Clusters of high-mass protostars:
From extreme clouds to minibursts of star formation

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November 3rd, 2014
1. Short introduction

2. Cloud: Where do high-mass star clusters form? in dense, massive, and dynamical ridges or hubs

3. Clusters: Are they different when they form in ridges/hubs? protostars fed from large-scale large SFE/SFR

4. Conclusion, warnings, and future work…
Tight link between clouds and protostars

CygOB2, 45-100 O stars

Hennemann et al. 2012

Cygnus X with Herschel 70 $\mu$m, 160 $\mu$m, 250 $\mu$m

$^{13}$CO(1-0)
IRAM 30m

8 pc

Gas inflow

100 pc

Bontemps et al. 2010; Duarte Cabral et al. 2014

DR21 ridge $10^4 M_\odot$

20 $M_\odot$
protostars

0.05 pc

IRAM PdBI

F. Motte, Early Life Stellar Clusters, Copenhagen 2014
Thermal dust emission is mostly optically thin at $\lambda > 100 \ \mu m$

$\Rightarrow$ Accurate measurements of the gas mass reservoir associated with star formation

($Herschel$ $N_{H_2}$ maps, see Hill et al. 2009, 2011)

• $Herschel$/HOBYS traces ~0.1 pc massive dense cores

• (Sub)mm interferometers trace ~0.01 pc individual protostars

• $Herschel$/PACS and SPIRE cover their SED peaks (10-50 K).

• Submm telescopes & arrays probe clouds and protostellar envelopes.

• $Spitzer$ traces heated envelopes and H$\Pi$ regions.
Different cloud structures form low- & high-mass stars

- Disorganized network of filaments versus single dominating ridges
- High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), elongated cloud structures dominating their surrounding.
Ridges/Hubs are extreme clumps forming clusters of high-mass stars

- ~50% of the high-mass stars form in clusters within high-density elongated ridges, the other 50% form in spherical high-density hubs

⇒ Ridge/Hub definition: 5-10 pc$^3$/1 pc$^3$ above $10^4$-$10^5$ cm$^{-3}$

We use the 100 A$_v$ level to identify them but it is not a physical threshold.

See also Hill+ 2011, Nguyen Luong+ 2011, Hennemann+ 2012, Didelon+ 2014, …

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Most ridges/hubs should form by cloud global collapse

- Forced-fall (pressure-driven infall) of the DR21 ridge further fed by filaments.

\[ N_{\text{H}_2} > 10^{23} \text{ cm}^{-2}, \ 15 \ 000 \ M_\odot, \ 5 \ \text{pc}^3, \ <n> \sim 10^4 \text{ cm}^{-3} \]

Hennemann, Motte, Schneider et al. 2012

- Similar kinematics found for other ridges/hubs (Peretto et al. 2013, 2014; Beuther 2012; Kirk et al. 2013…)

13CO(1-0) in fall speeds

Global infall

0.2-1 km/s
Interferometric images in $N_2H^+$, NH$_3$ or HN$^{13}$C display several pc filaments along ridges.

see also Tackenberg+ 2014

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Organized 0.05 pc flows in H$^{13}$CO$^+$ or N$_2$H$^+$ displaying shears at the location of high-mass protostars (Csengeri et al. 2011a, 2011b).

Consistent with numerical simulations by Smith et al. 2011, 2012.

Consistent with shock tracers (Csengeri et al. 2011b; Jiménez-Serra et al. 2011; Nguyen Luong et al. 2013; Sanhueza et al. 2013; …)

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Making a **direct link** between protostars and their cloud, *Herschel* measures instantaneous SFE, easier to compare with statistical models of SFR (e.g. Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

- *Herschel* or (sub)millimeter samples of protostars (lifetime \(\sim 10^5\) yr) (e.g. Motte et al. 2003; Nguyen Luong et al. 2011a; Louvet et al. 2014) ➞ ”Instantaneous” / ”Present-day” SFR

- *Spitzer* sample of pre-main sequence stars (lifetime \(\sim 10^6\) yr) or effect of OB stars (depletion time 2 x \(10^6\) yr) on the cloud (e.g. Heiderman et al. 2010; Kennicutt 1998) ➞ ”Integrated” / ”Past” SFR

With both SFRs, one may constrain the history of star formation...
Mini-starburst cluster in the G035.39-00.33 ridge

• Herschel census and SED (4μm-1mm):
  ⇒ 5 high-mass class 0 protostars or 20 protostars with 2 \( M_\odot \) on the main seq.

