

Embedded Clusters

Joana Ascenso

Abstract The past decade has seen an increase of star formation studies made at the molecular cloud scale, motivated mostly by the deployment of a wealth of sensitive infrared telescopes and instruments. Embedded clusters, long recognised as the basic units of coherent star formation in molecular clouds, are now seen to inhabit preferentially cluster complexes tens of parsecs across. This chapter gives an overview of some important properties of the embedded clusters in these complexes and of the complexes themselves, along with the implications of viewing star formation as a molecular-cloud scale process rather than an isolated process at the scale of clusters.

1 Introduction

The study of embedded clusters dates back to the first infrared detectors for astronomical use. Still enshrouded in the dusty environment of their natal molecular cloud, embedded clusters are invisible to optical telescopes but reveal themselves as rich and fascinating objects at longer wavelengths. They contain the youngest stars formed, and are therefore invaluable probes of the star formation process. Their stars share the initial conditions of their parent clump of gas, inheriting some of its characteristics, later probed by humans in an attempt to understand the sequence of events dominated by the interplay between gravity, turbulence, and magnetic fields that ultimately forms them.

Both observations and theoretical simulations of star formation have grown in number and in detail since the seminal review of Lada & Lada (2003) on embedded

Joana Ascenso

CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal *and* Universidade do Porto, Departamento de Engenharia Física da Faculdade de Engenharia, Rua Dr. Roberto Frias, s/n, P-4200-465, Porto, Portugal, e-mail: jascenso@fe.up.pt

clusters. Observationally, the largest leaps forward were the widespread shift from the study of individual embedded clusters to the larger context of their molecular clouds, and the large sky surveys to build an increasingly complete census of the star formation in the Galaxy. Also important, the detailed study of extreme star formation events, even by Milky Way's standards, has expanded the parameter space for studies of star formation to the limit of extragalactic studies. These advances were made possible at such a large scale by the deployment of near- and mid-infrared telescopes and instruments, both in ground-based and in space observatories. The Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006), that covers the entire sky, and later the *Spitzer Space Telescope* were invaluable at revealing the detailed intricacies of entire star forming regions as well as to allow a multitude of large scale surveys. *Spitzer* legacy programs such as the Cores to Disks (c2d, Evans et al., 2003), the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE, Churchwell et al., 2009; Benjamin et al., 2003), and the MIPS GAL (Carey et al., 2009) programs, as well as dedicated surveys of individual regions, have greatly advanced our understanding of star forming regions, producing numerous catalogues, most of which yet to be fully explored. Ground-based observatories have also contributed significantly with near-infrared telescopes used for surveys (e.g., 2MASS, UKIRT, ESO VISTA), and with near-infrared adaptive optics assisted instruments for deep and high-resolution studies of individual regions (e.g., GEMINI, VLT). In the far-infrared, the *Herschel Space Observatory* (André & Saraceno, 2005) is currently providing invaluable insight into the youngest stages of star formation, bridging the gap between the study of pre- and proto-stellar molecular clouds with sub-millimeter and radio telescopes, and the study of embedded clusters at NIR wavelengths. On the opposite end of the spectrum, sensitive X-ray observations of star forming regions, made possible greatly through the *Chandra X-ray Observatory*, have strongly contributed to the effort of assessing the stellar populations of star forming regions.

This chapter provides an overview of the observable properties of embedded clusters in the important context of their molecular clouds, brought to light by this massive technological development. The analysis is limited to Galactic regions - those that can be studied in greater detail -, and does not include the interesting star formation taking place at and around the Galactic Centre; the reader is referred to the review by Longmore et al. (2014) for the latter. Section 2 of this chapter elaborates on the difficulty of adopting one single definition of "cluster" for all studies of star formation, reviewing the most common definitions in the literature, and what they entail. Section 3 reviews the observed structure and morphology of embedded clusters and star forming regions, highlighting the trends that have emerged from the increasing sample of studied clouds, and what they reveal in terms of the underlying processes at play. Section 4 describes the constraints on the timescales for star formation, crucial in any theory of star formation, derived from the observations of the ages and age distributions in embedded clusters and cluster complexes.

Other very interesting topics could be addressed in detail in the context of embedded clusters, and are only mentioned briefly in this chapter. The stellar mass distributions in clusters and on the molecular cloud scale can reveal important prop-

erties of the star formation process; the universality of the initial mass function, and whether or not embedded clusters are mass segregated have been the subject of many interesting studies in the past decade; the consequences of the clustered environment to individual forming stars at different stages of their evolution, and in particular their formation along with massive stars is also an active topic of research, and one that can help understand the probability of a given star developing planets with certain characteristics. The analysis of the efficiency and of the rate of star formation, both at the embedded cluster and at the molecular cloud scales, is also starting to be possible at great detail for a statistically significant sample of known regions in the Galaxy. The topics included in this chapter are a naturally biased selection of the what the author considers the most robust observational advances in the last decade and most susceptible of providing solid constraints to existing theories.

2 What is an Embedded Cluster?

An embedded cluster is a group of young stars that is still embedded in its natal molecular cloud. Although seemingly simple, this definition is all but trivial. The definitions we adopt reflect and, at the same time, somehow limit our understanding of star formation. Let's start with the definition of "embedded" and then move on to the definition of "cluster".

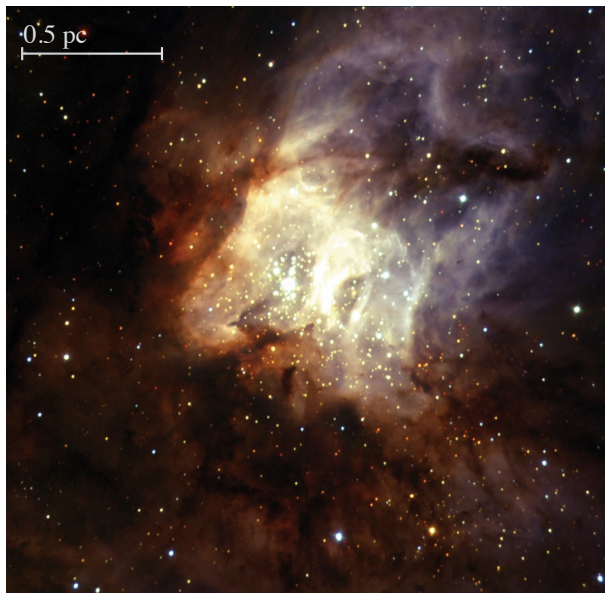


Fig. 1 RCW 38 is a young embedded cluster, imaged here in the near-infrared bands J , H , and K_S with ESO/NTT/SOFI (Ascenso, Alves et al).

2.1 Defining “*embedded*”

An embedded star (or cluster) is one that is still enshrouded in its natal molecular cloud. It is typically not (fully) observable at optical wavelengths due to the heavy obscuration caused by the dust grains in the cloud, but it can be seen in the near-infrared, where young stars emit significantly (e.g., Adams et al., 1987; Robitaille et al., 2006), and the dust is more transparent (Savage & Mathis, 1979; Cardelli et al., 1989; Rieke & Lebofsky, 1985; Draine, 2011). Near-infrared telescopes and instruments are therefore the choice of excellence to detect and characterise embedded objects, and indeed both ground-based and space telescopes equipped with infrared detectors and filters have boosted our demographics and our understanding of embedded clusters exponentially in the past three decades.

It should be noted, perhaps trivially, that not all heavily obscured objects are embedded: there are objects that are just seen behind molecular clouds, and are therefore not within them (e.g., Alves et al., 2001). Objects that are in fact embedded notoriously display signatures of youth. Since stars tend to disperse their natal gas and dust via accretion and feedback over time an embedded star or cluster is one that is necessarily young, and this leads to some unspoken confusion regarding the “embedded” nature of clusters.

The canonical timescale for a cluster to clear enough material to become optically visible is around 5 Myr (Leisawitz et al., 1989), although more recently Morales et al. (2013) analysed the association of several young clusters with molecular material, and proposed an upper limit of the embedded phase of 3 Myr, while Portegies Zwart et al. (2010) quote a duration of 1 to 2 Myr for the embedded phase of a cluster. But a cluster’s embedded phase should be a sensitive function of the mass of the stars being formed. For example, massive stars develop HII regions that are much more efficient in dispersing the cloud material than the outflows from low-mass stars (Matzner, 2002), so clusters with massive stars should be the fastest to clear their surroundings and to emerge from their molecular clouds. Therefore, although the condition of being embedded is enough to attest to an object’s youth, it is, by itself, a poor criterion for a sample of clusters of uniform age.

On some accounts, the definition of “embedded” is narrowed to refer to a state when the potential of the cluster is dominated by the mass of the molecular cloud (Gutermuth et al., 2009), according to which many known young clusters can no longer be considered embedded. Trumpler 14, Westerlund 2, and NGC3603, for example, are all believed to be well under 5 Myr old, but even though they are still partially obscured by cloud material, they have already cleared most of their intracluster gas. So these clusters are embedded only in the sense that they are still associated with the molecular cloud, since their gravitational potential is no longer dominated by the gas.

