SEQUENTIAL FORMATION OF MASSIVE STARS OR CLUSTERS AT THE PERIPHERY OF H II REGIONS

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Several physical processes can trigger star formation at the periphery of classical H II regions. We present and discuss some of them.

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1 Introduction

In this presentation we will concentrate on star formation observed at the periphery of *classical H II regions.* We will review different processes, linked to H II regions, which can trigger star formation at their border. We will present the models, and then some observations to illustrate these models. In the discussion we would like to draw up the balance sheet between what we know or understand and what we still do not understand and cannot explain.

First we can turn to statistics. The presence of an H II region adjacent to a molecular cloud has two effects: i) it favours star formation; ii) it favours the formation of massive objects. Dobashi et al. (2001)[3] have investigated the luminosity of protostars forming in molecular clouds as a function of the parental cloud mass, in a sample of about five hundred molecular clouds taken from the literature; half of these clouds are associated with protostellar candidates selected from the IRAS point source catalogue. They have shown that *the protostars in clouds associated with H II regions are more luminous that those in clouds away from H II regions.* In addition, Dobashi et al. have shown the existence of well-defined upper and lower limits in the luminosity distribution; they propose a very simple model which assumes that the luminosity function of protostars is controlled by the mass of the parental cloud and by some external pressure imposed on the cloud surface. The lower and upper limits in the luminosity distribution correspond respectively to $P_{\text{external}} = 0$ and $P_{\text{external}}/k \sim 10^{5.5}$ K cm^{-3}; this last figure is a reasonable value for the pressure of the ionized gas in a classical H II region.

A complete review of the processes triggering star formation has been given by Elmegreen (1998) [7].

2 Model 1 - Radiation-driven implosions - Bright rims and cometary globules

Due to the high pressure of the ionized gas relatively to that of the surrounding neutral material, H II regions expand. Their expansion velocity, ~11 km s^{-1} just after the ionization of the gas and the formation of the initial Strömgren sphere, decreases with time (Dyson & Williams, 1997 [5]).

In this scenario the H II region expands in a medium containing *pre-existing dense molecular clumps.* The pressure exerted by the ionized gas on the surface of a clump can lead to its implosion, and to the formation of a 'cometary globule' surrounded by dense ionized gas forming a 'bright rim'.

This configuration has been simulated by Lefloch & Lazareff (1994) [11]. These authors follow the evolution of a 20 $M_\odot$ clump submitted to the ionizing flux of a O7V star situated at 5 pc from the clump. A shock front progresses in the clump, leading to the formation of a dense core, near the centre of the initial clump. The maximum compression is obtained after 0.2 Myr. This collapse phase is followed by a transient phase of re-expansion, and by a quasi-stationary cometary phase. During this last phase the cometary globule presents a dense head and a tail extending away from the ionization source; it evaporates slowly, as the dense ionized gas flows away from the globule; it moves away from the ionizing star with a velocity of a few km s^{-1}. It is entirely ionized and disappears after 2.7 Myr. The collapse phase is rapid, lasting about 10% of the lifetime of the globule. It is possibly during this phase that star formation occurs.

Numerous observations of bright rims have been performed recently, at various wavelengths, mainly to study the structure of the molecular globules and their stellar content. Most of these observations show very good agreement between the models and the observations with regard to the morphology of the globules and to their velocity field; cf. Sugitani et al. (1997) [17], De Vries et al. (2002) [2], Thompson et al. (2004) [19].

Signposts of star formation are often observed in the direction of cometary globules: IRAS sources with colours of protostellar objects, MSX point sources, near-IR reddened objects, CO outflows, Herbig-Haro objects, Hα emission stars, etc. We will illustrate this by two examples.

• Fig. 1 shows the Bright Rim Cloud (BRC) no. 5 in the catalogue of Sugitani et al. (1991) [16]. The MSX emission at 8.3 μm is shown as contours, superimposed on an image of the bright rim (DSS-2 red survey); a bright MSX point source is observed *in the direction of the head of the globule*, which is also an IRAS source with a luminosity of $\sim$ 1100 $L_\odot$. A near-IR cluster (2MASS survey) is detected in the same direction; it contains two bright K stars presenting a near-IR colour excess, probably indicative of an accretion disk (Lada & Adams, 1992) [10]. A CO outflow, with a dynamical age of 1.5 10^4 yr, has been detected in the direction of the head of the globule (Duvert et al. 1990 [4], Lefloch et al. 1997 [12]).

