With the consortia of
- the HOBYS Herschel Key Program « the Herschel imaging survey of OB Young Stellar objects »
- the W43 IRAM & ATLASGAL Large program « Origin of molecular cloud and star formation in W43 »
The 9 closest cloud complexes forming high-mass stars.

- 50-100 pc at $d = 0.7-3$ kpc
- $M_{\text{cloud}} = 2 \times 10^5 - 1 \times 10^6 M_\odot$
- Forming up to 20 $M_\odot$ stars
- Herschel 70-500 $\mu$m

The nearest cloud complex at the tip of the Galactic bar.

- 140 pc at $d = 6$ kpc
- $M_{\text{cloud}} = 7 \times 10^6 M_\odot$
- Forming up to 50-100 $M_\odot$ stars
- HI, CO, SiO, ATLASGAL, Spitzer, …

Main open questions:

1) Origin of molecular cloud complexes and their high-density structures.

2) Link of the star formation efficiency to the cloud concentration and dynamics.
Cloud structure and OB star formation as seen by HOBYS, the Herschel imaging survey of OB Young Stellar objects


Frédérique Motte, Annie Zavagno, Sylvain Bontemps,


July 30th, 2012
A complete imaging survey of cloud complexes forming OB stars at <3kpc

⇒ enough statistics (~250 high-mass protostars expected) to study the precursors of stars up to 20 M☉.
⇒ Ideal to study feedback/trIGGERING (cloud under the influence of OB star clusters).

Near-IR extinction map of the Galaxy by S. Bontemps

9 complexes: 10⁵ - 10⁶ M☉ 50 - 100 pc at <3 kpc

Associated with OB clusters.

July 30th, 2012
F. Motte, GSSF Heidelberg
in this paper, indicated on the map. Note the extended coverage of the M16 region as detected by these respective regions. Here we present a structural analysis of the NGC 6611 cluster and the Pillars of Creation. Concurrently, Marston et al., (in prep) focus on an active ridge adjacent to the ionised cavity around the Pillars. They report evidence of a mini-starburst of high-mass star formation in an active ridge adjacent to the ionised cavity around the Pillars.

The Herschel image of the M16 region is presented in the top left panel of Fig. 1 (right). This 70 μm Herschel image of the M16 region is presented in comparison of the Pillars of Creation with existing studies. The three-colour (60, 160, 250 μm) composite image of the Eagle Nebula is given in Fig. 1 (left) with the full five bands presented by White et al. (2012). This 70 μm PACS image of M16 with well-known regions from the literature is also presented.

The regions identified (the ring feature) and discussed in the figures. Right: 1.5 deg was mapped using two orthogonal scan directions. The two sets of PACS data, from March and September, were combined within a 3% common area coverage (normally, the positional accuracy is better than 0.01% of the field of view). The high-resolution PACS data are presented here for the first time. The full five bands are presented in this paper by White et al. (2012) examines the stellar content of the M16 region as detected by the submillimetre regime, of the Eagle Nebula. These observations were mapped during this period. In September, the parallel HOBYS guaranteed time key program (Motte et al. 2010). In March, the SPIRE (250, 350, 500 μm) observations, spanning the far-infrared and submillimetre regime, of the Eagle Nebula. As a proxy, the hot regions in this map appear in the orange-red spectrum, while colder regions appear in the blue.

The 70 μm PACS image of M16 with well-known regions from the literature is also presented. For these September observations, the SPIRE data were combined for the first time with the PACS data, using the short PACS integration time of 0.5 s. This yields an effective field of view of 0.01 deg in the PACS bands, and thus only the small spatial extent of the telescope were used. Calibration of the PACS data was performed using the default pipeline to level-1 including calibration and deglitching. To improve the baseline subtraction, data taken during the test phase of the HOBYS program were submitted. The two sets of PACS data, from March and September, were combined within a 3% common area coverage (normally, the positional accuracy is better than 0.01% of the field of view). The high-resolution PACS data are presented here for the first time. The full five bands are presented in this paper.
Cloud structure: disorganized networks of filaments versus single dominating ridges

- Dust temperature & column density images from Graybody fits (36’’ resolution)
- Census of filaments with DisPerSE (Sousbie 2011) and MDCs (massive dense cores) with Getsources (Men’shchikov et al. 2012)

⇒ High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), elongated cloud structures dominating their surrounding.

