Formation, evolution, and survival of massive star clusters
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Clusters of high-mass protostars: From extreme clouds to mini-bursts of star formation

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Abstract. *Herschel* revealed high-density cloud filaments of several pc^3, which are forming clusters of OB-type stars. Counting *Herschel* protostars gives a direct measure of the mass of stars forming in a period of $\sim 10^5$ yrs, the "instantaneous" star formation activity. Given their activity, these so-called mini-starburst cloud ridges could be seen as "miniature and instant models" of starburst galaxies. Their characteristics could shed light on the origin of massive clusters.

Keywords. stars: formation, ISM: structure, star clusters, starburst

1. Introduction

Despite their low numbers, massive stars (OB-type, $>10\ M_\odot$ on the main sequence) produce much of the luminosity of galaxies and are the main driver of their evolution. Both their large impact on their environment and how their formation is linked to natal clouds remain poorly understood (see reviews by Elmegreen 2011; Krumholz 2014).

High-mass star formation scenarios currently undergo a change of paradigm, in which this process is no longer quasi-static but simultaneously evolves with both cloud and cluster formation. Theoretically, OB stars could either form through (1) a powerful accretion driven by a high degree of turbulence (e.g., McKee & Tan 2002; Hosokawa & Omukai 2009) or (2) colliding flows initiated by competitive accretion or cloud formation (e.g., Bonnell & Bate 2006; Hartmann *et al.* 2012). From an observational point of view, gravitational streamers and shearing motions have been reported from the cloud to the protostellar scales in a few high-mass star-forming regions (on $10 - 0.1$ pc scales, Schneider *et al.* 2010; Csengeri *et al.* 2011a). We hereafter show that these pioneering studies are now comforted by sensitive *Herschel* images, cloud kinematic studies, and (sub)millimeter interferometric images, favoring the second family of models.

"HOBYS, the *Herschel* imaging survey of OB Young Stellar objects" is a key program, which is exclusively dedicated to high-mass star formation (Motte, Zavago, Bontemps *et al.* 2010; see http://hobys-herschel.cea.fr). It uses the SPIRE and PACS cameras of the

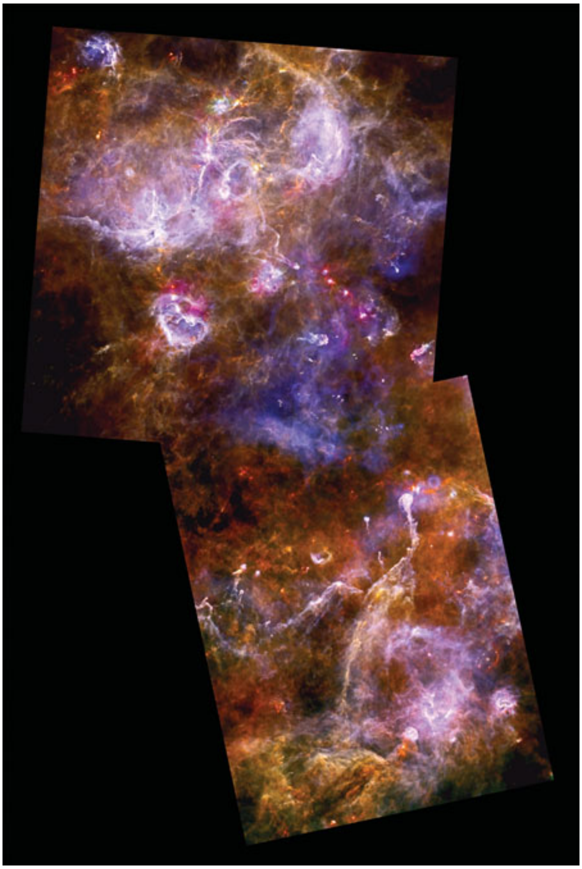

Figure 1. Composite 3-color *Herschel* image of the Cygnus X molecular complex with red $= 250\,\mu$m, green $= 160\,\mu$m, and blue $= 70\,\mu$m (taken from Hennemann *et al.* 2012 and Schneider *et al.* in prep.). The mosaic performed by the HOBYS key program approximately covers a $5^\circ \times 2.5^\circ$ or $120\,\mathrm{pc} \times 60\,\mathrm{pc}$ area. The diffuse blue emission at the center is an H II region powered by the massive Cyg OB2 cluster while earlier stage star-forming sites are seen as red filaments.

