Star clusters: basic galactic building blocks
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Insights into star cluster formation from $\lambda \gtrsim 1\mu$m

Rémy Indebetouw,[1,2] Rosie Chen, Crystal Brogan, Barbara Whitney, Thomas Robitaille, Leslie Looney and the SAGE team

[1]Astronomy Department, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904–4325, USA
email: remy@virginia.edu

[2]National Radio Astronomy Observatory, Charlottesville, VA, USA

Abstract. We would like to know how molecular clouds turn into stellar clusters, and with what efficiency massive stars form in those clusters, since massive stars are the main agents responsible for evolution of the interstellar medium of galaxies, and their subsequent star-formation history. The imprint of 'precluster' molecular cloud conditions can be observed, but only in the least evolved, most embedded clusters, necessarily at wavelengths that can penetrate more than 10 visual magnitudes of extinction. Mid-infrared photometric imaging, most recently and extensively from *Spitzer*, can be used to select young stellar objects in clustered star-formation environments in our Galaxy and nearby galaxies. Relatively sophisticated methods have been developed, but the fundamental principle remains the selection of sources that have excess infrared emission from circumstellar dust. By fitting radiative-transfer models to a source's spectral-energy distribution between ~ 1 and $\sim 100\mu$m, we constrain the circumstellar dust *distribution* and evolutionary state. We can explore many things with this protostellar distribution in mass/luminosity and time/evolutionary state. For example we do not see strong evidence for primordial mass segregation in initial studies. We find evidence of primordial hierarchical substructure, greater clustering at the youngest stages, and even imprints of the pre-stellar Jeans scale. We see correlation of the youngest sources with dense molecular clumps and constrain the timescales for chemical processing and dispersal of those clumps. We have only begun to mine the wealth of existing *Spitzer*, emerging *Herschel* and soon *ALMA* data.

Keywords. stars: formation, galaxies: star clusters, infrared: stars, submillimeter

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1. Introduction and motivation

The youngest star clusters still being formed are a critical laboratory to understand physics ranging from the formation of individual massive stars through the star-formation history of galaxies. Consider first galaxy scales. The evolution of a galaxy depends on the efficiency with which it converts interstellar material into stars and how effectively those stars process the clouds and either inhibit or enhance subsequent star formation. One of the most commonly used empirical tools in extragalactic astronomy is the Schmidt–Kennnicutt 'law', a proportionality between the surface density of dense gas and the spatially resolved star-formation rate (Kennicutt 1998). Recent work has improved the calibration of the star-formation-rate determination, and it is now relatively well accepted that either optical recombination-line emission (e.g., Hα) or ultraviolet continuum, plus mid-infrared continuum (e.g., 24μm) can accurately represent, respectively, exposed and embedded star formation, and an appropriate linear combination is a good measure of the total rate (Calzetti *et al.* 2007; Kennicutt *et al.* 2009). Understanding the physics which leads to the Schmidt–Kennicutt correlation depends more critically on the abcissa, i.e., whether one should measure the surface density of molecular gas, of atomic gas, or the total. Recent work by the THINGS collaboration (Walter *et al.* 2008) has clarified this, showing that in denser parts of galaxies, such as the inner parts of spirals, interstellar gas is primarily in the molecular phase, and that star formation follows the surface density of that star-forming molecular gas tightly. In the outer parts of spirals, and lower-surface-brightness galaxies, the interstellar medium phase balance shifts towards the atomic and the neutral-hydrogen column density must be taken into account (Bigiel *et al.* 2008; Leroy *et al.* 2008). A simple theoretical model including the phase state of interstellar gas and the formation of stars from molecular material can reproduce the observations fairly well (Krumholz *et al.* 2009).

A fundamental question is at what size scale the Schmidt–Kennicutt correlation breaks down—clearly, at size scales relevant to individual stars, the average star-formation rate and gas surface density no longer make sense. However, we would like to know if relatively universal behaviour persists on the scale of a star cluster: given a molecular cloud of a particular surface density or mass, is the formation of a cluster from that cloud relatively well determined, or does it depend on detailed physical conditions such as the clumpiness, heating by nearby stars, penetration of dissociating or even ionizing radiation, turbulent mixing by nearby stars, supernovae, supershells or kiloparsec-scale instabilities? Detailed study of the distribution of new star clusters relative to dense molecular material, on *regional* size scales $\lesssim$ 100 pc should show these effects and resolve the physics that we expect to break the Schmidt–Kennicutt correlation. In particular, the displacements of protoclusters from CO clumps, and the relative location of emission from denser gas tracers such as HCN, will reveal what physics is important and what molecular tracers most closely probe that physics.

