Massive Star Birth: A Crossroads of Astrophysics
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Triggered massive-star formation on the borders of Galactic H II regions

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Abstract. Various physical processes are believed to trigger star formation on the borders of Galactic H II regions. Among these, the collect & collapse process is particularly attractive as it allows the formation of massive objects (single stars or clusters). In order to identify specific cases of this way of triggering star formation we are carrying out a multi-wavelength study of Galactic H II regions that exhibit signposts of massive-star formation at their borders. Hereby, we present two typical examples of such sources and discuss the results in the framework of the collect and collapse process, which seems to be at work as the major triggering agent in these two cases.

Keywords. Star: formation, H II regions

1. Introduction

The way massive stars form (either by simple accretion or by coalescence of lower mass objects – see Bally & Zinnecker 2005 for a review) is still debated. The relative rareness of massive stars, their rapid evolution, and their lack of a pre-main sequence phase, make it difficult to observe the earliest stages of their formation.

Star formation may be triggered by various processes, depending mainly on the time scale and on the characteristics of the surrounding medium (Elmegreen 1998). The expansion of an H II region into the surrounding medium may favor the formation of a second generation of stars. We are particularly interested in the collect & collapse process, first proposed by Elmegreen & Lada (1977) because it leads to the formation of massive objects. The expansion of an H II region into the surrounding medium leads to the formation of a compressed layer of dense neutral material accumulated between the ionization and the shock fronts. This layer will then collapse gravitationally and form *massive* fragments. Those fragments are potential sites of second-generation massive-star formation. Whitworth *et al.* (1994) have developed an analytical model for the collect & collapse process which predicts the fragmentation time, the number and mass of the fragments. Hosokawa & Inutsuka (2005) point out that this way of forming massive stars contributes significantly to the star formation rate in our Galaxy.

We describe the aims of our study and the selected sample in § 2. We then propose two cases for this way of triggering massive-star formation in § 3, and compare the results derived from observations with models in § 4. We conclude and look to the future in § 5.

2. Observations

We are engaged in a multi-wavelength study of a sample of Galactic H II regions selected on the basis of their simple morphology (a circular ionized zone surrounded by an annular photo-dissociation region) and on the presence of signposts of massive star formation on their borders (ultra compact (UC) H II region, luminous mid-IR sources, maser emission – see Deharveng *et al.* 2005 for details about the sample). We are carrying out observations of the selected regions from the optical to the millimeter range (both line- and continuum emission) in order to derive the properties of the surrounding medium. We look at the optical emission of the ionized gas of the first generation H II region, to locate the ionization front. We use near-IR imaging to characterize the stellar properties of the embedded population. Observations in the mid-IR are used to map the warm dust emission (mainly due to band emissions from large aromatic molecules) located in the hot photo-dissociation region. This mid-IR emission is also useful in revealing the reddest and most deeply embedded sources. We complement those observations with millimeter line- and continuum data to look, respectively, at the distribution of molecular material and cold dust emission. These last two sets of data are particularly useful for revealing the presence of a fragmented dense layer around the ionized gas and in estimating the mass of the fragments present in this layer. The selected geometry facilitates the interpretation as it offers a clear separation of the various components (ionized, molecular) along the line-of-sight.

3. Two examples

3.1. *Sharpless 104*

Sh2-104 is a Galactic H II region of $7'$ diameter located at a distance of 4 kpc and ionized by an O6V star (Crampton *et al.* 1978). This region is described in detail in Deharveng *et al.* 2003. It is surrounded by a complete ring of dust, detected by MSX at $8.3\,\mu$m. An UC H II region is located on its eastern border (see Fig. 1 in Deharveng *et al.* 2003), which contains an embedded stellar population detected in the near-IR, and which is associated with a luminous MSX and IRAS point source.

Figure 1 shows the CO (2–1) emission integrated between -2 and 2 km s^{-1} (the LSR velocity of the ionized gas is 0 km s^{-1}) observed towards Sh2-104 with the IRAM 30-m telescope. This emission arises from an annular structure surrounding the H II region. Local bright spots are observed.

Figure 2 shows Sh2-104 observed in CS (2–1) with the IRAM 30-m telescope. This emission reveals the presence of four dense fragments regularly distributed in the molecular ring surrounding the H II region. The total mass of the ring, estimated from the ^{13}CO (1–0) emission and assuming an average temperature of 20 K, is 6000 $M_\odot$. The eastern fragment observed in CS (2–1) (at offset $150''$, $-25''$) has a mass of 670 $M_\odot$ and contains the UC H II region that hosts the near-IR embedded cluster. The map of the C^{18}O (2–1) emission of this fragment superimposed on the CFHT K image of the cluster (see Fig. 3 in Deharveng *et al.* 2003) indicates that the cluster is bracketed to the north-east and south-west by two peaks of C^{18}O emission.

