Star formation triggered by Galactic HII regions

Herschel first results and ALMA perspective

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Outline

Context: theoretical aspects

- First results from the Herschel Space Observatory
  - HOBYS, Hi-GAL programs
- Other programs: ATLASGAL, MALT90

Inputs for ALMA Early science
Thanks

In collaboration with
F. Motte, S. Bontemps, Schneider and the HOBYS consortium
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Star formation triggered by HII regions

1. Expansion of the HII region
   - HII region (10,000 K)
   - Outer molecular material (< 100 K)

2. Formation of a dense layer surrounding the HII region
   - Ionization front
   - Shock front

3. Gravitational collapse of the layer into dense fragments
   - Newborn star surrounded by a compact HII region

4. New stars forming in the fragments
The accumulation of neutral material around HII regions

Dyson & Williams: The Physics of the Interstellar Medium

<table>
<thead>
<tr>
<th>Massive Star</th>
<th>O6V</th>
<th>O6V</th>
<th>B0V</th>
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<td>Phot./s</td>
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<tr>
<td>n_0</td>
<td>1000 cm^{-3}</td>
<td>100 cm^{-3}</td>
<td>100 cm^{-3}</td>
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<tr>
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<tr>
<td>R</td>
<td>5 pc</td>
<td>10 pc</td>
<td>5 pc</td>
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<tr>
<td>V_{exp}</td>
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<td>n_e</td>
<td>50 cm^{-3}</td>
<td>17 cm^{-3}</td>
<td>5 cm^{-3}</td>
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<tr>
<td>M(HII)</td>
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<td>90 M_☉</td>
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<tr>
<td>M(shell)</td>
<td>16900 M_☉</td>
<td>12700 M_☉</td>
<td>1690 M_☉</td>
</tr>
</tbody>
</table>

Observations:
- (sub-)millimeter: the medium is optically thin \(\rightarrow\) good estimate of the mass
- CO: velocity \(\rightarrow\) isolate the material associated with the HII region
Different processes triggering star formation around HII regions

Gravitational instabilities in the collected layer

Radiation-driven compression of pre-existing molecular clumps

Small scale

Large scale

Collect & collapse

Ionizing radiation acting on a turbulent medium (Gritschneder et al. 2009, 2010)

Deharveng et al. (2010)
Results from the Spitzer mission

A global vision of the Galactic plane at high angular resolution

- We are living in a bubbling Galactic disk (HII regions, supernovae)
- Many of the bubbles impact on their surrounding
- They trigger the formation of a new generation of stars

What is the importance of this phenomenon?

Important (25% of the bubbles show TMSF) → see Deharveng et al. 2010 (102 bubbles with Spitzer and ATLASGAL 870 µm survey)
An example: The N36 bubble (Deharveng et al. 2010)

8 μm
870 μm (contours)
Methanol maser II

Compact and UC HII regions

8 μm
20 cm (MAGPIS)

D = 6.4 kpc
Herschel programs

Characterize this phenomenon

- Detailed studies of a sample of 8 HII regions (RCW71, RCW79, RCW82, RCW 120, Sh104, Sh241, G332, W5): PACS and SPIRE imaging and spectroscopy (HOBYS and ISM GT KPs)

Global study on a Galactic scale (Hi-GAL)

- What is the importance of this phenomenon (for the formation of massive stars) when we access the early stages of star formation?
Inputs for ALMA

Herschel PACS and SPIRE imaging
- census of YSOs
- properties through SED fitting, color-color diagrams
- spatial distribution (search for gradients in evolutionary stage)

Herschel PACS and SPIRE spectroscopy
- physical properties and their spatial variations

(Herschel HIFI: to be done for dynamics)

MALT90: MOPRA observations at 90 GHz: maps in 16 molecular lines of 3000 dense cores: chemistry, physical conditions, evolution stage (http://grunt.bu.edu/~grs/malt90/)
Herschel's interest to study young stellar objects

Spectral energy distribution

Radiated energy

Near-IR
Mid-IR
Far-IR

1.2mm

Herschel's interest to study young stellar objects

Spectral energy distribution
First results from Herschel
RCW 120

D = 1.3 kpc

Optical

2MASS Ks

Hα

Spitzer-GLIMPSE
3.5 μm
8 μm

APEX-LABOCA
870 μm
RCW 120 as seen by Herschel
A highly embedded population of young stars around RCW 120

Spitzer-MIPSGAL 24 µm

PACS 100 µm
A massive Class 0 on the border of RCW 120

Spectral energy distribution using the Robitaille et al. (2007) model.
A massive Class 0 massive ($8-10 \, M_\odot$)
$L_{350\mu m}/L_{bol} = 0.12$

Zavagno et al. 2010a
The T- $\beta$ relation

Dust opacity $\kappa_v = \kappa_{v_0} \left( \frac{v}{v_0} \right)^\beta$ cm$^2$/g