• Assumptions:

  ✓ Core-to-star mass efficiency: \( \varepsilon \sim 20-40\% \) in 0.1 pc \( 10^6 \) cm\(^{-3} \) dense cores

  ✓ Protostellar lifetime: \( 10^5 \) yr of IR-quiet/Class0-like massive protostars

  ✓ Fast episode of cloud formation: 1-3 \( 10^6 \) yr

  ✓ Kroupa IMF applied to the ridge

⇒ A mini-burst of SF (SFE \sim 20\%, SFR\sim 300 \( M_\odot/\)Myr, 40 \( M_\odot/yr/kpc^2 \) within 8 pc\(^2 \))
Ridges/hubs represent Galactic mini-starbursts

Starburst quadrant:

\[ \Sigma_{SFR} > 1 \, M_\odot/\text{yr}/\text{kpc}^2 \]

\[ \Sigma_{\text{gas}} > 100 \, M_\odot/\text{pc}^2 \]

Figure adapted from Motte et al. 2003; Nguyen Luong et al. 2011a, in prep., and Hennemann et al. in prep.

These pioneering studies need to be generalized...

Caveats: Core-to-star formation efficiency assumed to be constant

Extrapolation of a standard IMF to mini-starburst ridges
Clusters of low- to high-mass protostars

- 0.02 pc high-mass protostellar cores
- Mass segregation
- CFE = Mass within protostellar cores / Mass of the surrounding clump

Bontemps et al. 2010

(See also Motte et al. 1998; Palau et al. 2013)
Lada et al. (2010, 2012) relation between SFR and cloud mass implicitly assumes a constant SFE in regions above the SF threshold \((A_v > 8\, \text{mag})\). See also Evans et al. 2014, André et al. 2014,… and SFR theoretical models.

IRAM Plateau de Bure census of protostars in the W43-MM1 ridge
- finds the most massive class0-like protostar: N1a: 1100\,M_\odot \,0.03\,\text{pc}
- investigates SFE within subregions A, B, C, D

Louvet et al. 2014
In contradiction with Lada’s 2010/2012 prescription...

In agreement with previous CFE studies (Bontemps et al. 2010, Palau et al. 2013)

Cloud density sets SFE and the mass of the most massive stars that will form.

⇒ Environment matters!

SFE measured within the W43-MM1 ridge and in numerical simulations increases with $n_{H_2}$ (Louvet et al. 2014).

- Inconsistent with observations in W43.

=> Multi-freefall models (Hennebelle et al. 2012; Federrath et al. 2012) with more realistic cloud structure should be more adequate...
Conclusion, warnings, and future work

Proposed steps toward SF in ridges/hubs

1. MHD turbulent shocks build-up filaments that gently accrete from their surrounding.

2. Gravity braids filaments in a collapsing clump attracting more filaments.

3. Stars and filaments simultaneously form and grow. In these environments protostellar accretion is non-local & anisotropic.

The stellar content (higher mass star, SFE?, IMF?) of a cluster depends on the density and kinematics of its parental cloud.

⇒ The formation of mini-starburst clusters is different from that of low-mass star clusters.

But rough assumptions:
- **unknown core-to-star mass efficiency**
- IMF applied to ridges
- approximate protostellar lifetime
- ...

and often lack of angular resolution and kinematical data.

Need ALMA data and SF models adequate for ridges...