We have estimated the star formation efficiency for the brightest fragment observed at the border of Sh2-104. Assuming a standard initial mass function, a cluster containing a B0V star (corresponding to the ionization flux required for the UC H II region) has a mass of 500 $M_\odot$. The fragment has a mass of 670 $M_\odot$, pointing to a star formation efficiency of 40%.

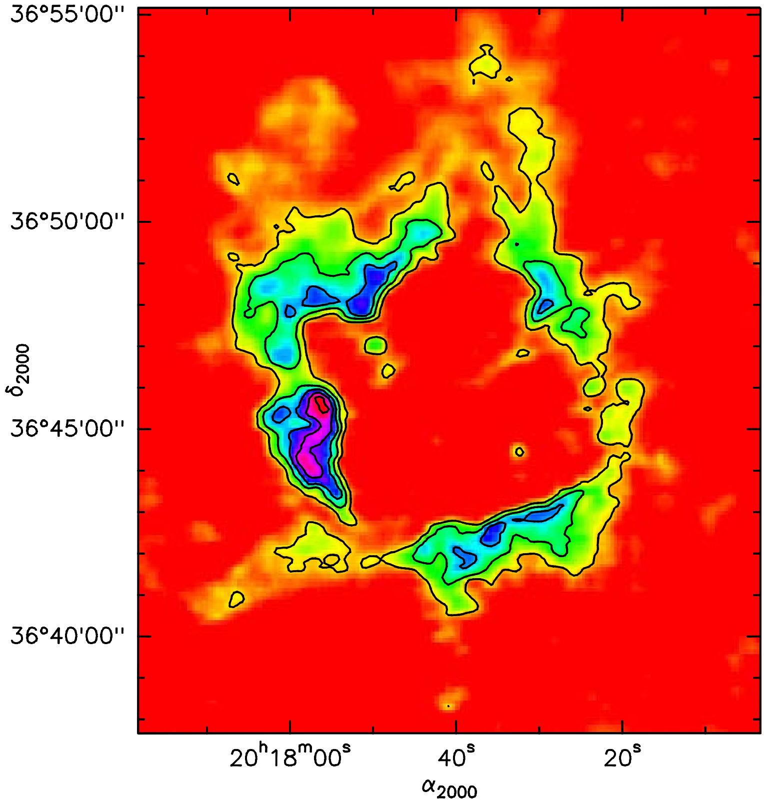

Figure 1. CO (2–1) emission observed towards Sh2-104 with the IRAM 30-m telescope. First contour and contour interval are 10 K km s^{-1} The ionized region fills the hole seen inside the annular structure.

3.2. *RCW 79*

RCW 79 (Rodgers *et al.* 1960) is a bright optical H II region of diameter ∼12′, located at a distance of 4.2 kpc (Russeil 2003). This region and its surroundings have been studied by Cohen *et al.* (2002). They present a 843 MHz map showing a shell nebula, coinciding with the optical H II region, and a compact source with no optical counterpart at the south-east border of the nebula's shell. RCW 79 is surrounded by a dust ring (see Fig. 2 in Cohen *et al.* 2002 and Fig. 17 in Deharveng *et al.* 2005), traced by its mid-IR emission in the MSX Band A at 8.3 μm. A detailed study of the whole region in the millimeter continuum emission and of the compact H II region in the near-IR is presented in Zavagno *et al.* (in preparation).

The 1.2-mm continuum emission of cold dust is shown in Fig. 3. This map, overlaid with the Hα emission, shows the presence of seven fragments that form an annular structure around the ionized region. The fragments are identified by numbers (see Fig. 3). We have estimated the masses assuming optically thin dust emission and using values of $T_{\rm dust}$ in the 20–30 K range and $\kappa_{1.2\rm mm} = 0.01$ cm^2 g^{-1} (Ossenkopf & Henning 1994), assuming a gas-to-dust ratio of 100.

