Gutermuth et al. obtained surface density maps of YSOs including Class I and II objects (see their Table 8). The surface density map of PS objects used

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**Figure 9.** Maps of the Corona Australis region. Contours represent the PS surface density, shown at 5%, 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the \( n = 4 \) surface density and positions of PS objects (red dots) overlaid.

**Figure 10.** Maps of the IC 5146-b region. Contours represent the PS surface density, shown at 5%, 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the \( n = 4 \) surface density and positions of PS objects (red dots) overlaid.
here seem to be consistent in their morphology with those of YSOs in Gutermuth et al. (2009). However, there are slight differences in the PS identification results in Gutermuth et al. (2009) and R. A. Gutermuth et al. (2018, in preparation). For example, the latter work identified four PS objects in Chamaeleon I-a, while the former identified only two PS objects in the same region.

We plot the PS mass surface density versus the molecular gas mass column density in Figure 18. We classified the groups into five categories using the PS ratio. There are 11 groups with a PS ratio larger than 0.8 (34%), three with a range from 0.6 to 0.8 (9%), 10 with a range from 0.4 to 0.6 (31%), six with a range from 0.2 to 0.4 (6/32%), and two with PS ratio smaller than 0.2 (2/32%). We can see from Figure 20 that most of the cluster-forming regions tend to be forming stars at a fairly moderate rate, and cluster around the $\Sigma_{\text{PS}}/\Sigma_{\text{gas}} = 0.2$ line at the bottom of the plot. Meanwhile, there are a few groups which are undergoing very vigorous star formation at the upper part of the plot and around the $\Sigma_{\text{PS}}/\Sigma_{\text{gas}} = 1$ line, including Serpens-b3 (1989), Serpens-b2 (1592), Aquila-b2 (1382), Aquila-b3 (1169), Aquila-b6 (688), Corona Australis (428), Aquila-b5 (398), and Oph L1688-1 (382). Aquila-b, which is also referred to as Serpens South, was already known to be an interesting and unusual example because of its high PS surface density and high PS fraction (Gutermuth et al. 2008). With properties similar to Serpens and Aquila, Corona Australis and Oph L1688 also appear to be interesting targets for studies of the earliest stages of clustered star formation.

Figure 11. Maps of the Ophiuchus-a region. Contours represent the PS surface density, shown at 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.

Figure 12. Maps of the Ophiuchus-b region. Contours represent the PS surface density, shown at 10%, 20%, 40%, and 80% of peak value. The right panel shows the Herschel column density map of the region with the $n = 4$ surface density and positions of PS objects (red dots) overlaid.
3.4. Statistical Properties of PS Groups

The statistics of PS group properties provides us with information about the typical physical conditions of young stellar clusters within the nearest kiloparsec. Figure 19 presents a series of histograms showing how the properties are distributed among these groups. The distribution of $r_{\text{eff}}$ is plotted in the top-left histogram, which shows that, despite a significant tail of large values, most of the PS groups lie in a relatively narrow peak between 0.02 and 0.3 pc in radius, with a median value of 0.17 pc. This is smaller than the median effective radius of these cluster cores (0.39 pc, Gutermuth et al. 2009), a single calculated effective radius of the high PS fraction region.

Figure 19(b) shows the distribution of PS counts. The PS counts are highly peaked, with a median value of 6. The major outlier on the far right end of the figure comes from NGC 1333, in which the number of PS objects is as large as 35.

Figure 19(c) shows the distribution of surface density of PS objects. In agreement with Gutermuth et al. (2009), the surface densities of PS and PMS objects are skewed to low values, with median values of 46 and 11 $M_\odot$ pc$^{-2}$, respectively. The densest PS groups are Serpens-b3, Serpens-b2, Aquila-b2, and Aquila-b3, with $\Sigma_{\text{PS}}$ values of 1989, 1592, 1382, and 1169 $M_\odot$ pc$^{-2}$, respectively. As stated above, Aquila-b, which is also referred to as Serpens South, was known to be an interesting cluster with high PS surface density and PS fraction (Gutermuth et al. 2008).