For the purpose of this chapter we will focus on clusters that are younger than 5 Myr and still associated with their molecular clouds, regardless of their potential being dominated by the gas.

2.2 Defining “cluster”

The definition of “cluster” is more controversial, and it is non-trivial for many reasons. The need to define “cluster” arises in several different contexts, each focused on different aspects. In the context of large-scale observational surveys, for example, a set of uniform criteria is paramount to detect (new) clusters against the field of the Galaxy in an automated yet robust way. When analysing the birth conditions and the evolution of clusters over time, the most useful criterion is probably their dynamical state. Depending on the question one is trying to address, the physical aspects that are considered relevant - and that should therefore be used to define clusters as entities - may vary. Additionally, the details that numerical simulations of star forming molecular clouds are increasingly capable of producing raise the pressure to find observable signatures of some key property of young stellar populations that can be tied to a dominant physical process. It is therefore not surprising to see several definitions of “cluster” in the literature, nor that they evolve alongside with the progress in our numerical capabilities.

Previous to any definition of cluster, one practical difficulty arises already in finding the stars that actually make up a population, since knowing whether a given star is physically associated with its neighbours or if it is only co-located in projection is challenging, especially for more evolved populations like open clusters. Stars younger than a few million years offer the advantage that they share properties that are distinguishable from older stars, providing important clues to their membership (e.g., Lada, 1987; Shu & Adams, 1987; Adams et al., 1987; Gutermuth et al., 2009; Meyer et al., 1997; Feigelson & Montmerle, 1999; Feigelson, 2010). Observational studies of clusters therefore often start by identifying the young stellar objects (YSOs), usually by analysing their near-infrared colours and/or X-ray properties, and then proceed to finding over-densities that qualify as clusters by some measure. The cloud material associated with embedded clusters in particular effectively blocks a fraction of background stars, partially filtering out stars unrelated to the cluster and increasing the local stellar density contrast.

Low density groups are sometimes distinguished from clusters and classified as O(B) associations if they contain O (and B) stars (e.g., Blaauw, 1964), T associations, if they only contain low-mass stars (Herbig, 1962), or R associations, intermediate between the two and associated with bright, reflection nebulae (van den Bergh, 1966). These classes overlap in many cases, and have largely fallen into disuse over time. When no criteria other than an overdensity of stars is used, the terminologies “stellar aggregate”, “stellar grouping”, or similar are also found. The concept of “Correlated Star Formation Event” was introduced by Kroupa et al. (2013) as an alternative to the concept of “cluster”; it refers to all the stars that were formed in one given star formation event over a spatial scale of about one parsec, regardless of their spatial distribution in a star forming region at present. These stars would be co-eval to within the duration of the star forming event. Although the identification of such events observationally is limited by our ability to determine individual stellar ages, this is an interesting concept that is perhaps more meaningful in understanding the progression of star formation in a cloud than the overdensity concept of cluster.

2.2.1 Morphological criteria

Empirically, a cluster is an overdensity of physically co-located stars. This definition is often used loosely to refer to all instances of stellar groups. In this sense, detecting clusters can be as straightforward as finding surface density peaks by eye on large-scale images, with or without some additional criterion to minimise contamination from spurious stellar density fluctuations. In the case of young clusters, these criteria are usually a minimum number of members, or the association with some tracer of youth, like outflows, ionised gas, or molecular gas and dust, for example (Faustini et al., 2009; Dutra & Bica, 2000; Bica et al., 2003a,b; Borissova et al., 2011, 2014; Majaess, 2013; Froebrich et al., 2007).

Quantitatively, several authors have defined several empirical criteria, most often calibrated to detect previously known clusters in blind surveys. Ivanov et al. (2002), for example, require a stellar surface density contrast of at least $3\text{-}\sigma$ above the galactic background, and at least 50 members to claim the detection of a cluster. Similarly, Kumar et al. (2006) require a stellar surface density contrast greater than $2\text{-}\sigma$ above the local background, but a minimum number of only 8 members. Carpenter (2000) requires that the total number of stars within a closed $2\text{-}\sigma$ surface density contour exceeds a $5\text{-}\sigma$ enhancement with respect to the expected stellar background. Porras et al. (2003) differentiate between “clusters” and “groups” based on whether a given region contains more or less than 30 stars, respectively. Alternatively, in a variation of the density-threshold algorithm, Gutermuth (2005), following Casertano & Hut (1985), use the distance to the Nth nearest neighbour as a proxy for local density, eliminating the need to bin the data spatially to produce density maps where to look for enhancements.

Gutermuth et al. (2009) devised a more sophisticated method to isolate what they called “cluster cores” from co-spatial, extended young stellar populations also associated with the cloud; they analyse the separation between neighbouring stars using the minimum spanning tree (MST) algorithm, and define the edge of a cluster core where the MST branch lengths become larger than some critical distance. Bastian et al. (2007) employ the minimum spanning tree in a slightly different way, truncating the separation between stars to a maximum allowed distance to define clusters. Mercer et al. (2005) detect clusters using an algorithm that calculates the probability of a given overdensity being an actual cluster and not a chance projection effect considering the statistical distribution of the background field, still based on geometrical and density enhancement arguments but also on luminosity and colour criteria.

Schmeja (2011) compares the performance of a few different algorithms in finding star clusters, and gives additional references to works where the algorithms were applied. This author finds, as expected, that strongly peaked clusters are easily detected by all algorithms, whereas low contrast clusters can fall below the radar, which reflects the ambiguity in the very definitions.

2.2.2 Dynamical criteria

The previous definitions of clusters as overdensities of stars, although powerful, lack physical grounds. A common physical criterion to define “cluster” observationally is the inferred relative stability of the stellar groups. Lada & Lada (2003) classify a group of young stars as a “cluster” on the basis of its survivability against tidal disruption up to the age of typical open clusters (100 Myr). According to this definition, a group of stars is considered a cluster if it contains more than 35 members, and if its density is higher than $1.0 M_{\odot} \text{pc}^3$; an *embedded* cluster is one that is also “fully or partially embedded in interstellar gas and dust”.

In theoretical work and in numerical simulations of star formation, “cluster” is usually synonymous with *bound* group of stars. This definition is useful because it simultaneously contains important information about the molecular cloud from which the cluster formed and about its long-term survivability, and because it leaves out any spurious overdensity of unrelated sources. It is also a *possible* definition in those contexts, since theory has all the information about a given system under investigation, which is almost never the case in the context of observations. Portegies Zwart et al. (2010) (see also Gieles & Portegies Zwart, 2011) distinguish between clusters (bound systems) and associations (unbound systems) on the basis of their age with respect to the system’s dynamical time¹. A system whose age is, at present, a few times its dynamical time has survived disruption by dynamical effects for long enough to be considered a “cluster” according to this definition. These systems are likely to survive as bound entities for a significant fraction of a Hubble time (Portegies Zwart et al., 2010).

A dynamical analysis enables many interesting studies, including a comparison between the molecular clouds and their stellar products: systems (or subsystems) that are bound when they are very young are likely to have formed monolithically from a bound, gravity dominated cloud, whereas their unbound counterparts are more likely to have formed from unbound, turbulence supported clouds. But the dynamical state of a cluster is often difficult to assess, and one subject to many uncertainties. In Portegies Zwart et al. (2010), for example, the definition of “cluster” depends strongly on the knowledge of the cluster’s age, of its mass, and of its virial radius. The determination of a cluster’s age from photometric surveys depends mostly on the knowledge of the distance to the cluster, which can be uncertain by a large amount for clusters that are too far away for current measures of parallax; for example, the distance to the cluster Westerlund 2 ranges from 2.8 to 8 kpc, even in the recent literature (Ascenso et al., 2007a; Carraro et al., 2013; Zeidler et al., 2015; Rauw et al., 2011). ESA’s mission Gaia (Gaia Collaboration et al., 2016) will be an invaluable resource for clusters that are already partially revealed in the optical. The determination of a cluster’s age (and age spread) is also importantly sensitive to uncertainties in other properties like unresolved stellar multiplicity, differential extinction between cluster members, and stellar variability, including episodic ac-

¹ The dynamical time is the time a typical star would take to cross the system ($t_{dyn} = R_{cl}/\sigma_V$). This is not to be confused with the system’s relaxation time – the timescale on which the system reaches equipartition of energy via two-body encounters –, which is much larger.

cretion, and to the accuracy of the stellar evolutionary tracks themselves (Hartmann, 2001; Jeffries, 2010; Preibisch, 2012). Estimates of cluster masses, on their turn, can be severely affected by incompleteness, poor membership assessment, or variable detectability over the surveyed area due to, for example, extended, uneven bright nebula or patchy extinction. Estimates of mass are also only as reliable as the measurements of distance and age of the cluster, which, as outlined above, are significantly uncertain. And depending on the wavelength, they are more or less sensitive to the shape of the local extinction law, and also to the specific pre-main-sequence evolutionary tracks chosen to convert luminosity into mass. Finally, a cluster's virial radius is taken as a factor of the half-light radius and assumes a given stellar density profile. In rigour, only a spectroscopic analysis of a significant fraction of cluster members at moderate spectral resolution can determine their velocity distribution and allow for a proper characterisation of a cluster's dynamical state, but this is discouragingly expensive in observation time. As a consequence, our knowledge of the dynamical state of the many known clusters is still limited to an educated guess, and in particular it is still too unreliable to be a strong observational constraint to theories of star formation.