Herschel spatial observatory to image essentially all of the regions forming OB-type stars at distances less than 3 kpc from the Sun ($d = 0.7 - 3.2$ kpc). HOBYS images revealed networks of filaments and clusters of burgeoning YSOs (see Fig. 1). Among the HOBYS highlights is the discovery of "mini-starburst ridges", defined as high-density dominating filaments supersonically contracting (see Sect. 2) and efficiently forming clusters of high-mass stars (see Sect. 3). Could these Galactic extreme cloud and star formation events help constrain the physical process at the origin of the formation of extreme extragalactic clusters? To start answering, we will list in Sect. 4 the physical processes acting within ridges and which qualitatively differ from the one advocated to form more classical low-mass star clusters.

2. Ridges & hubs: Hyper-massive clumps forming clusters of high-mass stars

2.1. *Discovery of hyper-massive clumps*

One of the most unexpected results of the *Herschel* mission was in revealing the importance and ubiquity of interstellar filaments (e.g., André *et al.* 2010; Hill *et al.* 2011).

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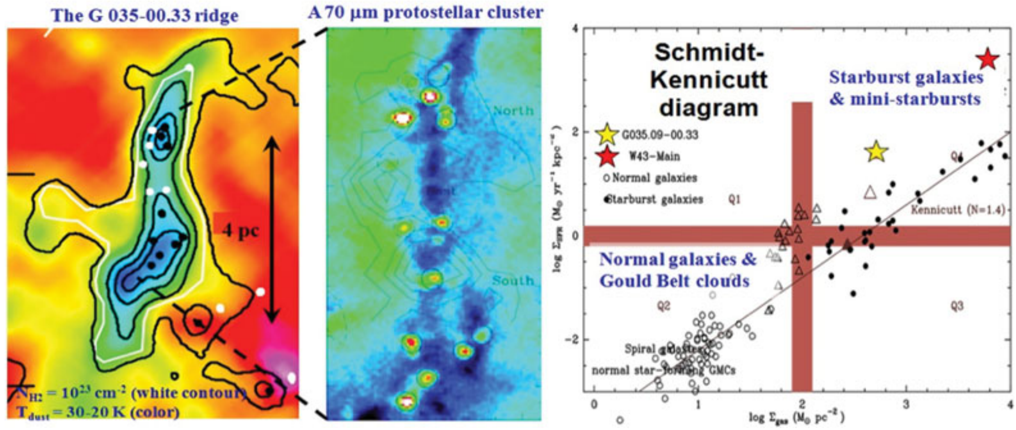

Figure 2. The G035-00.33 ridge and its cluster of high-mass protostars (Left and Center). Ridges are high-density clumps with large star formation activity (Right, see yellow and red star markers). On a Schmidt-Kennicutt diagram, they qualify as mini-starburst regions. Figures extracted from Nguyen Luong *et al.* (2011a) and (in prep.).

They were known from molecular line surveys but could, for the first time, be 1) quantitatively studied thanks to sensitive column density and temperature images and 2) directly compared with the protostellar population (see, e.g., Figs. 2 Left-Center). The HOBYS group has developed a definite expertise in building clean and reliable column density maps, in identifying and analyzing cloud filaments, in properly extracting protostars from their surroundings and characterizing them (e.g., Hill *et al.* 2012; Hennemann *et al.* 2012; Men'shchikov *et al.* 2012; Tigé *et al.* 2016). Within the high-mass molecular complexes imaged by HOBYS, we have discovered high-density dominating elongated clumps, which are the preferential sites to form massive stars and which we quote as ridges (see Figs. 2 Left-Center). The existence of ridges is predicted by dynamical models of cloud formation such as colliding flow simulations (e.g., Heitsch & Hartmann 2008; Federrath *et al.* 2010). The densest ridges should coincide with the precursors of "young massive clusters" that will become bound stellar clusters (e.g., Ginsburg *et al.* 2012).