$\beta$ dust spectral index

$\beta$ and T are linked (Dupac et al. 2003)
See also Hill et al. 2006
Fig. 3. Spectral index versus temperature, for fully independent pixels in Orion (black asterisks), M 17 (diamonds), Cygnus (triangles), ρ Ophiuchi (grey asterisks), Polaris (black squares), Taurus (grey square), NCS (grey cross) and NGC 891 (black crosses). The full line is the result of the best hyperbolic fit: $\beta = \frac{1}{0.4 + 0.008T}$. Dupac et al. 2003
Temperature map (with PACS and SPIRE images)
The $\beta - T$ relation
Anderson et al. (2010) + Anderson et al. 2011

RCW 120
D=1.3 kpc
Temperature map
The $\beta - T$ relation
Rodón et al. (2010) + Rodón et al. (2011)

Sh104
D=4 kpc

Sh 104
AKARI
IRC
15 $\mu$m
24 $\mu$m

UC HII
SPIRE-FTS: The UC HII region of Sh104
Rodón et al. (2010)
RCW 120 PACS 100 μm
+ FTS pointings
Physical conditions with spectroscopy
PDR diagnostics

Kaufman et al. 1999 (also used for extragalactic PDRs) ApJ 527, 795

Le Petit et al. 2006, ApJS 164, 506 → the one used

• Main PDR diagnostics (PACS and SPIRE ranges):
  
  [OI] 63 and 145 μm
  
  [CII] 158 μm
  
  [CI] 370 and 609 μm
  
  CO J=1-0, J=2-1, J=3-2, J=6-5, J=15-14
  
  Far-IR continuum

• Derive the density, temperature and UV radiation field from lines and continuum intensities
Combine different diagnostics to refine the physical conditions determination

\( G_0 \): radiation field: far UV flux \((1.6 \times 10^{-3} \text{ ergs cm}^{-2} \text{ s}^{-1})\)

n: density
The Rosette nebula: complex triggering

- Massive stars cluster at the centre
- NGC 2244
- Distance 1.6 kpc

HOBYS Program Motte, Zavagno, Bontemps et al.

Schneider et al. 2010
Hennemann et al. 2010
di Francesco et al. 2010
Aquila
Distance: 260 pc
Image width: 8 pc
Star formation and filaments

Gould Belt program: André, Saraceno et al.

André et al. (2010)
Könyves et al. (2010)

Study triggered star formation in nearby regions

PACS 70 μm
PACS 160 μm
SPIRE 250 μm

W40
Sh 62
The Gould Belt
Aquila
IRAS 100 μm
The Hi-Gal program

Survey the inner Galactic plane

- $-60° < l < 60°$ - $|b| < 1$
- 5 photometric bands 70-500μm with PACS and SPIRE
- 6″-35″ spatial resolution
Towards a global study with Hi-GAL

More than 600 bubbles in the Galaxy (Churchwell et al. 2006, 2007)

Use multiwavelength surveys to study the star formation triggered by HII regions

Statistics and efficiency
Census of massive star formation in our Galaxy (trace the mass and evolutionary stage)
A multiwavelength view of our Galaxy

76 HII regions in the $l=30^\circ$ field (red circles)

Distance determination is crucial to discuss the TSF
First results on N49 (Zavagno et al. 2010b)

Optical (I-band) + ATLASGAL 870 µm (contours and red)

N49: Galactic HII region d=4.5 kpc
First results on N49 (Zavagno et al. 2010b)
(5’x5’ field)
More to come…

SPIRE and PACS imaging
SPIRE-FTS and PACS spectroscopy

RCW 82

RCW 79

3 µm GLIMPSE
8 µm GLIMPSE
24 µm MIPSGAL
RCW 79
RCW 79: ongoing (massive) star formation

Methanol maser
Cluster

Martins et al. 2010
SINFONI @VLT

8 µm
24 µm
100 µm
160 µm

250 µm
350 µm
500 µm
870 µm
Summary

Many more results expected on Herschel

- Different well-known regions where TSF occurs (Rosette, M16, W5, …)
- Ground (and space)-based follow-ups

MALT90: Influence of HII regions and triggering

- Physical and chemical conditions, evolutionary stage in bright condensations around HII regions

Dedicated modeling: realistic and complete including all ingredients: gas, dust, B, chemistry and all expected feedback effects (ionizing flux, winds, …)
ALMA

ALMA Early Science

- Follow-up of very young massive stars detected with Herschel and other facilities
- Chemistry, geometry, dynamics (also PdBI, SMA, ATCA)

Triggered star formation in the ALMA context

An easy way to study star formation

But how « different » is this way of forming stars?
Role of winds
(Martins et al. 2010, A&A 510)

• Near-IR spectro-imaging study (SINFONI @VLT) of three Galactic HII regions: RCW 79, RCW 82, RCW 120

• YSOs properties through IR colors and spectra

• Wind properties of first generation ionizing stars → not dominant
Winds in RCW 79

Martins et al. 2010