The very significance of the definitions of “cluster” based on dynamical arguments inferred by observations has been called into question by studies that suggest that there is no fundamental difference between the stellar density distributions of “clusters” and “non-clusters” by any one definition. Bressert et al. (2010), for example, do not find any bimodal signature in the stellar density distribution of several star forming regions that suggests a preferred or a threshold density for “clusters”, although their sample includes only a few clusters, of relatively low-mass, and their diagnostics may be considered ambiguous (Pfalzner et al., 2012; Gieles et al., 2012).

In light of the previous arguments, it is clear that we are currently not in position to make a statistically accurate comparison of bound and unbound clusters, or of clusters and associations. At best, we can attempt to rank known clusters in order of density, mass, luminosity, or age, and try to find meaningful correlations that can be used to constrain the physical conditions for star formation under different environments.

In the context of this chapter, a “cluster” will be taken as its most simple literary meaning: a collection of physically associated stars.

3 Morphology and Structure

Embedded clusters come in a variety of forms. This can be inferred instantly by comparing the images of a few star forming regions. It was the striking morphological difference between different young clusters that led to their traditional classification as “centrally condensed” or “hierarchical” (Lada & Lada, 2003): the first refers to clusters where the surface density has one strong peak and then smoothly declines radially, and the latter to density distributions with multiple peaks and a high level of sub-structure.

The importance of defining a cluster's morphology extends beyond the need for uniform characterisation criteria. Rather, different morphologies are produced by different conditions of the progenitor cloud, they reflect different dominant physical phenomena, and they can be predictive of the cluster's survival as bound entities on large timescales or of their demise into field stars.

3.1 Observational challenges

Similarly to detecting clusters, analysing their morphology has important observational challenges. Incompleteness is the obvious enemy of morphological studies: often only a relatively small fraction of a cluster's members can be detected. The distance and the limited sensitivity of instruments act against the detection of faint stars; the limited resolution of the instruments acts against resolving individual stars in a cluster, an effect that is additionally amplified in very dense and/or distant clusters; the presence of bright stars hampers the detection of less luminous neighbours out to significant projected distances; and the interstellar extinction and the bright nebula typical of star forming regions, which are almost always variable in embedded clusters, change the detection limits and the completeness spatially, producing artificial structure in the observed distribution of cluster members. Also important is the contamination from field stars, as mentioned before in section 2.2; unless cluster members are efficiently distinguished from field stars, the analysis of their spatial distribution can be significantly biased, especially in the case of low surface density clusters.

Infrared observations can minimize some of these effects. Extinction at longer wavelengths is significantly lower than in the optical (Rieke & Lebofsky, 1985), providing deeper and more uniform completeness levels. Also, the dynamic range of stellar brightness is lower in the infrared than in the optical, i.e., the luminosity contrast between the massive and low-mass stars will be smaller, making the latter easier to detect.

3.2 Cluster morphologies

The human brain can readily distinguish between a centrally condensed distribution and one that is more substructured, but an objective measure of structure that can be applied uniformly to a large sample, and one that can be quantitatively compared with results from simulations and between different regions is required to build a statistical framework for the properties of star forming regions.

Clusters visually recognised as centrally condensed are generally relatively isolated clusters, with most members located in a relatively small projected area in the sky. It is possible to define a "centre" for the cluster as the location of the maximum stellar surface density, for example, and the surface density itself then decays

away from that centre as a smooth function in a way somewhat resembling globular clusters. Analytically, the surface density decay of a centrally condensed cluster is typically well described by a simple power-law, by a power-law with a flat core (Elson et al., 1987), or by a King profile (King, 1962, 1966). The latter is parametrised by the density at the cluster’s core, by its core radius, and by a tidal radius, and formally describes the density distribution expected of a single-mass dynamically relaxed population that is tidally truncated by an external (galactic) potential. While this is not an accurate description of embedded clusters, the King profile is used as a convenient function with few parameters, allowing for a uniform description of the morphology of centrally condensed clusters (e.g., Hillenbrand & Hartmann, 1998; Ascenso et al., 2007a,b; Gutermuth et al., 2008; Sung & Bessell, 2004; Wang et al., 2008; Harfst et al., 2010; Kuhn et al., 2010). The Elson et al. (1987) profile is often preferred in numerical simulations of clusters, although it is also used to fit observed density profiles of young clusters (Brandner et al., 2008; Gutermuth et al., 2008; Gouliermis et al., 2004; Sana et al., 2010).

Conversely, the stellar surface density of substructured clusters does not follow a smoothly decaying radial function, instead showing multiple peaks over some projected area. Several metrics have been proposed to describe their fractal-like structure, including the two-point correlation function (Gomez et al., 1993), to describe the probability distribution of any given star having a companion at increasing distances, the distribution of mean surface density of companions of cluster members (Larson, 1995, see also Bate et al. (1998)), the normalised correlation length, \bar{s} (Cartwright & Whitworth, 2004), defined as the mean separation between cluster members normalised to the radius of the cluster, and the normalised mean edge length, \bar{m} , of the minimum spanning tree defined by the cluster members. Cartwright & Whitworth (2004) review these methods in some detail (see also Schmeja & Klessen, 2006), and propose what they call the Q -parameter as the most robust parameter to characterise the morphology of a cluster. The Q -parameter is defined as the ratio between \bar{m} and \bar{s} , and is able to quantify the degree of subclustering, as well as to distinguish between a centrally condensed morphology and a hierarchical morphology: a Q parameter larger or smaller than 0.8 implies a large-scale radial density gradient or the presence of subclustering, respectively. This parameter has since become a widespread tool to analyse the structure of embedded clusters.

It is worth noting that, in rigour, a substructured distribution of stars, although commonly dubbed “hierarchical”, is not necessarily fractal. The loose classification of “hierarchical” in the context of clusters usually refers simply to clusters with more than one peak in stellar density, but Bate et al. (1998) caution that the surface stellar density distribution in a few known star forming regions previously classified as fractal was also consistent with the stars being distributed in random sub-clusters, a non-fractal distribution. This distinction is important when interpreting observations of cloud structure and stellar density distributions in young clusters in light of the dominant physical processes, and also when the number of stars is small enough that statistical fluctuations can lead to the illusion of substructure.

3.3 The molecular cloud scale



Fig. 2 The large-scale view of NGC 6334 imaged by ESO/VISTA in the near-infrared bands J , H , and K_s (galactic North is up, galactic East is to the left, credit ESO/J. Emerson/VISTA). NGC 6334 contains several embedded clusters along its actively star forming ridge.

The prolific effort to find new clusters in the Galaxy has already yielded a sizeable database of embedded cluster candidates. Some surveys target individual clusters, and are typically deep enough to produce a comprehensive census of the stellar population down to the low-mass end of the YSO mass spectrum; due to observational time constraints and spatial resolution limitations, these surveys are mostly limited to nearby, low-mass clouds, that harbour relatively low-mass clusters as well. Other works encompassed observations of entire molecular clouds, revealing interesting patterns of young stellar populations. A few examples of deep surveys covering the molecular cloud scale are the early works of Lada et al. (1991); Lada (1992) and Strom et al. (1993), for example, and the more recent dedicated surveys of, e.g., Allen et al. (2007); Carpenter (2000); Evans et al. (2009); Román-Zúñiga et al. (2008); Gutermuth et al. (2009, 2011) and Kuhn et al. (2014). On the massive end, only two surveys covered the molecular cloud scale to a level comparable to more nearby star forming regions: Preibisch et al. (2014) and Reipurth & Schneider (2008, see also Wright et al. (2014)) review the stellar population and the clusters of the Carina and of the Cygnus X complexes, respectively, each containing well over $10^4 M_{\odot}$ in young stars.

Blind, large scale or even full sky surveys provide more complete censuses of embedded clusters at the galactic scale, necessarily covering a wider range in cluster mass and different environments. Even though so far most of the cluster candidates identified in these surveys are not yet sufficiently characterised – for most cases even the number of stars belonging to each cluster is not yet properly assessed – several

tendencies have already begun to emerge, mostly supporting on a larger scale the understanding derived from surveys of local star forming regions.