It is possible that a $\sim 10^6$ $M_\odot$ molecular cloud forms a star cluster in a relatively universal way and that the fundamental physics determining star formation on galaxy scales is then merely the physics of forming a molecular cloud. This too has been an active area of recent research, with the prevalent theories being the formation of molecular material in the overdense regions of colliding or converging atomic flows: see Heitsch *et al.* (2009) for a recent study. These flows are subject to instabilities which fragment and drive turbulent motions in the molecular cloud formation zone, i.e., turbulence and substructure which, if stars and star clusters then form promptly ($\lesssim 10^6$ yr, rapidity for which there is significant evidence), will be preserved in the spatial distribution of nascent protostars.

Next, we consider smaller scales, and the formation of one massive ($\gtrsim$ 10 $M_\odot$) star. It is apparent that nearly all massive stars form in clusters (de Wit *et al.* 2005). What is less clear is whether that is *necessary*. Simple arguments based on accretion rate and Kelvin–Helmholz time show that a massive protostar will have a central object close to the main sequence (having a high enough effective temperature to emit significant ultraviolet radiation) by the time $\sim$ 15 $M_\odot$ have accreted, even if the accretion rate is still very high and the star is destined to be much more massive. Simple models of the formation of solar-mass stars in isolation break down when required to treat such extreme conditions in the protstellar core, and solutions require a combination of high pressure (likely nonthermal) in the core, accretion through a disk and may even require interactions with other protstars. In the clustered/cooperative-accretion picture, for example, gas drawn into the gravitational potential of the entire cluster is what enables the required very high accretion rates onto the most massive members (Bonnell & Bate 2006). A different theory posits that a turbulent core separates dynamically from the cluster-forming cloud before it accretes significantly onto its central protostar (Tan *et al.* 2006). These scenarios predict different interclump motions in the precluster cloud and different distributions (clustering versus fractal substructure) for the distribution of massive and less massive protostars. There are also questions regarding the relative ages of formation of the massive and less massive members, which can be addressed by observing the spatial and temporal distribution of protostars in protoclusters.

For all of these problems we need to study protoclusters $\lesssim 10^6$ yr old, because dynamical interactions between protostars will very rapidly erase the signatures we wish to detect (Allison *et al.* 2009; Fellhauer *et al.* 2009; Moeckel & Bonnell 2009).

2. Infrared study of Galactic protoclusters

Mid-infrared photometry is particularly powerful to identify young stellar objects. Even at 1–2 μm, somewhat more evolved but still protostellar objects (those denoted Class III for solar-mass protostars) will not show much excess above their Rayleigh–Jeans photospheric spectrum, but it has been long known that selection based on 3–5 μm excess results in a much more complete protostellar census (Strom *et al.* 1989).

In Galactic star-formation regions and protoclusters, certain parts of color–color space have been identified as mostly populated by young stellar objects (YSOs; Allen *et al.* 2004; Megeath *et al.* 2005). Such color selection of candidate YSOs can be made more sophisticated by explicit, simultaneous consideration of different color planes (Gutermuth *et al.* 2009) or by considering and fitting the spectral-energy distribution (SED) of each source over as wide a wavelength range as possible. Our group has generally used the latter, developing a set of 10 000 YSO radiative-transfer models and rapid code to find the best-fitting models for a set of data (Robitaille *et al.* 2006, 2007). The methods are not widely discrepant—we explore the differences in detail in the Eagle Nebula in Indebetouw *et al.* (2007)—because the SED is mathematically interchangeable with the position of the source in a set of color–color plots spanning all fluxes.

The Eagle Nebula study (Indebetouw *et al.* 2007) illustrates the power of this kind of analysis in a relatively modest stellar cluster. We clearly re-identify the young cluster NGC 6611 as containing mostly Class II or T Tauri-type protostars. In protostellar terms, that is young, but not extremely young. We discover a less evolved cluster to the north east of NGC 6611, still cospatial with the molecular cloud. NGC 6611 has already largely dispersed its end of that cloud, leaving only fragments—the famous pillars of creation—behind. We also show quantitatively how the younger sources are more clustered than older ones, a result now seen in many *Spitzer* studies of Galactic regions (e.g., Gutermuth *et al.* 2009). We also see that the spatial separation of protostellar objects is consistent with the fragmentation scales for the warm molecular material in the neighborhood of NGC 6611. Finally, we find a massive YSO to the north west that has not been discussed extensively in the literature.