Figure 19(d) shows the distribution of surface density of PMS objects. The major outlier on the far right end of Figure 19(d) comes from Aquila-b5.
The PS ratio in PS groups (f_{PS}) is presented in Figure 19(e). The median value of the PS ratio is 0.58. The highest PS ratios come from Aquila-b3, Aquila-b4, Aquila-b6, Perseus-b2, Serpens-a1, and Serpens-b2, in which only PS objects are seen.

The group age is presented in Figure 19(f). Most of these groups are younger than 0.5 Myr, with a median value of 0.25 Myr. The youngest groups are regions with the highest PS fractions. The major outlier on the far right end of Figure 19(f) is Auriga/CMC-3, which is the eldest group among the sample.

Figure 19(g) presents the distribution of the molecular gas column density, with a median value of $1.6 \times 10^{22}$ cm$^{-2}$. The densest group is Aquila-b3, with a column density of $1.2 \times 10^{23}$ cm$^{-2}$. As the histogram shows, most of the groups lie in the range $(1.0-4.0) \times 10^{22}$ cm$^{-2}$. The groups with the most diffuse gas are Cepheus and IC 5146-b, with values of $(2.75 \pm 2.96) \times 10^{21}$ and $(2.85 \pm 1.76) \times 10^{21}$ cm$^{-2}$, corresponding to $51 \pm 55$ and $53 \pm 35 M_\odot$ pc$^{-2}$. This result seems to be lower than from previous observational and theoretical studies (e.g., McKee 1989; Heiderman et al. 2010; Lada et al. 2010; Gutermuth et al. 2011). Recently, based on Herschel data of the Lupus complex, Benedettini et al. (2018) found that most prestellar cores are found above $\sim 3 \times 10^{21}$ cm$^{-2}$. They argue that the column density threshold should be interpreted more as a level over which a higher probability exists to find prestellar cores rather than a stringent limit under which star formation is inhibited.

Figure 19(h) shows the distribution of $\Sigma_*/\Sigma_{\text{gas}}^2$, with a median value of $0.00037$ pc$^2$ M$_\odot^{-1}$, indicating a relative youth and overdensity in the gas (Gutermuth et al. 2011) of these regions. The major outlier on the far right end of Figure 19(h) comes from Aquila-b6, which should have undergone significant gas dispersal (Gutermuth et al. 2011).
Evans et al. (2009) found that most stars form in clusters. Figure 19(i) presents the distribution of $\frac{N_{\text{ps}}}{N_{\text{ps, total}}}$, which ranges from 0.29 to 0.70, with a median value of 0.5. This means that about 50% of PS objects formed in high PS groups, as these groups are always aligned in dense filaments and are rich in molecular gas. Though 50% of PS objects formed outside of high PS groups, many PS objects formed in clusters with high PMS star counts, which means that they still formed in clusters.

4. Discussion

4.1. Nearest-neighbor Distance Distributions

As stated in Section 3, we adopt $n = 4$ while computing the surface density of PS objects. Groups with numbers smaller than 4 will be ignored. If we had used a smaller value of $n$ such as $n = 3$, some small groups with only three or four PS objects would be identified. Figure 20 shows the surface density map of PS objects for Chameleon I and Corona using $n = 3$. The $n = 3$ PS surface density map is similar to the $n = 4$ PS surface density map for Corona Australis. For Chameleion I, small groups with only three PS objects were identified in the $n = 3$ surface density map. Since groups with large numbers of PS objects are better for statistical studies of cluster star formation, we adopt $n = 4$ in this paper.

4.2. Continuous Star Formation Activity

We examine the star formation sequence of nearby embedded clusters with these data sets. Figure 21 shows a
comparison of the PS surface density versus the PMS surface density. We found that $\Sigma_{PS}$ correlates with $\Sigma_{PMS}$ ($r_{corr} = 0.78$), implying continuous and steady low-mass star formation over a period longer than the age of the Class II sources in some clouds, which is several Myr (e.g., Wilking et al. 1989; Evans et al. 2009). Such continuous star formation has also been observed for intermediate-mass stars in other galactic clusters (DeGioia-Eastwood et al. 2001). The dashed line in Figure 21 represents the best-fit linear line to the data with $n_{PMS} > 0$. The slope is 0.236 ± 0.001.