3.3.1 Cluster complexes

Surveys of individual molecular clouds have long suggested that star forming regions are significantly substructured. Rather than containing one single cluster with all or most YSO's, many nearby regions contain several clusters organised in a more or less hierarchical way (Fig. 3). A few well known examples covering the low-mass end are Serpens and Perseus, Lupus, and Chameleon (I and II); Orion, the Rosette Complex, Vela, the W3/W4/W5 complex, and RCW 106 are examples in the intermediate-mass range; and among the most massive we know the Carina complex, Cygnus X, NGC 6334, W51, W49A, that contain clusters that are more massive individually than entire lower-mass cluster complexes (see several authors in Reipurth (2008a,b), and Evans et al. (2009); Román-Zúñiga et al. (2008); Nguyen et al. (2015) for descriptions of these regions).

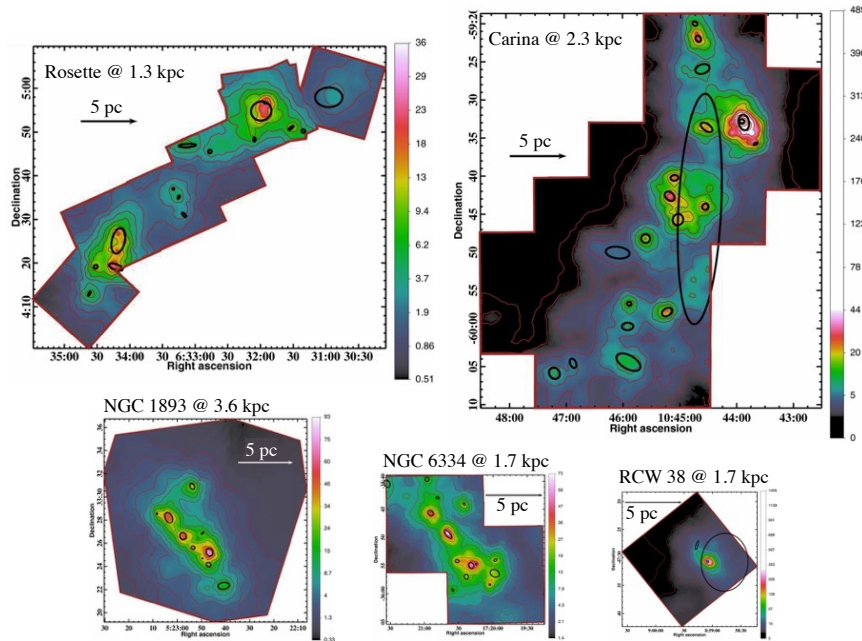
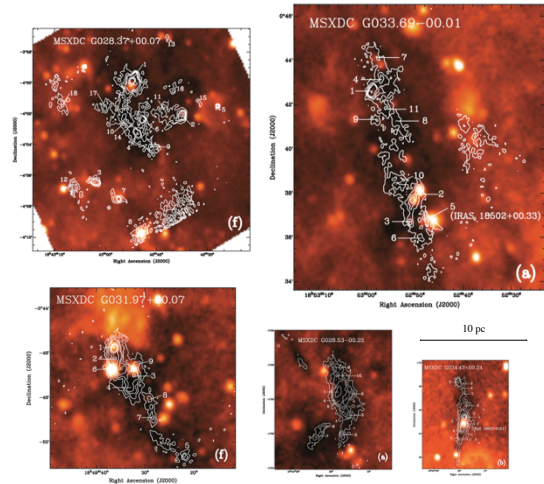


Fig. 3 Observed YSO surface density distributions for a few star forming regions registered to the same physical scale (adapted from Kuhn et al., 2014). These distributions illustrate well the cluster complex morphology in almost all regions that were observed in this work at the few-parsec scale. The colour bars are in units of stars pc^{-2} .

The same tendency is found in the most recent embedded cluster catalogues that span wider ranges in heliocentric distance, and presumably in mass; in the sample of Bica et al. (2003a) 25% of embedded clusters have other clusters in their immediate (projected) surroundings; Morales et al. (2013) find that more than 50% of the clusters in their sample are in cluster complexes; Kuhn et al. (2014) find substructured distributions of YSOs in all of their targeted clouds. In their sample of very young embedded clusters, Kumar et al. (2006) also find a strong tendency for complexes to show substructure with 80% of the clouds exhibiting multi-peaked surface density distributions, already at very young ages; these authors applied the same morphological classification to the relatively older embedded clusters of Lada & Lada (2003) and found a similar fraction. Although these numbers are not yet entirely reliable given the incompleteness of these surveys, they suggest that the most common outcome of star formation from molecular clouds is then cluster complexes², as opposed to single clusters.

The size of these cluster complexes in the Galaxy varies from a few to a few tens of parsecs along their largest dimension. The spread in their clusters' size is smaller, around 1 pc (e.g., Kuhn et al., 2014; Banerjee & Kroupa, 2017), mostly depending on the definition of cluster size and on differing observational limitations. To some degree, the distinction between a centrally concentrated and a hierarchical stellar distribution can be regarded as a matter of scale, as already hinted by Lada & Lada (2003): at the tens of parsec scale (cluster complex scale) substructure is ubiquitous, whereas at the 1-pc scale (cluster scale) whatever observed substructure is usually undistinguishable from statistical number fluctuations in a centrally peaked, more or less elongated, distribution.

Fig. 4 Infrared dark clouds, presumably the precursors to clusters, often show elongated morphologies with large aspect ratios and multi-peaked density distributions over scales of ~ 10 pc, similar to cluster complexes. Figure adapted from Rathborne et al. (2006).



² I will refer to “cluster complex” as the global clustered YSO population within one cloud, and to “cluster” as the individual clusters within the complex.

Overall, the distribution of young stars in cluster complexes is reminiscent of the distribution of dense gas in molecular clouds (e.g., Lada et al., 1996; Testi et al., 2000; Gutermuth et al., 2009), both with respect to their hierarchical structure and to their geometry. Like molecular clouds (e.g., Rathborne et al., 2006; Peretto & Fuller, 2009; Churchwell et al., 2009, see also Fig. 4), cluster complexes have elongated morphologies with large aspect ratios. This resemblance is expected if cluster complexes are younger than the dynamical timescale for the clouds, otherwise they would have had time to dissolve and take on more spherical geometries. At the cluster scale, because it is smaller, there may have already been significant dynamical mixing during the early embedded phase or even earlier, in the gas phase (Elmegreen, 2006). Still, although the presence of substructure in a stellar density distribution implies that the system is not yet dynamically relaxed, some authors caution against taking the similarity of cloud morphology and the distribution of YSOs at face value, showing numerical simulations that produce hierarchical distributions of YSOs that bear little resemblance to the original distribution of dense gas (Parker & Dale, 2015). Also, even though substructure is typically interpreted as evidence of turbulence as an important agent in driving the process of star formation, Krumholz (2014) argue that a hierarchical distribution of YSOs does not necessarily stem from turbulence-dominated initial conditions.

3.3.2 Isolated clusters

Although the majority of star forming regions that have been studied in detail exhibits a significant degree of substructure over scales of the order of tens of parsecs (cluster complexes), there are a few interesting exceptions – single clusters that appear to be the sole significant product of their natal molecular cloud. In the Galaxy, excluding the peculiar vicinities of the Galactic Centre, a few embedded clusters stand out as relatively isolated, as far as current data suggests: Westerlund 2, NGC 3603, NGC 6611, and RCW 38 are a few of those³, and it is likely that more examples will emerge as the new candidate catalogues start to be explored at higher detail with state-of-the-art instrumentation. These clusters exhibit centrally concentrated morphologies with faint hints of substructure at most, and sizes less than, or of the order of 1 pc, similar to individual clusters in the cluster complexes mentioned in the previous section. However, their progenitor clouds do not seem to harbour other clusters at present.

Low mass clusters are not considered in this context; since their density contrast with respect to their surroundings is typically small, any low-level extended population of young stars in the cloud will provide comparable numbers of stars that they cannot be considered isolated anymore. This introduces a bias that needs to be kept in mind: the fact that the four isolated clusters considered here are significantly

³ A few other known clusters could be mentioned, such as W40, GM 24, or NGC 6618, for example, but the YSO populations of these clusters are not yet sufficiently well characterised to establish them as isolated in their clouds, or they are too close to other star forming regions that they may be part of a larger complex.

more massive than the average individual cluster in cluster complexes does not necessarily mean that isolated clusters tend to be massive, nor that massive clusters tend to be isolated (Carina is an excellent counter-example of the latter). We will come back to these isolated clusters later.

