Mini-starburst ridges and “present-day” SFR in HOBYS, the Herschel imaging survey of OB Young Stellar objects

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1. HOBYS specificity
2. Cloud structure study, ridge definition
3. Census of young stellar objects, SFR estimates
4. Future HOBYS work and perspectives

Schmidt-Kennicutt diagram

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HOBYS molecular cloud complexes, pieces of the nearest spiral arms of the MW

HOBYS mol. complexes: $10^5 - 10^6 \, M_\odot$ 50 - 100 pc

(catalog by S. Bontemps; see Schneider et al. 2012)

Orion in Gould Belt: $10^5 \, M_\odot$ 50 pc

W43 in Hi-GAL: $7 \times 10^6 \, M_\odot$ 150 pc (Nguyen Luong et al. 2011b)
HOBYS molecular cloud complexes, one necessary step toward nearby galaxies

HOBYS mol. complexes: $10^5 - 10^6 \, M_\odot$ 50 - 100 pc
(catalog by S. Bontemps; see Schneider et al. 2012)

Orion in Gould Belt: $10^5 \, M_\odot$ 50 pc

Mass of gas

log(SFR) [M_\odot yr^{-1}]

ULIRGs

LIRGs

BXS

normal spirals

galaxies

galactic clouds

HOBYS complexes + W43

Lada et al. (2012)
Target all molecular cloud complexes forming OB-type stars at $d_{\text{Sun}} < 3$ kpc

Wide-field PACS/SPIRE imagings (70, 160, 250, 350, 500 µm) with 20''/sec

$\text{HPBW} = 6''-36.9'' \atop 0.7-3$ kpc $\Rightarrow$ down to 0.03-0.2 pc dense cores

$\Rightarrow$ census of intermediate- to high-mass protostars
$\Rightarrow$ link between cloud structure and (high-mass) SF
$\Rightarrow$ feedback effects

Complementary to other Herschel KPs:
- high-mass dense cores (small and isolated clouds) - EPOS (Krause et al.)
- low-mass cores (~0.02 pc) – HGBS, Cold Cores and HOPS survey (André et al.; Juvela, Ristorcelli et al.; Megeath et al.)
- protoclusters (~1 pc clumps) - Hi-GAL (Molinari et al.)
Feedbacks effects of OB star clusters: Heating, UV compression & triggered star formation

- **Rosette complex**
  - 70 μm, 160 μm, 250 μm
  - YSOs + cloud

- **RCW120**
  - Zavagno et al. 2010
  - 4 O stars

- **M16 complex**
  - 70 μm, 160 μm, 250 μm

- **Hill et al. 2012**
  - NGC 6611
  - 4 O stars

- **NGC 2244**
  - 7 O stars

- **Schneider et al. 2010**

See also Anderson+ 2010, 2012; Rodon+ 2010; Deharveng+ 2012; Minier+ 2012; Tremblin+ 2013
Fig. 1. 

In this paper, indicated on the map. Note the extended coverage of the M16 region as detected by observations and studies, which have focused more on the central OB cluster and the Pillars of Creation. A comparison of the Pillars of Creation with existing studies and protostars in this region. The three-colour (60, 160, 250 μm) image traces the hot dust, comparable to the Eagle Nebula. As a proxy, the hot regions in this map appear red, whilst colder regions appear blue, and as an extended PACS coverage to the east and south. A total area of 1.5 deg was mapped using two orthogonal scan directions. Each of the March and September data were reduced as part of the HOBYS guaranteed time key program (Motte et al. 2010). In March, the SPIRE (250, 350, 500 μm) wavelengths were mapped during this period. In September, were combined within parallel-locked frames from all scans' function, to produce a single map of the system. For these September observations, the SPIRE calibration is within 10% for all bands. These authors have been found to be within 10% and 20% at 70 and 160 μm, respectively, whilst SPIRE calibration is within 10% for all bands.

Feedbacks effects of OB star clusters: Heating, UV compression & triggered star formation

Hill et al. 2012

See also Anderson+ 2010, 2012; Rodon+ 2010; Deharveng+ 2012; Minier+ 2012; Tremblin+ 2013

Talks by Annie Zavagno, Nicola Schneider and Pascal Tremblin!

Schneider et al. 2010

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Example cloud filament forming a stellar cluster

IRDC G35.39-00.33
W48 complex
Rising $N_{\text{H}_2}$ contours

70 $\mu$m, 160 $\mu$m, 250 $\mu$m

Nguyen Luong et al. 2011a; Rygl et al. subm.