• BRC 44, also from the catalogue of Sugitani et al., presents a somewhat different configuration. Fig. 2 shows how it appears in the optical (DSS-2 red survey); the ionizing radiation comes from the south. CO observations (Ridge et al. 2003) [14] and 2-mm observations (Sugitani et al. 2000) [18] show the presence of a dense globule in the direction of the region of high absorption (Fig. 2). An IRAS point source of $\sim$ 700 $L_\odot$ lies in the direction of the globule. A CO outflow has possibly been detected in this direction (Sugitani et al. 1989) [15]. A cluster containing Hα emission stars lies at the periphery of the globule (Ogura et al. 2002) [13], in the direction of the ionized gas. The near-IR image of this region shows a small very red cluster (Fig. 2); it contains a very bright star (with a strong near-IR colour excess according to the 2MASS catalogue) which is probably a young object with an associated accretion disk. This

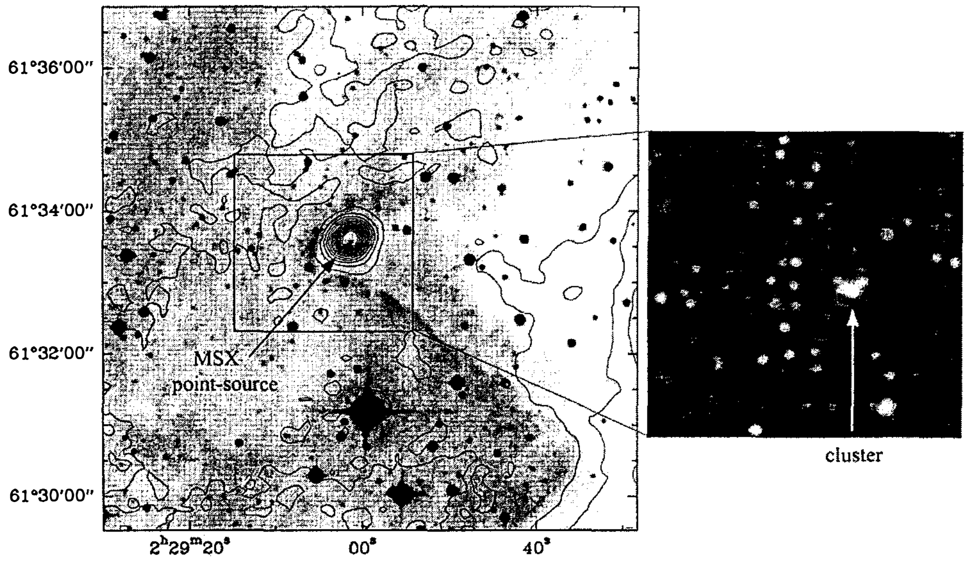

Figure 1: BRC 5. *Left:* The MSX emission at 8.3μm (contours) is superimposed on a DSS red frame (grey scale). *Right:* Colour composite *JHK* image (from 2MASS) of the head of the globule.

star lies at the border of the dense globule and definitively not inside. Only a faint but very red object lies in the direction of the globule.

Ogura et al. (2002) [13] present this region as a case of *small-scale sequential star formation.* If star formation occurs during the very short implosion phase, near the maximum contraction phase of the globule, small-scale sequential star formation is difficult to understand. The case of BRC 44 suggests that star formation occurs at the periphery of the globule more than in its centre, and with time moves away from the first-generation star(s) exciting the H II region. Ogura et al. present several other such cases.

3 Model 2 - The collect and collapse model

During the expansion of an H II region the ionization front (IF) is supersonic, and it is preceded by a shock front (SF) on the neutral side. Neutral material accumulates between the two fronts, forming a layer of dense shocked material. Instabilities can develop, on various time scales, within this compressed layer.

1. Dynamical instabilities can develop on a short time scale; a two-dimensional simulation of this process is presented by García-Segura & Franco (1996) [8]. According to these authors, the resulting structures are very similar to the bright rims and 'elephant trunks' observed at the periphery of H II regions. If confirmed, this process is interesting as it allows the formation of dense clumps in a formerly rather homogeneous medium.

2. Gravitational instabilities can develop on a long time scale, along the length of the layer. This process is interesting because it leads to the formation of *massive* fragments: because of the long time scale, the compressed layer becomes very massive, and it fragments into massive pieces. For example, according to Whitworth et al. (1994) [20], for an H II region evolving in a medium of density 1000 cm^{-3}, where the rms velocity dispersion is 0.5 km s^{-1},

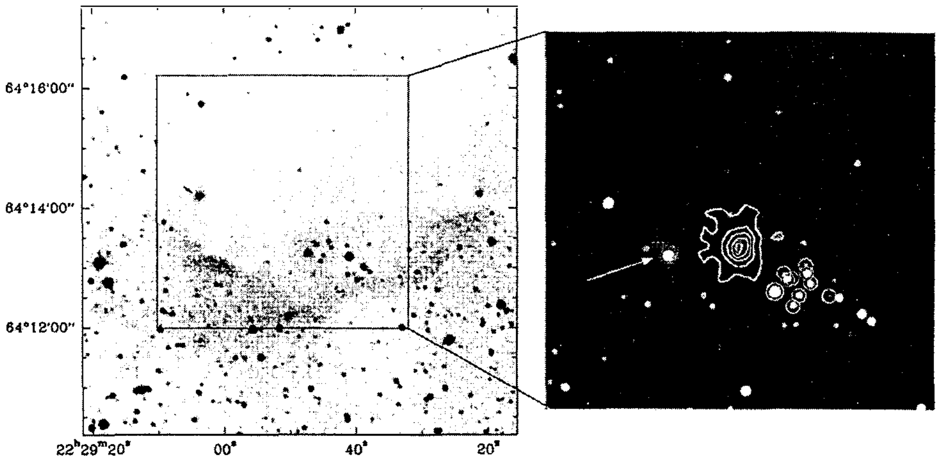

Figure 2: BRC 44. *Left:* DSS red frame (grey scale). *Right:* The 2-mm emission (contours) is superimposed on a colour composite JHK image (2MASS); the Hα emission stars are identified by circles; the arrow points to the K star with a strong near-IR colour excess.