N_H2 map  Vela C

RCW36
(Hill, Motte, Didelon et al. 2011)

RCW34
x 13 MDCs

Ridge
At high column density, Center-Ridge has a flatter PDF slope than South-Nest.

⇒ may suggest that gravity rather than turbulence is shaping its cloud (e.g. Klessen 2000)

Like coherent structures created via constructive large-scale flows (Federrath et al. 2010).

More mass is concentrated in single ridges than in the lower-$A_v$ filaments of nests.

⇒ The potential well of ridges is shaping their surrounding regions and/or vice-versa…
Ridges (5-10 pc², >100 Aᵥ) are extreme IRDCs formed by dynamical scenarios such as filament merging or global infall.

DR21 ridge: Hennemann, Motte, Schneider et al. 2012
IRDC G035.39-00.33 ridge: Nguyen Luong, Motte, Hennemann et al. 2011
W43-MM1, MM2-MM3 ridges: Motte, Schilke, Lis 2003

N₇₂ > 10²³ cm⁻², 10 000 M₆, 9 pc², <n> ~ 10⁴ cm⁻³

See also Schneider et al. 2012; Nguyen et al in prep.
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 of protostellar dense cores (Getsources extraction, SED fitting by graybody models):
⇒ 5 high-mass class 0 protostars or 20 protostars with $2\ M_\odot$ on the MS.

• Assumptions:
✓ Core-to-star mass efficiency: 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 $\sim 20\%$, SFR $\sim 300\ M_\odot/\text{Myr}$, $40\ M_\odot/\text{yr}/\text{kpc}^2$ within 8 pc$^2$)

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A mini-starburst region: a large amount of dense gas in a pc$^2$ area which is forming a cluster of high-mass stars.

(Motte et al. 2003; Nguyen Luong, Motte, Hennemann et al. 2011)
1. Feedback effects of OB star clusters on molecular clouds such as heating, pillars and triggered star formation.

2. Networks of filaments among which the “ridges” (well-ordered, high-$N_{\text{H}_2}$, dominating filaments) are forming high-mass stars/mini-starburst.

3. Precursors of high-mass stars: protoOB-stars, massive starless cores and their associated ministarburst clusters.  

*(see Martin Hennemann’s talk!)*

(Motte et al. 2010; Hennemann et al. 2010, in prep.; Giannini et al. 2011; Zavagno et al. 2010; Nguyen Luong et al. 2011)
Frédérique Motte & Quang Nguyen Luong  
(AIM, Paris Saclay)  (CITA, Toronto)  
With: P. Schilke, P. Carlhoff, F. Louvet, S. Bontemps  

And observers from the W43/ATLASGAL consortium:  
F. Schuller, N. Schneider, H. Beuther, T. Csengeri, K. Menten, R. Simon, C. Kramer,  
F. Wyrowski, Th. Henning, L. Bronfman, M. Walmsley, A. Zavagno, …  

With modelers of molecular cloud formation:  
F. Heitsch, P. Hennebelle, E. Vazquez-Semadeni, R. Banerjee, …  

July 30th, 2012  
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1. Definition of a new molecular cloud and star-forming complex: W43 (around the W43-Main, clouds with a velocity coherence over 140 pc)

2. Extreme characteristics (total mass, velocity dispersion, mass concentration, SFR, ...) of W43 and its location at the tip of the Galactic bar

3. Imprints in W43 of molecular cloud formation from HI gas and first signatures for converging flows (atomic envelope, global collapse, low-velocity shocks, ...)