In more details, Hill *et al.* (2011) studied the Vela C molecular cloud complex and defined the central ~3 pc-long filament with column density above 10^{23} cm^{-2} as a ridge. They showed that the Vela C ridge represents a gravitational well that is dominating and shaping its surroundings, in marked contrast to other more typical filaments (e.g., Arzoumanian *et al.* 2011). In parallel, Hennemann *et al.* (2012) analyzed the structure of the DR21 ridge (see Fig. 3 Left), previously identified by us as hosting a cluster of ~20 high-mass protostars (Motte *et al.* 2007; Bontemps *et al.* 2010). In agreement with the kinematical study and simulations of Schneider *et al.* (2010, see Fig. 3 Right), Hennemann *et al.* (2012) proposed the DR21 ridge is fed by and formed through the merging of several sub-filaments already forming stars. A handful of other $\sim 10^4\ M_\odot$ ridges were recently identified in *Herschel*/HOBYS and Hi-GAL images (Nguyen Luong *et al.* 2013; Hill *et al.* in prep.).

More spherical and less massive, $\sim 10^3\ M_\odot$, clumps were also found to form stellar clusters at the junction of filaments (Schneider *et al.* 2012; Didelon *et al.* 2015). These clumps recall the so-called "hubs" discovered in a few extreme infrared dark clouds (e.g., Peretto *et al.* 2013) and predicted by numerical simulations (e.g., Dale & Bonnell 2011). We propose to generalize the concept of ridges and hubs into that of "hyper-massive

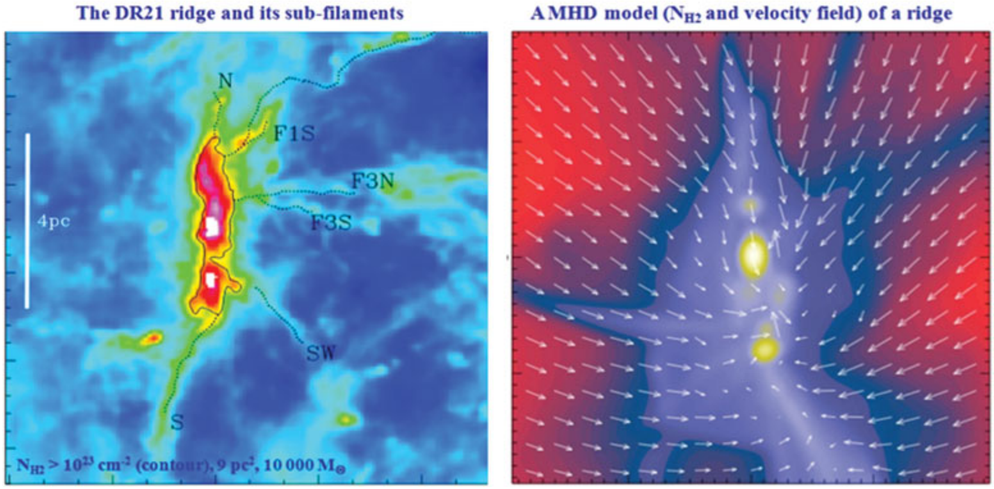

Figure 3. The DR21 ridge and its feeding sub-filaments network (Left), compared to numerical MHD simulations made by P. Hennebelle (Right). Figures are extracted from Hennemann *et al.* (2012) and Schneider *et al.* (2010).

clumps", which could either be spherical or filamentary and either form a couple or a rich cluster of high-mass stars.

2.2. *Dynamical processes at the origin of hyper-massive clouds*

Based on *Herschel* and kinematic studies (Schneider *et al.* 2010; Hill *et al.* 2011; Hennemann *et al.* 2012; Nguyen Luong *et al.* 2011a, 2013), we proposed that most ridges/hubs could have been formed by dynamical scenarios such as converging flows (see Figs. 3 Right). Minier *et al.* (2013) themselves used numerical simulations to show that the ionization of a very nearby H II region/OB cluster could be the main process responsible for shaping some ridges like Vela C (see his Fig. 5). In any case, whatever the origin of the additional pressure, arising from colliding flows or ionization, it supersedes the thermal and micro-turbulence pressure. Those dynamical scenarios for cloud and then subsequent star formation are part of the second family of models shortly described in Sect. 1. They are also consistent with the observational lack of high-mass pre-stellar cores (e.g., Motte *et al.* 2007, 2010; Russeil *et al.* 2010; Tigé *et al.* 2016).