> fragmentation into seven parts occurs after about 3 Myr, with masses of about 600 $M_{\odot}$. These fragments are very dense, and they fragment in turn, very quickly, leading to the formation of clusters. Because these second-generation stars conserve the velocity of the medium in which they form, they ought to be observable later on, in the direction of the layer.

This model has never been convincingly confirmed, mostly because the morphology of H II regions is generally complicated. To study the collect and collapse process, we have selected about twenty H II regions with a very simple morphology, allowing us to locate the ionization front, and separate the ionized and the surrounding neutral media. Each of these regions has a red cluster at its periphery (Deharveng et al., in preparation). Sh 104 is the prototype of such regions; it is spherically symmetric around a central exciting O6V star. A ring of molecular and dust emission (MSX emission at 8.3 μm, mainly due to PAHs) surrounds the ionized gas, showing the existence of a layer of dense molecular material surrounding the H II region. An MSX point source which is observed at the periphery of the H II region, in the direction of the ring, is also an IRAS source with a luminosity of $\sim$3 10^4 $L_{\odot}$; an ultra-compact (UC) H II region and a near-IR cluster are detected in the same direction. The mass of the molecular ring is $\sim$6000 $M_{\odot}$. This molecular ring contains four fragments regularly spaced along the ring. The brightest fragment, with a mass $\sim$670 $M_{\odot}$, contains several dense cores; the near-IR cluster, exciting the UC H II region, is observed in the direction of the brightest fragment. Details and illustrations can be found in Deharveng et al. (2003) [1]. The presence of *four fragments regularly spaced along the molecular ring* is a strong argument in favour of the collect and collapse model; it allows us to reject the spontaneous collapse or the implosion of a pre-existing molecular clump, the collision of the compressed layer with a pre-existing molecular clump, and the collapse of post-shock cores formed in a supersonic turbulent medium (Elmegreen et al. 1995) [6]. Also, the estimated star formation efficiency is high. The second-generation cluster contains at least a B1V star, exciting the ultra-compact H II region; assuming a standard IMF, the mass of the cluster is $\sim$330 $M_{\odot}$. The remaining parental fragment has a mass of 670 $M_{\odot}$, and thus a star formation efficiency of around 33%.

4 Discussion and conclusions

In this section I will try to summarize what we know about triggered star formation, and what is still uncertain.

Star formation is triggered by H II regions. I will illustrate this assertion by the case of the well-known H II region IC1848. Karr & Martin (2003) [9] have presented a multi-wavelength study of this region and have compared the distributions of the ionized gas (via radio continuum emission), the associated molecular material (via ^{13}CO emission), the associated dust (via the MSX emission at 8.3μm), and IRAS sources with colours corresponding to young stellar objects. Most of the IRAS sources lie at the periphery of the H II region. The number of IRAS sources per unit CO area is 4.8 times higher inside the zone of influence of the H II region than outside.

Young stars or clusters formed in clouds adjacent to H II regions are more luminous, and thus more massive, then those away from H II regions. For example in the Vela molecular ridge, Yamaguchi et al. (1999) [21] have shown that the mean IR luminosity of IRAS sources in clouds adjacent to H II regions is 780 $L_\odot$, whereas it is 63 $L_\odot$ for sources in clouds away from H II regions. The luminosity of the second-generation clusters formed by the collect and collapse process in the Sh 104, Sh 217, and RCW 79 regions is respectively 30000 $L_\odot$, 22700 $L_\odot$, and 55000 $L_\odot$ (Deharveng et al., in preparation). These clusters contain B stars exciting UC H II regions.

The radiation-driven implosion model is well-verified by numerous observations. But we do not know if the molecular clumps pre-exist, or if they are formed either by dynamical instabilities in the compressed layer surrounding the ionized gas or by supersonic turbulence. Also, we do not know where (in the core, or at its periphery) and when (during the maximum compression phase, or earlier) star formation occurs. Thus, at present, we do not understand the small-scale sequential star formation observed in the vicinity of bright rims.

The collect and collapse process (on the long time scale) works, at least in its basic trends, if not in all its details. It leads to the formation of relatively massive clusters with a high efficiency, of the order of 30%. But we do not yet know its relative importance compared with other star-formation processes.

An important future goal is to determine what fraction of star formation is triggered by massive stars and H II regions, and which process is dominant in the formation of massive objects.

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