The most massive fragments (numbers 2, 3 and 4) have masses in the 400 − 1400 $M_\odot$ range. Using near-IR data (from ESO-NTT observations and the 2MASS survey) we have been able to study the stellar content of these fragments. Several bright red sources, some having a near-IR excess, are observed on the borders of these fragments. Images at different wavelengths from 3.6 to 8 μm of this region have been obtained in the Spitzer

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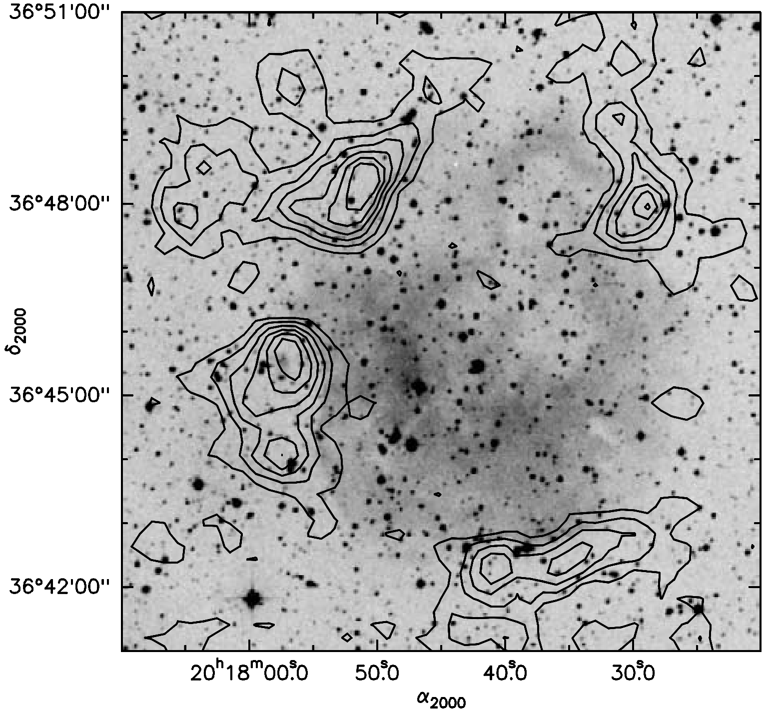

Figure 2. Distribution of the CS (2–1) emission integrated between −3 and +5 km s^{-1} superimposed on the DSS-red image of Sh2-104. First contour and contour interval are 0.3 K km s^{-1}

GLIMPSE survey (Benjamin *et al.* 2003) using the IRAC camera (Fazio *et al.* 2004). These images were used to identify the reddest objects in the field and to determine their spectral energy distributions. These data confirm that massive objects are formed on the borders of the fragments. No objects are detected *at* the millimetre peaks in RCW 79.

As for Sh2-104, we have estimated a star formation efficiency for the fragment observed towards the compact H II region located at the edge of RCW 79, using the results from the near IR observations. Assuming a standard initial mass function, a cluster containing an O6.5V star has a mass of 860 $M_\odot$. The remaining fragment has a mass of about 1050 $M_\odot$, pointing to an efficiency of 45%, similar to the value obtained for Sh2-104.

4. Discussion

A model describing the dynamical expansion of ionization and dissociation fronts around a massive star has been developed by Hosokawa & Inutsuka (2005). They specifically applied this model to Sh2-104 using the observations reported in Deharveng *et al.* (2003) and assuming an initial density of $n_{\rm H,0} = 10^3$ cm^{-3} ($n_{\rm H_2} = 500$ cm^{-3}). The radius of Sh2-104 is 4 pc and, in their calculation, the ionization front reaches this radius at $t = 0.7$ Myr. According to the model, the shell mass at that time is 9000 $M_\odot$, in reasonable agreement with observation. The model predicts that the shell is mostly molecular. By the age of Sh2-104, the outer part of the shell becomes unstable. Therefore, dense molecular fragments are formed around the H II region and triggered star formation may occur in the cores, as observed.

The analytical model developed by Whitworth *et al.* 1994 allows one to predict the fragmentation time, the radius of the H II region at that time, the number and the mass