3.3.3 Unclustered young stars

As implied above, not all young stars reside in the cores of embedded clusters. Rather, a variable fraction of these stars is found distributed throughout the embedding molecular cloud in relative isolation (Fig. 5). Large scale infrared surveys, and later the *Spitzer Space Telescope* were instrumental in showing that these distributed populations are ubiquitous in star forming regions, most notably in cluster complexes. X-ray and infrared combined YSO maps, less vulnerable to contamination from unrelated sources albeit also less complete in particular mass ranges, confirm the presence of widespread populations of young stars outside the main clusters in star forming regions.

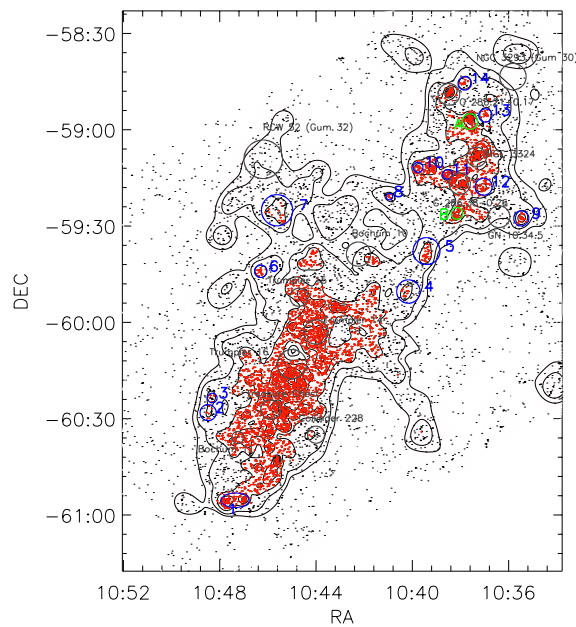


Fig. 5 YSOs are often found permeating entire star forming regions. This plot of the position (*left*) and surface density (*right*) of YSOs in the Carina Nebula from Zeidler et al. (2016) shows a widespread population of unclustered YSOs throughout the complex.

A reliable estimate of the actual fraction of isolated stars is contingent on the definition of cluster and on several observational parameters. To zeroth order, accounting for a significant fraction of the YSOs in a given region requires a sensitive sample with uniform completeness limits, which is often challenging (see sect. 3.1). Also, since these objects are scattered over large areas, observations should cover a large enough field of view outside the main clusters, ideally covering the full extent

of the molecular cloud at comparable depth, which is observationally expensive. It is equally important to accurately estimate the number of stars that are *in* clusters, since underestimating this number will enhance the weight of the extended population; this often requires high resolution observations to adequately resolve the crowded cores of dense clusters and account for the most of their stellar population as possible. And finally, a reliable de-contamination from field stars and distant galaxies is paramount, since unrelated objects will artificially inflate the fraction of distributed YSOs fairly easily. Once the young star population is properly accounted for, the definitions of cluster and of the boundaries of clusters obviously play a critical role in the calculation of the fraction of stars that are outside clusters.

With this in mind, most estimates point to a relatively low fraction of stars found outside clusters: in Orion A and B estimates are of a maximum of 25% distributed YSOs (Allen et al., 2007; Carpenter, 2000), around the same fraction as for Ophiucus (11-32%, Allen et al., 2007) and Perseus (20%, Carpenter, 2000; Jørgensen et al., 2008; Evans et al., 2009); in Lupus and in the Rosette complex, the fraction of YSOs found outside clusters is estimated around 15% (Merín et al., 2008; Román-Zúñiga et al., 2008, respectively); Monoceros R2 has a higher fraction of distributed YSOs, about 44% (Carpenter, 2000). On the more massive end, in the W3/W4/W5 complex more than 50% of the stars are found in the five most massive clusters; since the complex contains nineteen clusters in total, this suggests that only a small fraction of YSOs is distributed (Carpenter, 2000); in the Carina complex an estimated 35% of YSOs is found outside the main cluster cores (Feigelson et al., 2011), although the number of cluster members could be underestimated in this particular case since these observations cannot fully resolve the highly crowded cores of the most massive clusters, significantly underestimating the number of stars in these clusters. Surveys including multiple star forming regions estimate an overall fraction of “isolated” objects between 10 and 20%, with upper limits of 40% (Porrás et al., 2003; Koenig & Leisawitz, 2014; Gutermuth et al., 2009; Evans et al., 2009).

The spatial distribution of these isolated stars in the cloud can be useful in constraining their origin. They are often found to be spread throughout the molecular clouds in a more or less uniform way, or, in more quiescent clouds, still tracing the dense gas. These stars can have formed at their current locations in relative isolation, they can have been ejected from the nearby clusters, or they can be the populations of slightly older clusters formed in the same cloud that have already begun to disperse away. A typically small fraction of these stars is found in the nearby outskirts of clusters, toward structures that were created by their feedback, for example at the edges of bubbles or in pillars carved by the strong winds of the most massive stars. Theoretically, stellar feedback is capable of collecting and compressing existing molecular gas and create the conditions for star formation in regions that would otherwise probably not form stars, and this is likely the origin of some of the stars in the distributed populations, but results from numerical simulations suggest that this may account for only a small fraction. All these scenarios produce stars with different ages compared to the stars in clusters.

4 Age Spreads

As we have seen above, embedded clusters and star forming regions in general are complex systems. It is not surprising that their histories are also not simple. A molecular cloud does not form only one generation of stars; rather, it is common to find populations separated in age by a few million years associated with the same molecular cloud, clearly suggesting that star formation does not occur in a single burst and then stops. Understanding these age spreads, which reflect the star formation history of the cloud, is fundamental to understand the very process of star formation.

A review of the methods used to determine ages is beyond the scope of this book, and the reader is referred to recent reviews (Preibisch, 2012; Soderblom, 2010, and references therein) for a discussion. It is nevertheless important to mention that the determination of ages is subject to many uncertainties, and that it is common for different methods to return significantly different values. This is caused both by observational limitations and by uncertainties in the pre-main-sequence evolutionary models used to convert luminosities and colours into ages and masses (e.g., Getman et al., 2014; Jeffries, 2010; Baraffe et al., 2012; Preibisch, 2012; Naylor, 2009; Hartmann, 2001; Burningham et al., 2005; Hillenbrand et al., 2008). Using synthetic clusters, Preibisch (2012), for example, showed that a coeval population of 3 Myr stars with the stellar variability, excess emission from circumstellar material, and binarity fraction expected for young stars, and subject to the differential interstellar extinction typically found toward embedded clusters can present near-infrared colours consistent with an age spread of more than 1 Myr.

For this reason the absolute ages inferred observationally for star forming regions are still rather unreliable. Relative ages can be more robust, as these are often inferred indirectly through the analysis of the presence of circumstellar material. Circumstellar envelopes and discs dissipate over time, such that the fraction of stars in a cluster with circumstellar discs, for example, can provide a good handle on the relative age of a cluster (Haisch et al., 2001; Briceño et al., 2007): clusters with a large fraction of stars still with strong disc emission are presumably younger than clusters where the majority of stars is already discless. The characterisation of the emission from the circumstellar material via spectral energy distribution (SED) fitting (Robitaille et al., 2006) provides a finer age classification, since the dispersal of discs follows a predictable logic. These have the inconvenient that the timescale for the dissipation of discs is mass-dependent, and that the fraction and characteristics of discs may vary for the same age as a function of environment; for example, the circumstellar material of stars that have close massive neighbours may be affected by their strong feedback (e.g., Preibisch et al., 2011; Johnstone et al., 1998). But in general SEDs allow the distinction between younger and older pre-main sequence stars, which, along with colour information and reasonably complete censuses of the young stellar populations, is useful in constraining the progression of star formation in a cloud.

Understanding age spreads in star forming regions is important at several different scales, which again argues for surveys of entire molecular clouds as important

complements to narrower surveys of individual clusters. On the scale of individual clusters, it is interesting to assess the timescale over which their stars form, whether individual clusters are formed rapidly, in a timescale comparable to their dynamical time, or slowly and in quasi-equilibrium (e.g., Elmegreen, 2000; Tan et al., 2006); it is interesting to assess whether they are formed monolithically already as large clusters from a massive clump of gas, or are assembled from several subclusters. These different scenarios require different conditions from the progenitor cloud, and they operate under the influence of different dominant physical processes, so they provide invaluable constraints towards a predictive theory of cloud evolution and star formation. At the scale of cluster complexes – essentially the molecular cloud scale – it is interesting to understand whether a cloud forms stars as a whole, or rather if different regions collapse to form stars at different times; if the prompter for star formation is internal or external to the cloud; if star formation develops spontaneously from quiescent gas or if it is induced by some event. Often neglected, the unclustered population distributed in the cloud is intimately connected with the star formation on the clustered scales, and its age distribution also contains important information.