July 30th, 2012
Two episodes of efficient star formation
1. A OB/WR stellar cluster powering a giant H II region:
   - $3 \times 10^6 L_\odot$, $10^{51}$ photon/s
   - 5 pc, $A_v = 30$ mag (Blum et al. 1999)

2. An active star-forming cloud:
   - 20 pc, $10^6 M_\odot$
   - more than 50 high-mass protostars
   $\Rightarrow$ SFE $\sim 25% /10^6$ yr
   $\Rightarrow$ SFR $\sim 1500 M_\odot$ Myr$^{-1}$ over 60 pc$^2$
   SFR density $\sim 25 M_\odot$ yr$^{-1}$ pc$^{-2}$
   (Motte, Schilke, Lis 2003)
   - global collapse of the MM1 and MM2 ridges (Motte et al. 2005)
W43, an extreme molecular complex of the Milky Way

Column density of the gas (GRS, Jackson et al. 06)

Star formation activity (GLIMPSE, Churchwell et al. 09)

Regions of high-density gas (ATLASGAL, Schuller et al. 09)

(from Nguyen Luong, Motte, Schuller et al. 2011)

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W43, a coherent molecular complex in space/vel

- Main velocity range: 80-110 km/s
- Line wings: 60-80 km/s (partly associated) and 110-120 km/s (most probably associated) (Nguyen Luong et al. 2011)

$^{13}$CO 1-0 line averaged over the complete W43 complex

$^{13}$CO 1-0 image integrated over 3 velocity ranges

Gaussian FWHM ~22 km/s
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Comparison with other molecular and star-forming clouds/complexes

With its size (~140 pc), mass (7.1 x 10^6 M_☉), and velocity dispersion (FWHM ~ 22.3 km/s), W43 defines as a GMC Association (GMA quoted in extragalactic studies) or molecular complex.

Large amount of gas: at least 1 order of magnitude larger than nearby Gould belt molecular complexes

Its concentration of cloud material in dense structures and its star formation rate are exceptional for such large amount of gas. \textit{(Nguyen-Luong et al. 2011)}

<table>
<thead>
<tr>
<th></th>
<th>Distance (kpc)</th>
<th>Diameter (pc)</th>
<th>Gas mass (M_☉)</th>
<th>Concentration of mass into cold dense &lt;5 pc clumps</th>
<th>SFR present-future (M_☉ yr^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>W43</td>
<td>6</td>
<td>140</td>
<td>7 x 10^6</td>
<td>12%</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>Cygnus X</td>
<td>1.7</td>
<td>160</td>
<td>5 x 10^6</td>
<td>1%</td>
<td>0.003-0.07</td>
</tr>
<tr>
<td>CMZ</td>
<td>8.5</td>
<td>350</td>
<td>3 x 10^8</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Orion</td>
<td>0.5</td>
<td>50</td>
<td>5 x 10^5</td>
<td></td>
<td>0.0004-0.001</td>
</tr>
</tbody>
</table>
Star formation activity in W43

- Past Star Formation Rate (SFR):
  from the 8 µm image (GLIMPSE, Churchwell et al. 2009) with SFR equations generally used for extragalactic studies
  \[
  SFR_{8\mu m} = \frac{\nu L_{\nu}[8\mu m]}{1.57 \times 10^9 L_{\odot}} \sim 0.01 M_{\odot} \text{ yr}^{-1} \times \left( \frac{d}{6 \text{kpc}} \right)^2
  \]
  (Wu et al. 2005, Kennicutt 1998)

- Future SFR:
  from the total molecular mass of the W43 cloud and assuming typical star formation efficiency and cloud lifetimes (1-3 x 10^6 yr)
  \[
  SFR_{\text{CO}} = 0.05 - 0.14 M_{\odot} \text{ yr}^{-1} \times \left( \frac{M_{\text{total}}}{7.1 \times 10^6 M_{\odot}} \right) \times \left( \frac{\text{SFE}}{2\%} \right)
  \]

Are we witnessing the formation of a new starburst cluster? (Nguyen Luong et al. 2011)

- Past and Future SFRs can be compared with the Present SFR derived from the YSOs population found with Herschel (Nguyen Luong et al. in prep.)
History of the star formation (SFR) in W43

- **Spitzer** mid-IR flux ➔ Past SFR ★
- **Herschel** (Hi-GAL) sample of protostars ➔ Present SFR ★
- Total mass of the gas ➔ Future SFR ★

Figure adapted from Nguyen Luong, Motte, Schuller et al. (2011b), Nguyen Luong et al. in (prep.). But huge uncertainties for all these SFRs! Crude assumptions, rough extrapolations, often indirect measurements…