### 4.3. Correlations with Gas Surface Density

The visual similarity between the distribution of Spitzer-identified YSOs and maps of gas structure has been noted previously (e.g., Allen et al. 2007; Evans et al. 2009; Gutermuth et al. 2009). Moreover, Gutermuth et al. (2011) found a positive power-law correlation between the YSO surface densities and the molecular gas mass column densities in eight nearby molecular clouds, with a power-law index of about 2, which agrees with the star formation law $\Sigma_{SFR} = A \Sigma_{gas}^2$. We fit lines to the log $\Sigma_{PS}$ and $\Sigma_{PMS}$ versus log $\Sigma_{gas}$ data, finding them well fit with power-law indices of 1.40 ± 0.01 and 1.13 ± 0.02 (Figure 22), respectively. The power-law index that we found here seems to be lower than those found by Gutermuth et al. (2011), which are 1.87 ± 0.03 in Ophiuchus, 1.95 in Serpens, and 3.8 ± 0.1 in Perseus. The possible reason is that Gutermuth et al. (2011) used the 2MASS extinction maps to measure the gas column density, which might underpredict the gas column densities toward the dense regions of clusters (Pokhrel et al. 2016). The deviation of the

| Region$^a$ | R.A.$^b$ (J2000) | Decl.$^b$ (J2000) | $\Sigma_{peak}^a$ (deg$^{-2}$) | contour$^a$ | $r_{eff}^b$ (pc) | $N_{ps}^b$ | $N_{ps}/N_{ocalPS}$ | $N_{il}^b$ | TD$^b$
|---|---|---|---|---|---|---|---|---|---
| Aquila-a | 18:39:20.001 | 00:33:59.93 | 120 | 20% | 0.53 | 4 | 0.29 | 7 | 3 |
| Aquila-b1 | 18:29:37.989 | −01:51:02.99 | 123120 | 1.25% | 0.10 | 6 | ... | 4 | 0 |
| Aquila-b2 | 18:29:58.999 | −02:01:18.00 | ... | 20% | 0.024 | 5 | ... | 1 | 0 |
| Aquila-b3 | 18:30:03.002 | −02:03:03.00 | ... | 20% | 0.035 | 9 | ... | 0 | 0 |
| Aquila-b4 | 18:30:09.973 | −02:06:03.50 | ... | 5% | 0.044 | 4 | ... | 0 | 0 |
| Aquila-b5 | 18:30:25.973 | −02:11:03.67 | ... | 5% | 0.049 | 6 | ... | 7 | 0 |
| Aquila-b6 | 18:30:47.982 | −01:56:17.28 | ... | 2.5% | 0.034 | 5 | ... | 0 | 0 |
| Aquila-c | 18:27:51.747 | −03:46:03.53 | 282 | 20% | 0.44 | 5 | ... | 12 | 0 |