3. Infrared study of extragalactic protoclusters

Moving to extragalactic studies, we developed a set of criteria to select protostars in the color–magnitude spaces formed by 2MASS and SAGE *Spitzer* IRAC and MIPS point-source photometry of the Large Magellanic Cloud (LMC; Meixner *et al.* 2006; Whitney *et al.* 2008). The cuts were designed to reject the majority of evolved stars found in the LMC by Blum *et al.* (2006), but accept the majority of our grid of 10 000 radiative-transfer models of dusty protostars (Robitaille *et al.* 2006, 2007). Figure 1 shows a figure from Whitney *et al.* (2008) of one color–magnitude diagram and the location of various types of sources. Gruendl & Chu (2009) used a somewhat different color cut, designed to more conservatively reject evolved stars, at the expense of also rejecting some more

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evolved (Class/Type II–III) young stellar objects. In Indebetouw *et al.* (2008) we also explored different color–magnitude cuts, this time accounting for somewhat extended sources such as ultracompact and compact H^+ regions, which can also be considered 'young stellar objects'. whitney *et al.* (2008) found over 1000 massive YSO candidates in the LMC, 50 times more than previously known. The correlation with interstellar gas is striking and quantitatively significant (Figure 2). Yang *et al.* (2007) used a similar YSO candidate list generated by Gruendl & Chu (2009) to assess the global stability of the LMC and found significant numbers of YSO candidates in regions considered stable from a Toomre-type stability analysis of the molecular and atomic gas. The distribution of protostellar candidates can be much better explained if one includes the gravitational potential of the older stellar population in the analysis, i.e., one must consider where stars already are in predicting where more stars will form in a galaxy.

We can also perform detailed regional studies of star formation in the Magellanic system. In N44, Chen *et al.* (2009) found a concentration of massive YSOs in the central molecular cloud, which may be triggered by a neighboring bubble H^+ region. A cloud of similar mass to the south also contains massive protostars, but with a sparser spatial distribution. Differences in evolutionary state between the YSOs in the two different molecular clouds may correlate with those different formation mechanisms. The N159 region is more striking, also containing two highly active molecular clouds and a third very quiescent one of equal or greater mass. The protostellar distribution in space and evolutionary state in N159 suggests that one of the active clouds may have been triggered, while the other probably formed stars spontaneously (Chen *et al.* 2009, submitted). We are further exploring the physical properties of dense (HCN, HCO^+-emitting) gas in the quiescent cloud to determine why it has so little massive star formation (Chen *et al.*, in prep.)

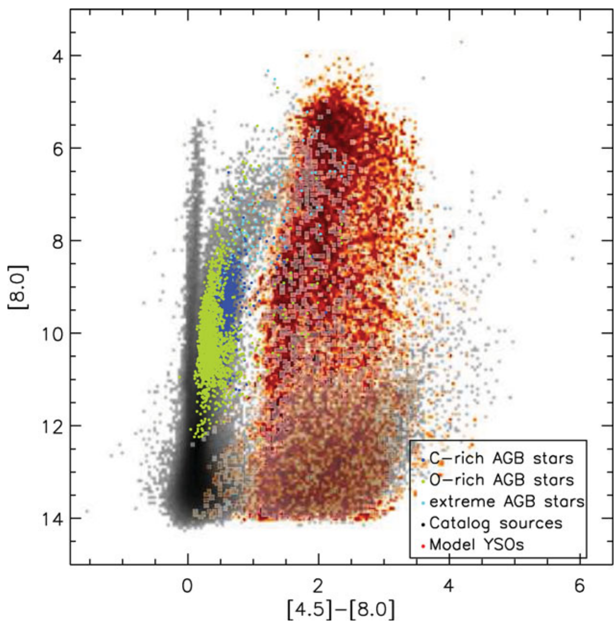

Figure 1. Color–magnitude diagram of sources in the LMC, showing how a cut at about [4.5]–[8.0] > 1 mag, somewhat increasing in color with decreasing magnitude, would select YSO candidates and exclude most evolved stars.

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The molecular ridge south of 30 Doradus in the LMC contains nearly one third of the molecular gas of the entire galaxy (Mizuno *et al.* 2001), but has very little apparent activity in Hα or near-infrared tracers. The region is also rather discrepant when plotted on the Schmidt–Kennicutt correlation: given the surface density of molecular gas, the star-formation rate calculated from optical tracers is at least an order of magnitude below the trend. We explored the region using *Spitzer* data, and found that it does contain a number of modest mid-infrared star-forming sites (Indebetouw *et al.* 2008). Analysis of these sites, both with individual protostar models and modeling them as groups of stars or protoclusters, reveals that they are *poor* clusters of total mass $\lesssim 10^5$ $M_\odot$, too small to fully sample the stellar initial mass function up to massive OB stars. Thus, although there is a reasonable total mass of solar-mass star formation in the ridge (and enough to make it consistent within uncertainties with the Schmidt–Kennicutt correlation), the activity that is taking place is low-mass and poor. Thus, given the steep mass–luminosity and even steeper mass–ionizing flux relations for stars, the *integrated* Hα and infrared emission does not fully reflect the total star formation in the cloud. Why this giant cloud is only forming lower-mass stars, similar to Taurus in the Galaxy, remains a mystery.