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W43, bridging galaxies to Gould Belt clouds

Adapted from Lada et al. (2012)
Kinematic distance of W43:

\[ <V_{\text{LSR}} > = 95.9 \text{ km/s} \ @ \ l = 30.5^\circ \]

=> \[ d_{\text{near}} = 5.9 \text{ kpc}, \ d_{\text{far}} = 8.7 \text{ kpc} \]

Given its peculiar characteristics

(large mass, exceptionnal concentration, large velocity dispersion, high star formation rate),

W43 is most probably at the meeting point of the Scutum-Centaurus arm and the Bar and thus at the tip of the Bar \(~6 \text{ kpc from our Sun.} \)  

(Nguyen-Luong et al. 2011)
1. Definition of a new molecular cloud and star-forming complex: W43 (around the W43-Main, clouds with a velocity coherence over 140 pc)

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The W43 complex formed out of HI gas

W43: HI from VPS (color) & $^{13}$CO 1-0 from GRS (contours)

Preliminary analysis: HI gas is turned into H$_2$ gas @ 150-70 pc. The molecular cloud complex is close to Virial equilibrium or collapsing on 20-200 pc scales.

An HI envelope (200 pc) surrounds the molecular complex (150 pc).

(Nguyen Luong, Motte, Schuller et al. 2011)

(Motte, Nguyen Luong et al. in prep.)
Identifying HI flows around W43

Do HI flows forming CO reflect initial colliding flows?

Position-Velocity diagram of $^{13}$CO 1-0 from GRS

(Mottn, Nguyen Luong, Motte, Schuller et al. 2011)

Position-Velocity diagram of HI from VGPS

(Motte, Nguyen Luong et al. in prep.)
Origin of molecular clouds and star formation in W43 - a large IRAM program

by F. Motte, P. Schilke, Q. Nguyen Luong P. Carlhoff, et al.
152 hours with HERA/EMIR at the IRAM 30m

Target: W43 is the closest molecular complex of the Galactic Bar.

Goal: Build up a complete database for W43 to test the numerical simulations of converging flows (e.g. Heitsch & Hartmann 2008; Banerjee et al. 2009; Vazquez-Semadeni et al. 2011).

Imagings: (Carlhoff et al. in prep.; Nguyen Luong et al. in prep.)
- of the entire complex with HERA in $^{13}$CO 2-1 & C$^{18}$O 2-1
- of dense regions with EMIR in HCO$^+$ 3-2 & H$^{13}$CO$^+$ 2-1, SiO 2-1...

First results: the densest filaments/ridges are undergoing supersonic global infall ($\sim$2 km s$^{-1}$ over 5 pc) and display low-velocity SiO shocks.
Extended SiO emission not associated with protostars

SiO 2-1: bright line and emission extended over ~5 pc dominating filaments /ridges.

Clearly detected at position far from protostars: 70 \(\mu\)m from. EPOS KP or 3mm IRAM PdBI cores.
SiO, a signature of low-velocity shock flow?

In W43, SiO lines are at rest, with no clear outflow wings $\Rightarrow$ shocks from streamers/converging flows shears?

Their integrated intensity are among the largest (See also Motte et al. 2007; Jimenez-Serra et al. 2010)

(Cygnus X: Motte et al. 2007
Lopez-Sepulcre et al. 2011
W43: Nguyen Luong et al. in prep.)
With HOBYS, we have: (see also Martin Hennemann’s talk)
1. Shown feedback effects of OB star clusters on the clouds.
2. Discovered ridges: dominating filaments inside which high-mass stars preferentially form.
3. Measured SF rates and shown they are high in ridges/mini-starbursts.

In the W43 case-study, we have:
1. Defined of a new molecular cloud and star-forming complex.
2. Interpreted its extreme characteristics as due to its location at the tip of the Galactic bar.
3. Revealed first imprints of molecular cloud formation from HI gas through converging flows.

The HOBYS and W43 surveys are two more steps towards understanding Galactic-scale star formation. Their results points towards linking highly-dynamical molecular cloud formation to intense star formation activity.