The characterisation of age spreads and of star formation histories at any scale is most meaningful in young regions for two reasons. First, the relation of age with the fraction of stars with circumstellar material becomes less sensitive for older populations, as stars dissipate their discs. While the class 0/I phase is very short, around 0.5 million years (Evans et al., 2009), class II and III stages last longer, around a few million years. Second, given enough time, dynamical processes will erase most of the imprint of the properties of the progenitor molecular cloud on the stellar distributions, decreasing the sensitivity of the analysis of ages and age spreads in the context of their spatial distributions to the star formation history of the cloud.

The term “age spread” will be used here to refer to the age distribution of stars in a given context. We will review age spreads within individual clusters, age spreads in molecular clouds, and age spreads of the distributed/unclustered population of molecular clouds. Some authors prefer the term “age difference” when referring to the different ages of several clusters in the same molecular cloud, reserving the term “age spread” to populations that have formed together, in the same local event of star formation (Preibisch, 2012).

4.1 Age spreads in cluster complexes

There is still not sufficient evidence to say whether different parts of the same molecular cloud “know” about each other’s status of star formation. Depending on which phenomenon triggers star formation in a cloud, it is possible that it occurs independently in regions that are sufficiently far apart, that events of star formation are sequentially triggered internally, or that the same trigger initiates star formation in the cloud as a whole in a more or less synchronised way. The differences are signif-

icant from the point of view of the mechanisms at play, which means that studies of star formation benefit greatly from analysing molecular clouds globally rather than only individual regions within them. Cluster complexes in particular offer a unique opportunity to study the progression of star formation in a cloud, since each cluster can be viewed as a local event of star formation within the common global history of the cloud.

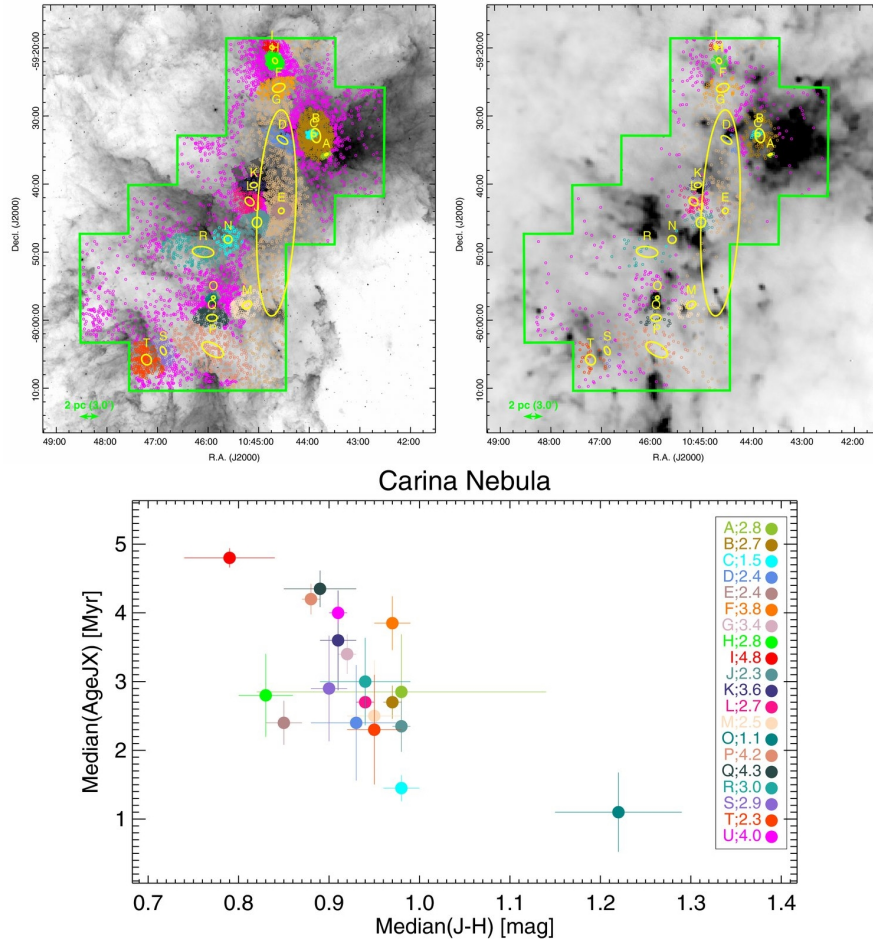


Fig. 6 Most cluster complexes harbour clusters with different ages but the global age spread is not too wide, nor is the age gap between any two clusters ordered chronologically. As in the Carina Nebula shown in this figure (from Getman et al., 2014), the spatial distribution of ages is often inconsistent with internal triggering being the dominant mechanism for the propagation of star formation within the cloud.

Clusters of the same cluster complex often show different ages, separated by as much as a few million years, as is illustrated in Fig. 6 for the Carina Nebula.

This is seen across the mass spectrum of star forming regions. In the low-mass end, Palla & Stahler (2000), for example, found age spreads larger than 3 Myr in several nearby star forming regions (Taurus-Auriga, Lupus, Chamaeleon, Upper Scorpius, and NGC 2264). Massive complexes, such as Orion, Carina, or Cygnus, for example, show similar age spreads. Interestingly, the maximum age gap between clusters of the same complex if ordered chronologically is not too wide. There are a few known examples of clouds that have “very old” (a few tens of million years) and very young clusters with nothing in between (Chamaeleon may be one such example), but most clouds show smaller inter-cluster age gaps of the order of 1 Myr or less. In other words, molecular clouds do not typically take long breaks between forming clusters once they start, but they do not seem to collapse as a whole either.

It is tempting to interpret the temporal proximity between different clusters in the same cloud as evidence for sequential star formation, with the first star formation event(s) triggering the formation of the following, especially in clusters containing massive stars, those that produce the most feedback. Although feedback can have a destructive potential at small distances from the source star (e.g., Ngoumou et al., 2015), it can also collect and compress less dense gas farther in the molecular cloud, or just precipitate the collapse of pre-existing neighbouring clumps that would otherwise take longer to, or never even, form stars and clusters (Elmegreen & Lada, 1977; Bertoldi, 1989; Whitworth et al., 1994; Dale et al., 2007). The exact importance of these mechanisms as triggers for star formation depends on the density distribution of the cloud prior to the influence of feedback, and on the mass and location of the star(s) that produce the feedback. The latter is particularly relevant because only stars capable of producing an HII regions are able to trigger the collapse of neighbouring clumps. In theory, the perturbation from the first generation of stars is able to propagate and produce new stars (and clusters) at the necessary speed across a typical cloud to reproduce the observed age spreads at the observed distances between clusters⁴ (e.g., Elmegreen & Lada, 1977), but in this scenario the spatial distribution of ages at the scale of the cloud should show a coherent progression. In the sample of star forming regions of Getman et al. (2014) – the largest to date with stellar ages determined uniformly within molecular clouds – only about one third of the complexes show reasonably coherent age gradients between clusters, suggesting that internal triggering may not be the dominant controller of the progression of cluster formation in molecular clouds.

Alternatively, an external event such as the passage of a spiral density wave, nearby supernova events, or cloud-cloud collisions (e.g., Elmegreen, 1998; Cedrés et al., 2013; Dobbs & Pringle, 2009; Dobbs et al., 2015; Dale, 2015; Fierlinger et al., 2016) could produce age distributions in clusters that are not necessarily ordered, depending on the geometry and alignment of the cloud relative to the triggering event. This would explain the lack of a coherent age gradient mentioned above, and

⁴ For a 10 pc long cloud with a global age spread of 5 million years, star formation would have to propagate at an average speed of at least 2 pc Myr⁻¹, or 2 km s⁻¹. This is about 10 times the typical sound speed in molecular clouds assuming a temperature of 10 K ($c_s = (kT/m_{H_2})^{1/2} \sim 0.2$ km s⁻¹). E.g., Getman et al. (2014) suggest a propagation speed of star formation around 5 km s⁻¹ in some of their clouds.

that some cluster complexes show no significant age spread between clusters at all. For example, Ybarra et al. (2013) suggest that star formation started everywhere in the Rosette Complex around the same time, suggesting that star formation was somehow synchronised globally, presumably by an external event. Also NGC 6334, the Cat's Paw Nebula, hosts a couple of slightly older clusters, already partially revealed in the optical, and then a molecular ridge spanning 10 pc of active star formation occurring in discrete pockets at present (Persi & Tapia, 2008), challenging any reasonable internally triggered star formation interpretation. The external trigger scenario is attractive to explain such a large scale coordination of star formation, although it is equally difficult to prove. At some level it is not much different to discuss the formation of stars at the molecular cloud scale and the formation of the density structure in molecular clouds themselves, since it is not likely that molecular clouds and dense clumps within them form spontaneously from the interstellar medium. Considering that stars form everywhere there is dense enough gas (Lada et al., 2010), the problem of the progression of star formation within a cloud is reduced to the problem of the formation of molecular clouds.