4. Beginning to observe the gas as well

With millimeter receivers on the *Australia Telescope Compact Array* (Wong & Melatos 2002), we recently started to be able to observe dense gas tracers such as HCN and HCO^+ in the Magellanic system, at parsec-scale spatial resolution, comparable to the infrared studies. For example, in N44, we find that the least-evolved massive YSOs are most closely spatially associated with dense molecular clumps. Even within 10^6 years, the slightly more evolved (Type II) massive YSOs have begun processing their molecular material by heating and changing the HCN-to-HCO^+ ratio, and dispersing those clumps, leaving a weaker spatial association (Chen *et al.* 2010). Observations

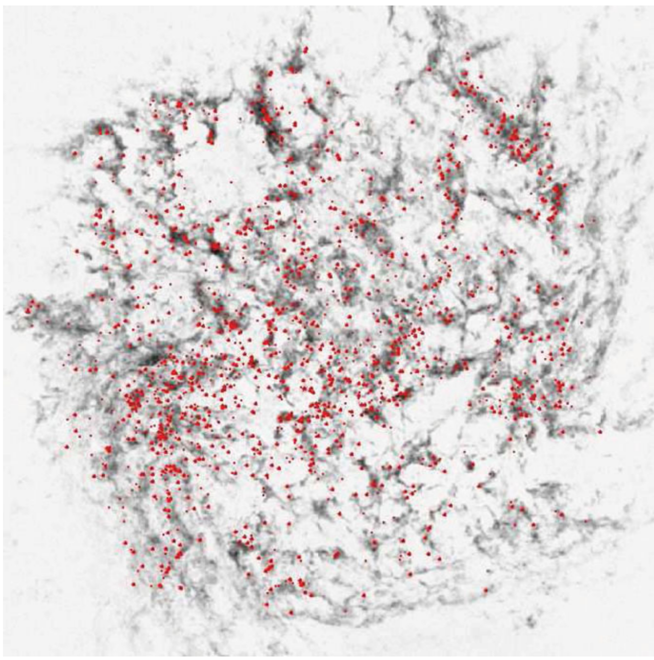

Figure 2. HI in the LMC with positions of YSO candidates.

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of N159 in the LMC (Ott *et al.*, in prep.; Chen *et al.*, in prep.) promise to be even more interesting.

5. A sobering lesson from detailed Galactic studies

The largest caveat in the analysis discussed, especially using *Spitzer* data, which at 24μm has a spatial resolution of more than a parsec in the Magellanic system, is the small-scale structure of massive YSOs. We see repeatedly in submillimeter and infrared studies of Galactic regions such as NGC 6334 (Hunter *et al.* 2006; Brogan *et al.* 2009), that a parsec-scale region, which would be identified as a point source extragalactically, *nearly always* contains multiple massive members, *nearly always* in rather different apparent evolutionary states. In the very young region NGC 6334I(N), there are four massive sources within 10 000 AU. Only one has an H^+ region, two have prolific submillimeter line emission (hot-core chemistry) and one shows very little line emission, perhaps not yet warm enough to drive intense chemistry (Brogan *et al.* 2009). Clearly, modeling this as a single massive protostar has limitations. We have investigated this carefully in some Magellanic regions for which we have higher-resolution near-infrared imaging, even with adaptive optics, to better identify the multiplicity. Because of the steep mass–luminosity relation for stars, we find that the physical parameters (evolutionary state) determined from fitting two massive members of a small group or cluster do not differ very much from those determined by fitting the unresolved SED. More careful investigation with high-resolution observations is still required, but at least for the small number we have been able to look at, the main change in conclusions is that splitting the source into N sources for the same total luminosity, results in the expected $\simeq N^{2/3}$ increase in total mass for the group.

Clearly, we need to continue these studies of protoclusters with high-resolution infrared observations from adaptive-optics-enabled telescopes like *Gemini* and the *VLT*, and then with *JWST*. *ALMA* will soon permit direct observation in nearby galaxies of the molecular gas on the subparsec scales relevant to individual star formation and submillimeter continuum detection of the very most embedded protostars and protoclusters. Together, we expect to make great progress with these data in unraveling the complex and (optically) invisible process of cluster formation.

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