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Ridges are extreme clumps forming clusters of high-mass stars

- ~50% of high-mass protostars are forming in clusters within high-density elongated clumps

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

For convenience, we use the 100 A$_v$ level to identify ridges but it is not a physical threshold

- Surrounding gas concentrates toward ridges at high column-density (seen e.g. with PDF studies of N. Schneider)
  - Vela C ridge (Hill, Motte, Didelon et al. 2011)
  - DR21 ridge in Cygnus X (Hennemann, Motte, Schneider et al. 2012)
  - IRDC G035.39-00.33 ridge (Nguyen Luong, Motte, Hennemann et al. 2011a)
  - W43-MM1, MM2 ridges (Nguyen Luong, Motte, Carlhoff et al. 2013)
Some ridges could have formed by compression by UV radiation…

Vela C ridge

RCW36

70 μm, 160 μm, 250 μm

Column density (contours)

A model of ridge formation within a sheet compressed by the OB cluster UV radiation explains the observed structure and kinematics (Minier, Tremblin, Hill et al. 2012)
Most ridges should form by cloud global collapse

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

Gas flows along sub-filaments

\[ ^{13}\text{CO}(1-0) \]

0.2-1 km/s infall speeds

Global infall

\[ \text{Column density (cm}^{-2}\text{)} \]

- Similar kinematics for the W43-MM1 & MM2 ridges (Motte et al. 2005; Louvet et al. in prep.)

Hennemann, Motte, Schneider et al. 2012

\[ N_{\text{H}_2} > 10^{23} \text{ cm}^{-2}, 10000 \text{ M}_\odot, 9 \text{ pc}^2, <n> \sim 10^4 \text{ cm}^{-3} \]

Schneider, Csengeri, Bontemps et al. 2010

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Steps toward SF in ridges:

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

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


⇒ Prestellar cores may not exist in such environment

See Csengeri et al. 2011a-b for gas inflow shears in DR21 cores

See also Henshaw et al. 2013; Louvet et al. in prep. for other ridges
Bright & extended SiO emission along W43 ridges

SiO classically associated with protostellar outflows but here >70% is associated to 5-10 km/s shocks (Nguyen Luong et al. 2013; Louvet et al. in prep.)

Observations compared with shock models with Si in gas or SiO in grain mantles to constrain the filament merging (Gusdorf et al. in prep.).

See also Jiménez-Serra et al. 2011 for the IRDC G035.39-00.33.
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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. 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)
  
  ➔ ”Present-day” SFR

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

With both SFRs, one may constrain the history of star formation...
Warning: Spatial scales used for SFR/SFE estimates

High-res. extragalactic beam

CygX-North cloud

CygOB2, 45-100 O stars

Hennemann et al. 2012

70 μm, 160 μm, 250 μm

Global SFR on the CygX-North cloud (50 pc)

Local SFR on the DR21 ridge (5 pc)

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Mini-starburst cluster in the G035.39-00.33 ridge

(Nguyen-Luong, Motte, Hennemann et al. 2011)
Contours: SiO from Jimenez-Serra et al. 2010

- Herschel census:
  ⇒ 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

⇒ A mini-burst of SF (SFE ~20%, SFR~300 $M_\odot$/Myr, 40 $M_\odot$/yr/kpc$^2$ within 8 pc$^2$)
Galactic mini-starburst ridges location in a SK diagram

All these values must be refined with new protostar catalogs. 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

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Constraining statistical theories of SFR on W43-MM1...

An IRAM Plateau de Bure census of protostars in the W43-MM1 ridges provides an estimate of the clump to core formation efficiency (CFE, Louvet et al. in prep.).

According to models of Lada et al. 2012; Krumholz et al. 2011, 2012; Padoan & Nordlund 2012, …

\[
\text{SFR}_{\text{ff}} = \epsilon \int_{s_{\text{crit}}}^{\infty} \frac{t_{\text{ff}}(\rho)}{t_{\text{ff}}(\rho_0)} \frac{\rho}{\rho_0} p(s) \, ds
\]

- They predict a constant CFE = SFR\text{ff} / \mathcal{E} in regions above the SF threshold (Av> 8 mag).
- It is inconsistent with first measurements!!!

Multi-freefall models (Hennebelle et al. 2012; Federrath et al. 2012) with more realistic cloud structure should be more adequate...

\[n_{H_2} \text{ (cm}^{-3}\text{)}\]
Conclusion and perspectives

• Summary of HOBYS findings:

Networks of filaments among which the “ridges” are globally collapsing clumps formed through filaments merging driven by cloud or ionization compression.

Ministarburst clusters containing numerous high-mass class 0-like protostars leading to high local and present-day SFR within ridges.

Feedback effects of OB star clusters are important for cloud and star formation.

• Future prospects:

combining Herschel Galactic-scale and ALMA studies to

- Constrain the physics at the origin of the SK relation found in x-gal studies.
- Constrain the statistical SFR theories.