| Aquila-d | 18:28:56.104 | −01:37:55.26 | 5071 | 20% | 0.12 | 6 | ... | 1 | 0 |
| Aquila-e | 18:31:37.943 | −02:13:30.88 | 1628 | 20% | 0.18 | 4 | ... | 3 | 0 |
| Auriga/CMC-1 | 04:28:36.876 | 36:28:05.55 | 893 | 5% | 1.10 | 7 | 0.48 | 7 | 0 |
| Auriga/CMC-2 | 04:30:34.632 | 35:47:52.44 | ... | 10% | 0.92 | 7 | ... | 15 | 1 |
| Auriga/CMC-3 | 04:30:14.646 | 35:16:06.29 | ... | 10% | 0.90 | 9 | ... | 66 | 7 |
| Auriga/CMC-4 | 04:30:55.690 | 34:56:05.25 | ... | 40% | 0.36 | 7 | ... | 5 | 0 |
| Cepheus | 21:01:36.00 | 68:14:15.00 | 280 | 20% | 0.62 | 7 | 0.54 | 24 | 1 |
| Chamaeleon I | 11:05:46.231 | −77:20:28.63 | 120 | 20% | 0.36 | 4 | 0.36 | 4 | 0 |
| Corona Australis | 19:01:57.839 | −36:57:04.09 | 15304 | 10% | 0.051 | 7 | 0.5 | 2 | 0 |
| IC 5146 | 21:53:36.066 | 47:19:01.43 | 1513 | 20% | 1.01 | 7 | 0.57 | 68 | 0 |
| Ophiuchus-a | 16:31:53.420 | −24:02:31.30 | 176 | 20% | 0.25 | 4 | 0.32 | 5 | 0 |
| Ophiuchus-b | 16:31:52.301 | −24:56:01.50 | 803 | 20% | 0.11 | 4 | ... | 8 | 0 |
| L1688-1 | 16:26:22.668 | −24:23:29.72 | 5447 | 20% | 0.05 | 6 | ... | 3 | 0 |
| L1688-2 | 16:27:28.611 | −24:39:59.83 | ... | 5% | 0.16 | 11 | ... | 14 | 0 |
| IC 348 | 03:43:54.877 | 32:02:59.91 | 4018 | 20% | 0.15 | 7 | 0.53 | 6 | 0 |
| Perseus-a | 03:42:06.579 | 31:47:58.05 | ... | 5% | 0.19 | 4 | ... | 6 | 0 |
| NGC 1333 | 03:29:02.634 | 31:19:59.92 | 5151 | 2.5% | 0.71 | 35 | ... | 87 | 2 |
| Perseus-b1 | 03:25:37.879 | 30:45:49.01 | ... | 5% | 0.28 | 5 | ... | 0 | 0 |
| Perseus-b2 | 03:33:24.314 | 31:07:44.62 | ... | 10% | 0.14 | 5 | ... | 1 | 0 |
| Serpens-a1 | 18:29:48.198 | 01:16:31.50 | 114657 | 2.5% | 0.14 | 8 | 0.70 | 0 | 0 |
| Serpens-a2 | 18:29:57.701 | 01:13:01.50 | ... | 2.5% | 0.20 | 16 | ... | 11 | 0 |
| Serpens-b1 | 18:28:45.996 | 00:52:29.98 | 18029 | 2.5% | 0.23 | 4 | ... | 1 | 0 |
| Serpens-b2 | 18:29:07.999 | 00:31:00.00 | ... | 20% | 0.02 | 4 | ... | 0 | 0 |
| Serpens-b3 | 18:28:55.997 | 00:30:00.00 | ... | 40% | 0.02 | 5 | ... | 1 | 0 |