In parallel to these *Herschel* structural studies, we have investigated the kinematics of three ridges identified as such from HOBYS data (Hennemann *et al.* 2012; Nguyen Luong *et al.* 2013). A long-term survey of Cygnus X and an IRAM large program on W43 (W43-HERO, Motte, Schilke *et al.*, see http://www. iram-institute.org/EN/content-page-292-7-158-240-292-0.html) has shown that the DR21, W43-MM1, and W43-MM2 ridges are all undergoing global collapse on the ridge scale with supersonic inward velocities ($1 - 2$ km s^{-1} over $1 - 10$ pc^2; Schneider *et al.* 2010; Motte *et al.* in prep.). Such infall motions, sometimes called gravitational focusing, are expected both in colliding flows and ionization compression models (e.g., Vázquez-Semadeni *et al.* 2005; Tremblin *et al.* 2012). We started studying the inner kinematic structure of these ridges, which suggests they are braids/bundles of filaments or gas layers (Louvet *et al.* in prep.; Bontemps *et al.* in prep.). We have also studied the shocks associated with gas shears created by sub-filaments braiding, using SiO imaging and detailed shock modeling (Nguyen Luong *et al.* 2013; Duarte-Cabral *et al.* 2014; Louvet *et al.* 2016). Such extreme kinematics is observed by other groups at the clump scale (e.g. Galván-Madrid *et al.* 2010; Henshaw *et al.* 2014)

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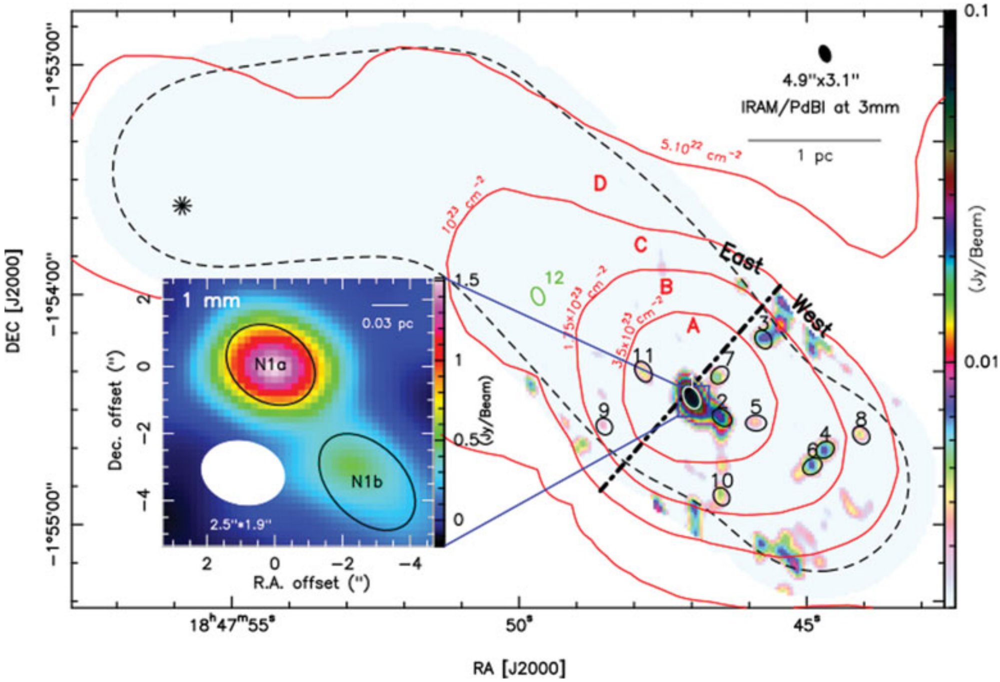

Figure 4. Interferometric mosaic obtained at the IRAM Plateau de Bure toward the W43-MM1 ridge (Louvet *et al.* 2014). A cluster of high-mass protostars, pinpointed by black and white ellipses, forms within the ridge outlined by the 10^{23} cm^{-2} red contour. Clustering properties are evolving through regions A-D, and are different in the eastern and western parts of the ridge.

and is reminiscent to gas flows and shocks observed at the protostellar scale by Csengeri *et al.* (2011a-b).