At the molecular cloud scale, massive isolated clusters (see Section 3.3.2) are particularly interesting from their age distribution perspective. These are apparently the sole products of their molecular clouds: what is their history? Can they just be the first generation of star formation in clouds that will later form other clusters and host cluster complexes? Since the known clusters of this type are already around 1 to 2 Myr old and their clouds do not show evidence for substantial ongoing star formation, this scenario would produce complexes with considerable age spreads, depending on the timescale for star formation in different parts of the cloud. This would not be unseen; the age spread in Chamaeleon between regions I and III is likely larger than 10 Myr, and there does not seem to be any cluster with an age intermediate between these two regions. But this appears to be a rather atypical case. Carina, for example, has an estimated age spread for clusters of ~ 8 million years, between Trumpler 15 and the Treasure Chest cluster (Preibisch et al., 2011; Smith et al., 2005) but small age gaps between consecutively formed clusters. Westerlund 2, classified above as one such isolated clusters, has a very young, very embedded cluster forming just outside its borders, with hints of massive star formation even, suggesting that clustered star formation is still ongoing in its progenitor cloud. This is, however, the only site of active cluster formation known in the cloud, which suggests that this cloud is not likely to form a complex with many clusters, at least not with a small age spread. Other clouds that contain clusters as massive as Westerlund 2 (e.g., Carina, Cygnus, W49A) all contain several similarly massive clusters, reinforcing the idea that Westerlund 2 (and also NGC 3606 by similar arguments) is indeed different from cluster complexes. RCW 38, the youngest of the three isolated clusters considered here, also shows some evidence for ongoing clustered star formation in its vicinities (Winston et al., 2011); given its younger age (0.5 Myr) this cluster is more likely to evolve into a (small) cluster complex than Westerlund 2 or NGC 3603.

The observation of cluster complexes is thus unveiling a non-obvious scenario for the progression of star formation in molecular clouds. It is clear that molecular

clouds do not collapse globally but rather in clumps that form clusters, and that there is no unique trend for the age distribution of the clusters they produce. Also important, molecular clouds seem to exhaust their star formation potential fairly rapidly, on timescales of the order of a few Myr, the maximum age spreads found in cluster complexes and the time in which they typically disperse.

4.2 Age spreads in individual clusters

Individual clusters refer here to clusters that have formed in a single event, regardless of having formed alongside other clusters in the same cloud. The Orion Nebula Cluster is an example of an individual cluster in a molecular cloud (Orion A) that hosts other clusters.

Most detailed studies suggest that the age spread in individual embedded clusters is very small, typically within the age determination uncertainties, if it exists at all (e.g., Preibisch et al., 2002; Moitinho et al., 2001; Jeffries et al., 2011; Banerjee & Kroupa, 2014, 2015; Getman et al., 2014). The main observational difficulty when analysing individual clusters – more important even than the uncertainties from the age determination method – is contamination from stars that do not belong to the cluster under study. Since clusters often reside in cluster complexes, the contamination by stars from the complex may be significant, and since the contaminant stars will also be young, distinguishing them from a given cluster population can be difficult. As such, published claims of significant age spreads within young clusters are often challenged by subsequent larger scale surveys that reveal populations of older YSOs spread out in the cloud, distributed more or less uniformly far beyond the cluster’s borders, suggesting that they are not part of that cluster but are rather different populations within the complex (see section 4.3). If these stars are taken as cluster members they will misleadingly present as evidence for age spreads within the cluster.

The Orion Nebula Cluster is an example where considerable age spreads have often been reported (Palla & Stahler, 1999; Huff & Stahler, 2007; Da Rio et al., 2010). The recent study of Getman et al. (2014) suggests a shallow radial gradient of increasing age that is interpreted by the authors as the cluster having formed outside-in. However, these results are equally compatible with the cluster having a small age spread and being immersed in a distributed population of older stars that do not belong to the cluster: the cluster stars would bias the age toward younger values in the centre, and the older, extended population would start to weigh in toward the peripheries as it outnumbered the cluster members. An older population, unrelated to the ONC but extending well into its foreground, has indeed been found by Alves & Bouy (2012), which could account for the older stars that make up the observed pseudo age spread. On the more massive end, Ascenso et al. (2007b) found hints of a core-halo morphology in their small field survey of the cluster Trumpler 14, where the “halo” stars seemed older and appeared unclustered; later, a significant

population of older stars permeating the entire Carina Complex was uncovered by a large-scale survey (Preibisch et al., 2011).

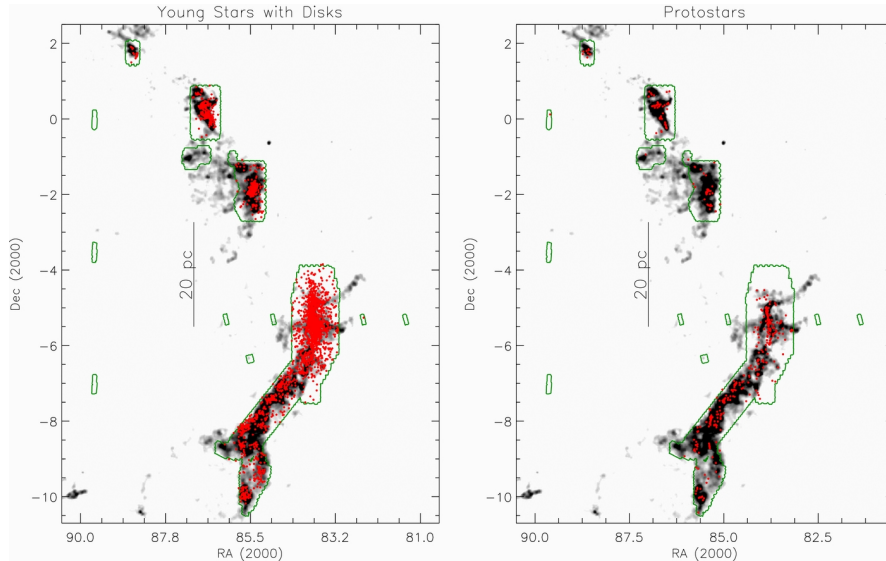


Fig. 7 Younger, class 0/I sources are typically found more tightly clustered than the older, class II sources. This is illustrated in this figure from Megeath et al. (2012) of the Orion molecular clouds showing the distribution of protostars (*right*) and the distribution of older stars with discs (*left*).

Indeed, studies of the population of YSOs in different stages of evolution at the molecular cloud scale, made possible largely through *Spitzer* observations, reveal this as a pattern: although young sources are clustered in general (see section 3), class 0/I YSOs – those with the most circumstellar material and the youngest – consistently appear more tightly clustered than their class II and class III counterparts. Fig. 7 illustrates this typical distribution for the Orion clouds. Since the class 0/I stage is very short-lived, the position of these stars is very likely the position at which they formed, supporting the view that stars form in dense configurations within clouds (e.g., Lada & Lada, 2003). The wider distribution of class II and class III sources likely reflects the characteristics of the unclustered population of stars in molecular clouds (see section 4.3).

Massive clusters are particularly interesting in terms of their age spreads. They contain extraordinary numbers of stars, which means they were formed from an extraordinarily massive gas clump or assembled by mergers of smaller clusters. Observationally, some of the most massive embedded clusters known in the Galaxy outside the Galactic Centre, do not show evidence for significant age spreads (Kudryavtseva et al., 2012; Stolte et al., 2004; Ascenso et al., 2007a,b). Banerjee & Kroupa (2014, 2015) find that the observed properties of NGC 3603 in particular are compatible with a starburst scenario and incompatible with it hav-

ing been formed through the coalescence of smaller clusters. The suggested near-instantaneous, monolithic formation of such massive clusters raises important questions regarding the support of molecular clouds against gravitational collapse over long enough timescales to assemble the necessary amount of dense gas (see section 6).

In light of existing evidence, individual clusters do not seem to have significant intrinsic age spreads. Events that form individual clusters seem to operate on very small timescales, of the order of, or smaller than, the local dynamical times (less than 1 Myr for typical clusters).

4.3 Age spreads of the unclustered stars

The distributed stars found both in and around cluster complexes and isolated clusters (see section 3.3.3) show a wide range in ages. Several of these populations⁵ were found and studied in multiple works using observations and methods sensitive to different ages, from less than 1 Myr to 20 Myr. Adding to the results of the individual studies, this diversity shows that the age spreads of these distributed populations is rather large; and rather extreme as well: the oldest, and often the youngest, stars in a star forming region are found in the distributed population.

The youngest distributed stars are often found toward the edges of the clouds, projected against shells, bright-rimmed clouds, or pillars, that are illuminated and carved by the action of a cluster of slightly older stars. This spatial correlation, sometimes backed by other indicators, has been widely interpreted as evidence for star formation triggered by existing stars or clusters. Dale et al. (2015) compiled a list of the many studies that have claimed observational evidence for triggered star formation, most from positional arguments.