Notes.

$^a$ Regions identified, position of the center, peak surface density of PS objects, and contours used to select regions.

$^b$ Effective radius, number of PS, Class II, and TD objects within identified regions.

$^c$ Percentage of PS stars within the identified regions compared to the total number of PS stars in the entire region.
Table 3

Properties Derived from Dust Associated with the Identified Clumps

| Region          | R.A. a (J2000) | Decl. a (J2000) | Distance (arcmin) | $\Sigma_{gas}$ (cm$^{-2}$) | $\Sigma_{ps}$ (M$_{\odot}$ pc$^{-2}$) |
|-----------------|----------------|----------------|-------------------|--------------------------|-------------------------------------|
| Aquila-a b      | 18:38:56.001   | 00:33:59.95    | 6.0 ± 2.0         | 0.81 ± 0.44              | (7.28 ± 4.01) × 10$^{21}$            | 134 ± 76                           |
| Aquila-b        | 18:29:41.991   | −01:50:18.00   | 8.3 ± 0.25        | ...                     | (3.82 ± 1.11) × 10$^{22}$            | 670 ± 20                           |
| Aquila-c        | 18:30:54.043   | −02:10:04.25   | 0.32 ± 0.25       | ...                     | (5.64 ± 0.94) × 10$^{22}$            | 1044 ± 174                         |
| Aquila-d        | 18:30:25.980   | −02:10:48.56   | 0.25 ± 0.25       | ...                     | (1.83 ± 0.17) × 10$^{22}$            | 339 ± 31                           |
| Aquila-e        | 18:30:50.028   | −01:56:02.56   | 0.56 ± 0.25       | ...                     | (1.70 ± 0.45) × 10$^{22}$            | 315 ± 83                           |
| Cepheus         | 21:01:36.00    | 68:12:07.50    | 2.125 ± 0.50      | ...                     | (2.75 ± 2.96) × 10$^{21}$            | 51 ± 55                            |
| Chamaeleon I    | 11:06:31.337   | −77:23:30.30   | 11.68 ± 0.50      | ...                     | (6.14 ± 5.96) × 10$^{21}$            | 114 ± 110                          |
| Corona Australis| 19:01:55.335   | −36:58:01.36   | 1.14 ± 0.25       | ...                     | (4.30 ± 2.56) × 10$^{22}$            | 861 ± 506                          |
| NGC 2466        | 21:53:36.206   | 47:21:11.85    | 2.17 ± 0.25       | ...                     | (2.85 ± 1.76) × 10$^{21}$            | 53 ± 55                            |
| Ophiuchus-a     | 16:31:42.469   | −24:00:44.99   | 3.26 ± 0.50       | ...                     | (5.39 ± 4.54) × 10$^{21}$            | 100 ± 84                           |
| Ophiuchus-b     | 16:31:56.825   | −24:58:04.98   | 2.28 ± 0.25       | ...                     | (1.32 ± 0.70) × 10$^{22}$            | 239 ± 137                          |
| L1688-1         | 16:26:27.058   | −24:23:59.78   | 1.21 ± 0.50       | ...                     | (4.16 ± 3.66) × 10$^{22}$            | 770 ± 678                          |
| L1688-2         | 16:27:24.211   | −24:40:29.88   | 1.21 ± 0.50       | ...                     | (1.88 ± 0.64) × 10$^{22}$            | 348 ± 119                          |
| IC 348          | 03:43:59.26    | 32:02:55.58    | 1.10 ± 0.50       | ...                     | (1.99 ± 0.85) × 10$^{22}$            | 369 ± 157                          |
| Perseus-a       | 03:42:06.916   | 31:47:53.75    | 0.11 ± 0.50       | ...                     | (4.52 ± 2.27) × 10$^{21}$            | 85 ± 42                            |
| NGC 1333        | 03:29:02.241   | 31:15:59.94    | 4.0 ± 1.0         | ...                     | (1.05 ± 1.14) × 10$^{22}$            | 194 ± 211                          |
| Perseus-b1      | 03:25:37.879   | 30:45:49.01    | 0                | ...                     | (2.18 ± 1.37) × 10$^{22}$            | 404 ± 254                          |
| Perseus-b2      | 03:33:14.971   | 31:07:45.74    | 2.3 ± 1.0         | ...                     | (2.98 ± 1.01) × 10$^{22}$            | 552 ± 187                          |
| Serpens-a1      | 18:29:48.198   | 01:16:46.50    | 0.36 ± 0.13       | ...                     | (5.73 ± 2.04) × 10$^{22}$            | 1054 ± 389                         |
| Serpens-a2      | 18:29:56.70    | 01:13:09.00    | 0.29 ± 0.13       | ...                     | (4.62 ± 2.3) × 10$^{22}$             | 856 ± 426                          |
| Serpens-b1      | 18:28:43.796   | 00:52:56.98    | 0.71 ± 0.50       | ...                     | (1.00 ± 0.47) × 10$^{22}$            | 185 ± 87                           |
| Serpens-b2      | 18:29:05.80    | 00:30:27.00    | 0.78 ± 0.50       | ...                     | (5.83 ± 0.26) × 10$^{22}$            | 1080 ± 48                          |
| Serpens-b3      | 18:28:53.80    | 00:28:57.00    | 1.19 ± 0.50       | ...                     | (4.20 ± 0.55) × 10$^{22}$            | 778 ± 102                          |

Notes.

a Position of the extinction peak nearest to the identified clusters.

b The $\Sigma_{ps}$ for Aquila-a is derived from 2MASS data, while $\Sigma_{ps}$ for other clusters is derived using Herschel data.

results presented here from the star formation law $\Sigma_{SFR} = A \Sigma_{gas}$ can be explained by gas dispersion and non-coevality within the molecular clouds (Gutermuth et al. 2011).