3. Mini-starburst activity within ridges

The extreme characteristics of ridges and hubs, in terms of density and kinematics (see Sect. 2), could lead to an atypical star formation activity. Star formation efficiency (SFE) is indeed predicted to continuously increase with gas density (e.g., Hennebelle & Chabrier). Analytical theories in fact argue for the star formation rates (SFRs) to be measured as a function of the free-fall time, which itself directly depends on the cloud density (e.g., Krumholz & McKee 2005; Padoan & Nordlund 2011). The clear accumulation of massive protostars we observed along ridges (see, e.g., Fig. 2 Center) traces the present star formation activity (Sect. 3.1), which we will show is intense (Sect. 3.2; Nguyen Luong 2011a; Louvet *et al.* 2014).

3.1. *Various SFR estimates, tracing the history of star formation*

Spitzer/IRAC legacies have measured SFRs in a direct and indirect way by either counting pre-main sequence stars (also called T Tauris) or integrating the diffuse mid-infrared PAH emission attributed to the luminosity impact of recently formed OB stars on the cloud. The first method was successfully applied by the c2d survey of nearby (<500 pc) low-mass star-forming regions (e.g., Heiderman *et al.* 2010). The second method was used when the angular resolution was not sufficient for counting purposes, for example in galaxies (e.g., Wu *et al.* 2005) and more recently for Galactic molecular complexes (Nguyen Luong *et al.* 2011b; see also Eden *et al.* 2012 using *Herschel* 70 μm). If the star

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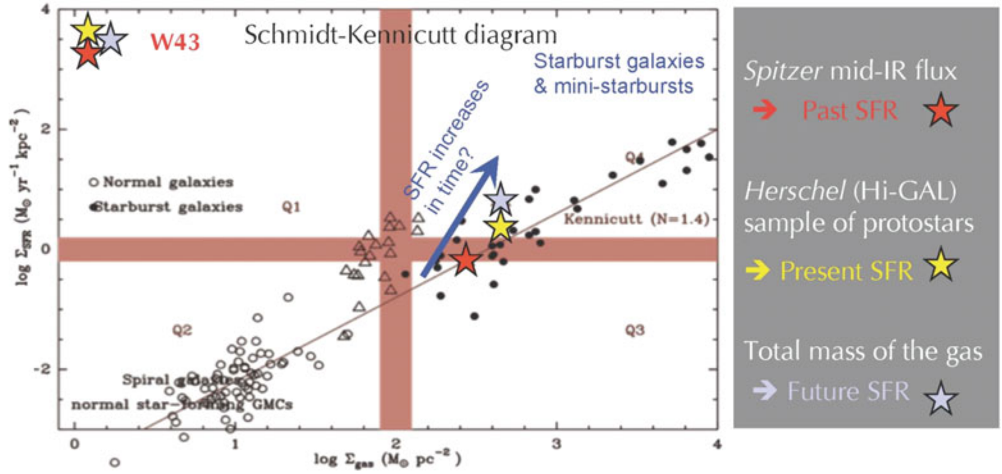

Figure 5. History of star formation in the W43 molecular complex traced by the SFR estimates made from *Spitzer*, *Herschel*, and molecular line surveys. Measures are extracted from Nguyen Luong *et al.* (2011b) and Nguyen Luong *et al.* (in prep.). The Schmidt-Kennicutt relation which is followed by most GMCs and galaxies (examples displayed by filled and open circles) is shown by a black line. The present-day and future SFRs suggest an increase of the SF activity in W43.

formation activity varies with time, these two methods, based on $\sim 10^6$ years-old T Tauri and OB stars, would measure "past integrated" SFRs.