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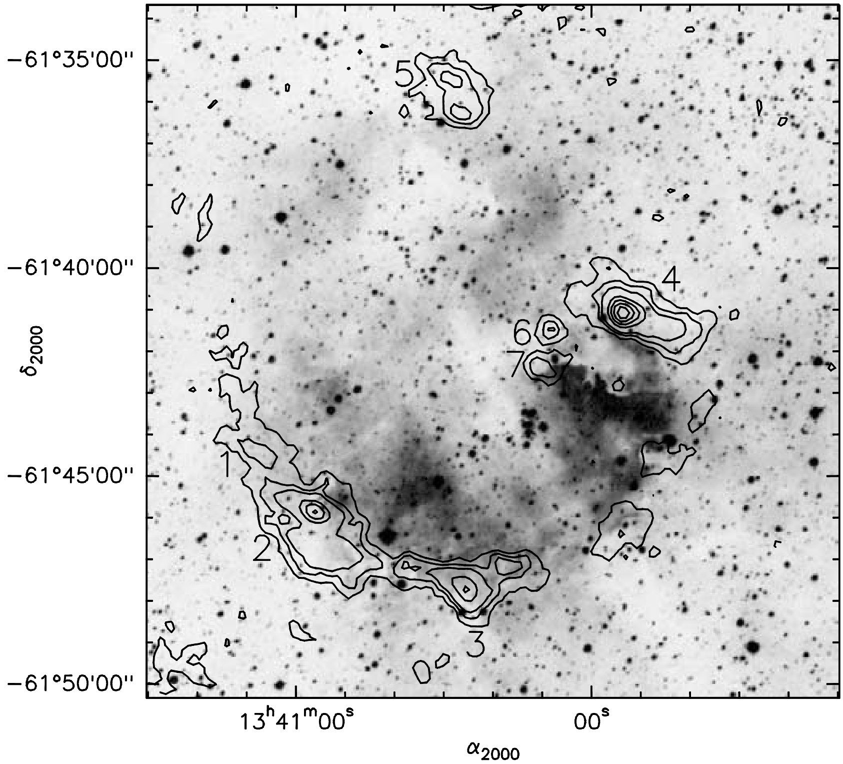

Figure 3. Millimetre continuum emission (contours; data obtained with SIMBA at SEST) superimposed on an Hα image of the region. The first levels are 50, 100 and 150 and then increase in steps of 100 mJy/beam, from 300 to 700 mJy/beam. The condensations discussed in the text are identified by their number (from 1 to 7). Their limits, used for the mass derivations, are defined by the 100 mJy/beam contour (5σ level)

of the fragments. We have compared those predictions with the quantities estimated from the observations of RCW 79. A high value for the isothermal sound speed in the layer ($a_s > 0.4$ km s^{-1}), and a high value of the initial density ($\rho_0 > 1000$ cm^{-3}), are needed to reproduce the size of the H II region and the mass of the fragments derived from the observations. Assuming a initial density of 2000 cm^{-3} and a sound speed in the layer of $a_s = 0.4$ km s^{-1}, we estimated a dynamical age of 1.7 Myr, larger than the Whitworth *et al.* model's fragmentation time (1.6 Myr). This is consistent with the observations, which already show the presence of fragments on the borders of the H II region.

Models of expanding H II regions in non-infinite and/or non-uniform media are needed to better fit the observations. They are currently being developed (Hosokawa & Inutsuka 2005; Whitworth, private communication). Accurate measurements of a_s and ρ_0 in these regions will also be an important step towards our understanding of this process.

Several massive fragments are observed at the borders of the two selected regions, and massive-star formation occurs in these fragments. Bright IR sources are observed at their borders. However, no IR source is detected towards the millimetre peaks in RCW 79.

5. Conclusions and perspectives

Observations of Sh2-104 and RCW 79 confirm that the collect & collapse process is at work on their borders and has induced the formation of massive objects, as shown

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by the presence of several *massive* fragments regularly distributed around the borders of the H II regions together with near-IR clusters, bright IR point sources and compact H II regions.

The efficiency of this process seems to be high, as previously estimated (≃45%). If the extensiveness and efficiency of this process are confirmed, the dense zones located on the borders of H II regions may represent ideal sites for looking at the earliest stages of massive-star formation.

The Spitzer and Herschel satellites with their large wavelength coverage (respectively 3–160 μm and 60–670 μm) offer interesting perspectives for this program. The imaging capabilities of Herschel will make it possible to detect highly embedded sources down to a spatial resolution of 3″ at 60 μm attained by the Herschel-PACS instrument. The spectroscopic facilities will allow one to obtain the physical conditions in the hot photo-dissociation region. Dedicated guaranteed time programs using the Herschel-PACS and SPIRE instruments will be carried out to better constrain the collect and collapse mode of triggering massive-star formation. The large open time program Hi-GAL, which proposes a complete survey of the Galactic plane for $|b| < 2.5°$, will allow us to study the efficiency of this specific process compared to others such as the compression of pre-existing clumps or larger-scale mechanisms. Only the use of large-scale surveys with a wide wavelength coverage will allow us to obtain the significant statistics needed for such an estimate.

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