4.4. Jeans Analysis

The identified PS groups and their associated gas in this work allow us to perform a statistical Jeans analysis. The mean neighboring separations between PS stars could be used to study the fragmentation of clouds during the star formation process. We calculated the typical PS separation $\lambda_{ps}$ from $\lambda_{ps} = \left( \frac{r_{eff}}{\Sigma_{gas}} \right)^{1/3}$, and the Jeans length $\lambda_{J} = \sigma \times \sqrt{\frac{2}{G \rho}}$, where $\sigma$ is the velocity dispersion for 10 K gas, $\rho$ is the mean density from $\Sigma_{gas}$ and $r_{eff}$, and $G$ is the gravitational constant. Figure 23 shows $\lambda_{ps}$ versus $\lambda_{J}$. The separation between PS stars ranges from 0.02 to 0.9 pc. We found that, while taking into account the 70% uncertainty of $\lambda_{ps}$ in the fitting, a slope of 1.017 ± 0.007 was found, with a Pearson correlation coefficient of 0.92. Therefore, the observed fragments in PS clusters seem to be in reasonable agreement with thermal Jeans fragmentation. While the red line in Figure 23 represents $\lambda_{ps} = \lambda_{J}$, we can see from the figure that $\lambda_{ps}$ correlates well with $\lambda_{J}$ for $\lambda_{ps} < 0.4$ pc, which is consistent with Pohkrel et al. (2018). For $\lambda_{ps} > 0.4$ pc, most $\lambda_{ps}$ values are larger than $\lambda_{J}$, Gutermuth et al. (2011) presents a simple evolutionary model which is quite effective in explaining the observed star–gas correlation. They found that the correlation itself can be a direct consequence of thermal Jeans fragmentation, which agrees with our finding that the group spacings are similar to Jeans length for $r < 0.4$ pc.

4.5. Comparison with Gas Freefall Time

The role that PS feedback, such as PS outflows and stellar radiation, plays in clustered star formation is still under debate.
Table 4
Derived Physical Properties of Identified Clumps

| Region      | $\Sigma_{PS}$ ($M_\odot$ pc$^{-2}$) | $\Sigma_{gas}$ ($M_\odot$ pc$^{-2}$) | $f_{PS}$ | age (Myr) | $\tau_{ff}$ (Myr) |
|-------------|-----------------------------------|------------------------------------|----------|-----------|------------------|
| Aquila-a    | 2.3                               | 5.7                                | 0.30     | 0.64      | 0.53             |
| Aquila-b1   | 95                                | 64                                 | 0.6      | 0.22      | 0.10             |
| Aquila-b2   | 1382                              | 276                                | 0.83     | 0.08      | 0.04             |
| Aquila-b3   | 1169                              | 0                                  | 1        | ...       | 0.11             |
| Aquila-b4   | 329                               | 0                                  | 1        | ...       | 0.06             |
| Aquila-b5   | 398                               | 464                                | 0.46     | 0.37      | 0.10             |
| Aquila-b6   | 688                               | 0                                  | 1        | ...       | 0.09             |
| Aquila-c    | 4.1                               | 9.9                                | 0.29     | 0.66      | 0.39             |
| Aquila-d    | 66                                | 11                                 | 0.86     | 0.06      | 0.17             |
| Aquila-e    | 20                                | 15                                 | 0.57     | 0.25      | 0.27             |
| Auriga/CMC-1| 0.9                               | 0.9                                | 0.50     | 0.32      | 0.82             |
| Auriga/CMC-2| 1.3                               | 3.0                                | 0.30     | 0.63      | 0.60             |
| Auriga/CMC-3| 1.8                               | 14                                 | 0.11     | 1.81      | 0.59             |
| Auriga/CMC-4| 8.6                               | 6.1                                | 0.58     | 0.24      | 0.36             |
| Cepheus     | 2.9                               | 10                                 | 0.22     | 0.9       | 0.93             |
| Chamaeleon I| 4.9                               | 4.9                                | 0.50     | 0.32      | 0.48             |
| Corona Australis | 428                           | 122                               | 0.78     | 0.1       | 0.068            |
| IC 5146     | 0.9                               | 11                                 | 0.09     | 2.2       | 1.17             |
| Ophiuchus-a | 10                                | 13                                 | 0.44     | 0.39      | 0.42             |
| Ophiuchus-b | 53                                | 105                                | 0.33     | 0.57      | 0.18             |
| L1688-1     | 382                               | 191                                | 0.67     | 0.17      | 0.068            |
| L1688-2     | 68                                | 87                                 | 0.44     | 0.39      | 0.18             |
| IC 348      | 50                                | 42                                 | 0.54     | 0.28      | 0.17             |
| Perseus-a   | 18                                | 26                                 | 0.4      | 0.45      | 0.40             |
| Perseus-b   | 11                                | 28                                 | 0.29     | 0.70      | 0.51             |
| Perseus-b1  | 10                                | 0                                  | 1        | ...       | 0.22             |
| Perseus-b2  | 41                                | 8.1                                | 0.83     | 0.08      | 0.13             |
| Serpens-a1  | 65                                | 0                                  | 1        | ...       | 0.10             |
| Serpens-a2  | 64                                | 44                                 | 0.59     | 0.23      | 0.13             |
| Serpens-b1  | 12                                | 3.0                                | 0.80     | 0.09      | 0.30             |
| Serpens-b2  | 1592                              | 0                                  | 1        | ...       | 0.036            |
| Serpens-b3  | 1989                              | 398                                | 0.83     | 0.07      | 0.043            |