A small fraction of very young stars and protostars is sometimes found along dense filaments of gas and dust in more quiescent regions of the clouds, although not far from the location of the older stars and clusters. These are not randomly distributed in the clouds, but apart from their ordered location along the filaments, they are not significantly clustered at the individual cluster (~ 1 pc) scale, unlike the majority of stars of the same age.

Most of the distributed population of stars in a cloud is made up of intermediate age pre-main-sequence stars (class II). Although they usually also follow the overall clustering pattern of the star forming region, they are typically less clustered than class 0/I objects. It is not uncommon to find class II stars pervading the clouds at the cluster complex scale (a few to a few tens of parsecs), both in embedded and in less embedded regions. At this point it is useful to note that class II (and III) sources can represent a wide range of stellar ages, since more massive stars dissipate their circumstellar material more rapidly, therefore acquiring the SED signatures characteristic of class II YSOs at younger ages (Williams & Cieza, 2011). It

⁵ In this context, I use the term “population” loosely to refer to the collection of stars that are not clustered, without any implication regarding common properties or origin.

is therefore expected that (younger) class II sources be found clustering with coeval class I sources, and that older class II sources be found spread out in the cloud, as observed.

Wide distributions of old pre-main-sequence stars, as old as 20 Myr, have also been reported in star forming regions dominated by younger stars and clusters. In the Galaxy, Orion A, the Carina Complex, NGC 3603, and NGC 6611 in the Eagle Nebula all have reports of “old” populations in their clouds. Interestingly, in Orion A and in Carina, these populations can tentatively be attributed to an identifiable cluster, namely NGC 1980 and Trumpler 15, respectively, both containing massive stars. Conversely, the “old” populations of NGC 6611 and of NGC 3603 have not been associated to any existing cluster, although a giant molecular shell is observed in the Eagle Nebula that can be the remnant of a supernova event (Moriguchi et al., 2002), suggesting a possible association with the old pre main sequence population.

5 Stellar mass distributions

This chapter would not be complete without a dedicated word about stellar mass distributions in clusters. It is widely accepted that the observed stellar mass distribution of a young cluster is a good approximation of its initial mass function (IMF), and that this IMF seems to be fairly universal across the spectrum of cluster properties (e.g., Lada & Lada, 2003; Bastian et al., 2010; Kroupa et al., 2013). On the theoretical side, we have presently reached a stage where all accepted theories of star formation are capable of producing the observed IMF of clusters, undermining its predictive or constraining power. But recent and upcoming observing facilities may change that, by changing the focus of IMF studies slightly.

For example, it is not yet clear when exactly the IMF becomes fully assembled, or whether massive or low mass stars preferentially form first, or what impact, if any, the first formed stars have on the formation of the subsequent population. In the future it will become increasingly easy to study extremely young clusters, including of the more distant massive clusters in the Galaxy, with adequate resolution and sensitivity. Is the IMF of these clusters any different from that of older clusters that have presumably already finished most of their star formation activity, suggesting that different mass stars form at different stages?

Also, it is only apparently clear that the IMF is indeed universal in all environments. The same IMF is found in most star forming regions, but some “regions”, especially the less massive, include stars from large physical volumes, sometimes from entire clouds, whereas others refer only to individual clusters at the 1-pc scale. It is not clear how these similar IMFs over such different scales can be made consistent. As more and more cluster complexes are studied it will become increasingly possible to assess the mass distribution of the entire stellar population formed by one cloud with respect to the IMF of the individual clusters, and to the IMF of the distributed population. We must then understand what is the meaning of an IMF at the molecular cloud scale. If different star formation events (clusters) in the same cloud

(cluster complex) are independent from each other, then so should their IMFs, otherwise star formation must be set at the global scale of the cloud rather than locally, reducing the distance between studies of stars in clusters and cluster complexes and studies of molecular clouds and assembly of dense gas, towards a consistent picture of star formation.

6 Embedded Clusters and Star Formation

Clusters and cluster complexes reveal intricate and often puzzling star formation histories in molecular clouds. Observational results suggest that star formation is a rapid and likely discontinuous process at the molecular cloud scale. Rather than forming one cluster, each cloud typically forms multiple clusters over timescales of a few million years. Individual clusters themselves appear to be mostly coeval, but around and between them significant populations of stars with wide age spreads are often found. What can these spatial and age distributions tell us about the origin and the progression of star formation in clouds?

Different possibilities considered by theory and reproduced by several flavours of numerical simulations predict different properties for star forming regions that are becoming increasingly possible to compare with observations. To this end one important step has been taken in the last decade: more and more star forming regions are being studied at the molecular cloud scale. The structure and age distributions of young stars in molecular clouds are particularly relevant in constraining the timescales for star formation, both locally and globally, indirectly favouring one or other aspect of the theoretical possibilities.

Individual embedded clusters span a wide range in mass and density, but there is very little convincing evidence that they have large age spreads (see section 4.2). Individual embedded clusters younger than ~ 1 Myr are common, which suggests that clusters are formed fairly rapidly, on timescales comparable to their dynamical times. Their smoothly peaked morphologies at the ~ 1 pc scale already at these very young ages suggest that they were formed from a molecular cloud clump that was itself already dense with a peaked density distribution, or that any initial substructure must have been erased very efficiently. The latter would argue for a slower process of star formation that would allow time for dynamics to act on pre-existing structure, but large scale observations of pre- or proto-stellar clumps in massive, infrared dark clouds, presumably the precursors to embedded clusters, often show individual clumps about the size of embedded clusters already with fairly symmetric density distributions (Shirley et al., 2003; Ragan et al., 2012; Traficante et al., 2015). A large fraction of these clumps shows signs of star formation, supporting further the view that the starless phase of a dense molecular clump is very short. Taken at face value, this and the small age spreads in individual embedded clusters require that, for each cluster, a significant amount of dense gas be gathered prior to the onset of star formation, and that it does not fragment significantly in the process. This may require a support against gravitational collapse until conditions are met that precipitate the

quasi-instantaneous formation of a whole cluster of stars, especially for the most massive; or, alternatively, this could be achieved if the dense gas itself was gathered by a rapid phenomenon, such as collisions between molecular clouds, collisions of filaments within molecular clouds, or through the action of external agents, such as supernovae.

Cloud-cloud collisions have been recently invoked to explain the rapid formation of massive clusters such as NGC 3603 and Westerlund 2. Based on radio kinematic data, Furukawa et al. (2009) and Fukui et al. (2014) find that each of these clusters lies at the interface between two massive molecular clouds that seem to be moving towards each other with relative velocities of ~ 20 km/s. Hydrodynamical simulations confirm that cloud-cloud collisions can form bound and massive clumps and cores (Habe & Ohta, 1992; Anathpindika, 2010; Inoue & Fukui, 2013; Wu et al., 2015), but studies of the characteristics of the produced stellar population are still necessary to show that this mechanism is capable of forming entire (massive) clusters. The same type of kinematical signature is found in clouds harbouring lower mass and more substructured star forming regions, such as M20 (Torii et al., 2011) and RCW120 (Torii et al., 2015), suggesting that this mechanism, if indeed capable of forming clusters, can reproduce a range of observed properties. This scenario is particularly appealing in the cases of isolated massive young clusters, where the gathering of the required amounts of dense gas is particularly challenging.

Competing theories, complete with numerical simulations, posit that clusters may be assembled hierarchically, with stars forming along filaments and then falling to the deepest part of the potential well, forming a cluster (Bonnell et al., 2003; McMillan et al., 2007; Bate, 2009; Maschberger et al., 2010). Filaments are a distinct characteristic in all molecular clouds, and young stars within them are also ubiquitous in star forming regions, especially in low-mass environments, lending support to this scenario. These simulations do not require a mechanism to assemble massive clumps of gas prior to star formation, and they also form clusters very rapidly, although the actual duration of the star formation event depends sensitively on the initial conditions. As a by-product, very extended haloes of stars must form from stars that are ejected from the cluster core through dynamical interactions as the subclusters merge together. This could provide a natural origin for the extended population of young stars that is very often found in star forming regions (sections 3.3.3 and 4.3), and an overall consistent picture for the formation of all stars in star forming regions. However, the age of the extended population should be consistent with the (narrow) age range of the final clusters, whereas the majority of the distributed stars is often older than the clustered population. Unless, since ages are often inferred through the presence of circumstellar material, the ejection process strips or truncates the discs from these stars, making them appear older to such age diagnostics. For lack of computational power, it is also not yet clear that numerical simulations that form clusters via hierarchical assembly can produce clusters as massive as the most massive observed, or that they can reproduce the larger scale cluster-complex morphology prevalent in clouds with the observed age spreads under realistic initial conditions.

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