In contrast, counting $\sim 10^5$ years-old protostars allows to evaluate the "present-day instantaneous" star formation activity, meaning the star formation developing for one single free-fall time of the direct progenitors of single stars. We first applied this method to W43-main, a region imaged by ground-based submillimeter radio-telescopes (Motte *et al.* 2003). Members of the HOBYS consortium now use *Herschel* and interferometric images, which more properly identify massive dense cores and their embedded protostars (see Fig. 2 Center and Fig. 4).

If one assumes a constant $1-3\%$ SFE and a $\sim 10^6$ cloud lifetime, the total gas mass of clouds provides a good estimate for their "future integrated" star formation activity. Using SFR values estimated this way in a Schmidt-Kenicutt diagram is meaningless since it will only reflect our assumptions on SFE and cloud lifetime. However, comparing SFRs estimated through the three methods above can give crucial insights into the history of cloud and star formation. As a matter of fact, an increase of the star formation activity has been suggested, for the W43 molecular cloud complex, when using *Spitzer*, *Herschel*, and cloud mass measurements (see Fig. 5, Nguyen Luong *et al.* 2011b, in prep.). This SFR rise could be the consequence of the fact that clouds are currently forming, rather efficiently, within this complex (Motte *et al.* 2014).

3.2. *Galactic mini-starburst events*

On cloud and ridge spatial scales ($1-10$ pc), we measured the present-day instantaneous SFR of the W43-main cloud as well as the G035.39-00.33 and W43-MM1 ridges (Motte *et al.* 2003; Nguyen Luong 2011a; Louvet *et al.* 2014). These cloud structures are the preferential sites for the formation of high-mass star clusters in their host complex (see, e.g., Figs. 2) and W43-MM1 is the most extreme clump of the W43-main cloud. They all have star formation rate densities, $\Sigma_{\rm SFR} \sim 10-100\ M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}$, on $1-10\ {\rm pc}^2$ areas, worthy of starburst galaxies, usually defined by $\Sigma_{\rm SFR} > 1$ (see Fig. 2 Right). For this

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reason, W43-main, G035.39-00.33, and W43-MM1 were called mini-starburst regions, i.e. miniature and instantaneous models of starburst galaxies.

These mini-starburst events most probably follow the formation of the ridges, which were proposed to develop through colliding flows (see Sect. 2). Indeed, short mini-bursts of star formation are to be expected after a fast episode of cloud formation (e.g., Vázquez-Semadeni *et al.* 2008) or, equivalently, for a cloud under compressive turbulent forcing (Federrath & Klessen 2012). In this scenario the star formation should gradually settle within ridges. We should thus measure very different SFR levels depending on the evolutionary status of the ridge. To investigate this statement, one must calculate present-day instantaneous SFRs, whose timescale, over which the SFR is integrated, remains much shorter than the ridge formation timescale ($\sim 10^5$ yr vs. $\sim 10^6$ yr). Louvet *et al.* (2014) measured instantaneous SFRs within regions A-D of the W43-MM1 ridge (see Fig. 4) and found a clear correlation of SFR with cloud density or, equivalently, SFR with the evolution of cloud concentration. Moreover, SFR is smaller within the eastern part of the ridge, where shocks associated with more recent cloud formation are the strongest (Louvet *et al.* 2014, 2016). Therefore, the dynamical ridge formation may well be followed by series of intense bursts of star formation.

4. Conclusion

While star cluster properties, among which the initial mass function of stars (IMF, see, e.g., Kroupa 2001) seem universal, our present review suggests that stellar clusters formed in extreme clouds like ridges could have different properties. Indeed, if low-mass stars should accrete their final mass from well-defined pre-stellar cores with a mass distribution mimicking the IMF (Motte *et al.* 1998, Konyves *et al.* 2015), (high-mass) stars within ridges most probably accrete gas from their parental clumps, through sporadic gas flows. Moreover, the star formation activity within ridges may not be constant over 10^6 yrs but present bursts favoring the formation of high-mass stars.

High-resolution studies will be necessary to investigate the core mass function and angular momentum distribution within the protocluster ridges and define if the global properties of the resulting massive star cluster will be classical or not.

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