(e.g., Nakamura & Li 2014). Two main scenarios have been proposed for this issue. In the first scenario, PS feedback is believed to destroy the cluster-forming clump and terminate the cluster formation, thus star formation in clusters should be rapid and brief (Elmegreen 2007; Hartmann & Burkert 2007). This scenario is referred to as rapid star formation. In the second scenario, the PS feedback is believed to play the role of maintaining the internal turbulent motions of the clumps, and star formation should be slow and last for several freefall times or longer (Tan et al. 2006; Nakamura & Li 2014). This scenario is referred to as slow star formation. Clarifying how clustered star formation proceeds could help discriminate whether star formation is rapid or slow, and which kind of role the PS feedback plays in clustered star formation.

To investigate this question we compare the age of the clusters with high PS surface density in nearby embedded clusters. Some groups show extremely high PS surface density and molecular gas surface density. These sources provide ideal targets for future high-resolution spectral line and continuum observations with facilities such as the SMA or ALMA to study the physical condition of these very young groups in more detail. Through such observations, we could quantify the Jeans number as in Pokhrel et al. (2018), estimate the mass accretion rate from spectral line velocity and asymmetry, and estimate the depth of the gravitational potential well as a guide to each region’s ability to attract more gas for regions with high PS surface density.

Figure 18. Surface densities of PS objects vs. gas column densities. The red circles indicate clusters with PS ratios ($ratio_{PS}$) higher than 0.8. The blue triangles indicate clusters with $ratio_{PS}$ ranging from 0.6 to 0.8. The green triangles indicate clusters with $ratio_{PS}$ ranging from 0.4 to 0.6. The yellow stars indicate clusters with $ratio_{PS}$ ranging from 0.2 to 0.4. The diamonds indicate clusters with $ratio_{PS}$ below 0.2.

4.6. Future Applications

In this paper we present a catalog of 32 groups with high PS surface density in nearby embedded clusters. Some groups show extremely high PS surface density and molecular gas surface density. These sources provide ideal targets for future high-resolution spectral line and continuum observations with facilities such as the SMA or ALMA to study the physical condition of these very young groups in more detail. Through such observations, we could quantify the Jeans number as in Pokhrel et al. (2018), estimate the mass accretion rate from spectral line velocity and asymmetry, and estimate the depth of the gravitational potential well as a guide to each region’s ability to attract more gas for regions with high PS surface density.
5. Summary

Using data from the Spitzer c2d and GB legacy surveys and Herschel column density maps, we identified 32 groups with high PS surface density in nearby embedded clusters. Their properties, including their effective radius, PS and pre-main-sequence star surface densities, ages, and average molecular gas column densities are derived. The main results of this work are summarized as follows.

1. Several groups show extremely high PS surface density and high molecular gas surface density, including Serpens-b3, Serpens-b2, Aquila-b2, Aquila-b3, Aquila-b6, Corona Australis, Aquila-b5, and Oph L1688-1. These groups seem to be undergoing vigorous star formation activity, and will be good targets for future high-resolution spectral line and continuum observations to study the fragmentation process.
2. The median molecular gas column density of these groups is $1.6 \times 10^{22} \text{ cm}^{-2}$, corresponding to $296 \, M_\odot \, \text{pc}^{-2}$.

The lowest gas column density of these sub-clusters is about $(2.75 \pm 2.96) \times 10^{21}$ and $(2.85 \pm 1.76) \times 10^{21} \text{ cm}^{-2}$, corresponding to $51 \pm 55$ and $53 \pm 35 \, M_\odot \, \text{pc}^{-2}$.

3. We found a possible correlation between $\Sigma_{\text{PS}}$ and $\Sigma_{\text{PMS}}$ ($r_{\text{corr}} = 0.78$), implying continuous and steady low-mass star formation over several Myr.

4. We found a positive power-law correlation between the YSO surface densities and the molecular gas column densities. The power-law indices were $1.62 \pm 0.01$ and $1.42 \pm 0.01$ for PS and pre-main-sequence stars, respectively.

5. The average separation between PS sources seems to agree well with thermal Jeans fragmentation for sub-clusters with $\lambda_{\text{PS}} \leq 0.4 \, \text{ pc}$, and $\lambda_{\text{PS}}$ is always larger than $\lambda_J$ for $\lambda_{\text{PS}} \geq 0.4 \, \text{ pc}$. These results support the picture that the thermal Jeans fragmentation dominates at smaller scales.

6. The calculated gas freefall time of these sub-clusters seems to correlate with the cluster age derived with the theoretical model ($r_{\text{corr}} = 0.65$), suggesting that regions with shorter dynamical times have a greater PS fraction. This result also suggests that star cluster formation is likely to be a relatively fast process. A possible correlation was found between the group age and $\tau_{\text{ff}}$: age $= (1.31 \pm 0.02) \, \tau_{\text{ff}}$ ($r_{\text{corr}} = 0.78$).
\[
\lambda_{\text{PS}} = -0.01 + 1.23 \lambda_J \\
\lambda_{\text{PS}} = \lambda_J
\]

Figure 23. Mean spacing of PS objects vs. Jeans length. The blue dashed line represents the best fit to the data: \( \lambda_{\text{PS}} = (-0.008 \pm 0.001) + (1.017 \pm 0.007) \lambda (r_{\text{corr}} = 0.92) \). The red solid line represents \( \lambda_{\text{PS}} = \lambda_J \).

\[
\text{age (Myr)} = 1.31 \pm 0.02 \ t_f (r_{\text{corr}} = 0.78).
\]

Figure 24. Age of PS groups vs. gas freefall time. The blue dashed line represents the best fit to the data: age = (1.31 ± 0.02) \( t_f \) (\( r_{\text{corr}} = 0.78 \)).

This research has made use of Starlink and GAIA software. The Starlink software (Currie et al. 2014) is currently supported by the East Asian Observatory. GAIA is a derivative of the Skycat catalog and image display tool, developed as part of the VLT project at ESO. This research has made use of data from the Herschel Gould Belt survey (HGBS) project (http://gouldbelt-herschel.cea.fr). The HGBS is a Herschel Key Programme jointly carried out by SPIRE Specialist Astronomy Group 3 (SAG 3), scientists of several institutes in the PACS Consortium (CEA Saclay, INAF-IFSI Rome and INAF-Arcetri, KU Leuven, MPIA Heidelberg), and scientists of the Herschel Science Center (HSC). J.L. would like to thank the staff of the Smithsonian Astrophysical Observatory (SAO) for supporting her visits, and Xingwu Zheng and Jim Moran for helping to arrange these. We also thank James Lane for assistance with using Marco Lombardi’s extinction mapping. We are grateful to Marco Lombardi, who worked to make his programs available on the web. We also thank the referee for the very helpful report which improved our paper. This work was supported in part by the National Natural Science Foundation of China (11590780, 11590784, 11773054, and U1713237), and Key Laboratory for Radio Astronomy, CAS. R.A.G.’s participation in this project was supported by NASA ADAP grants NNX11AD14G, NNX15AF05G, and NNX17AF24G, NASA JPL/Caltech contract 1489384, and NSF grant AST 1636621 in support of ToTEC, the next generation mm-wave camera for LMT.

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