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

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RESUMEN

El modelo de "colectar y colapsar" predice que los objetos masivos—estrellas o cúmulos—deben formarse en la capa neutra chocada alrededor de una región H II en expansión cuando esta capa se vuelve inestable gravitacionalmente y se fragmenta. Presentamos varios casos de regiones H II y sus cúmulos asociados que parecen ser ilustrativos de este proceso de formación estelar provocada.

ABSTRACT

The "collect and collapse" model predicts that massive objects—stars or clusters—should form in the shocked neutral layer surrounding an expanding H II region when this layer becomes gravitationally unstable and fragments. We present several cases of H II regions and their associated clusters that seem to be good illustrations of this process of triggered star formation.

Key Words: **ISM: H II REGIONS — STARS: FORMATION**

1. INTRODUCTION

The formation of massive stars is still an open question. It is probably linked to the formation of clusters. Indeed, massive stars are often observed at the centers of dense clusters. The physical conditions present there (high stellar and gas densities) should allow the formation of massive stars, either by coalescence of intermediate mass protostars (Bonnell 2001), or by accretion (Maeder & Behrend 2001).

Dobashi et al. (2001) have shown that *IRAS* sources with colors typical of protostars, in molecular clouds associated with H II regions, were more luminous than those in clouds without associated H II regions, indicating that the presence of a nearby H II region favors the formation of massive objects in the adjacent molecular cloud. Hence our search for massive stars or clusters in the vicinity of H II regions.

2. PHYSICAL MECHANISMS FOR MASSIVE-STAR FORMATION TRIGGERED BY THE EXPANSION OF AN H II REGION

The high pressure of the ionized gas causes an H II region to expand into the surrounding neutral medium, increasing in size as its expansion velocity decreases (Dyson & Williams 1980).

The expansion of an H II region may trigger star formation in many ways (see the review by Elmegreen 1998). Pre-existing molecular cores may implode when surrounded by high-pressure ionized gas; star formation may occur, and newly formed stars should be observed in the direction of the ionized gas. As an H II region expands, dense neutral material accumulates between the ionization front and the shock front which precedes it on the neutral side; this decelerating shocked layer may become unstable and may collapse on various timescales. This is the "collect and collapse" model (Elmegreen & Lada 1977; Whitworth et al. 1994; and other references in Elmegreen 1998). The stars formed in the short-timescale instabilities should not be massive, and should be observed in the direction of the neutral material, ahead of the swept-up layer. The objects formed in the long-timescale instabilities should be massive (stars or clusters), and are predicted to be observed in the direction of the parental layer.

3. WHERE TO SEARCH FOR YOUNG CLUSTERS

3.1. *The MSX Survey*

We have used the *Midcourse Space Experiment* (*MSX*) Survey (Egan et al. 1999) to search for young clusters lying at the periphery of H II regions. Band A, which covers the 6.8 to 10.8 μm range, provides high angular resolution ($\sim 20''$), and high sensitivity. It contains the 7.7 μm and 8.6 μm emission bands, often attributed to polycyclic aromatic hydrocarbons (PAHs). PAHs cannot survive in ionized regions. In the photodissociation region (PDR) they absorb strong UV radiation leaking from the H II region, are excited, and radiate in the PAH bands (see Deharveng et al. 2003). This is most probably the origin of the band-A emission forming the ring surrounding the Sh 104 H II region in Figure 1. Continuum emission due to small grains at high temperature may also contribute to the *MSX* band A emission.

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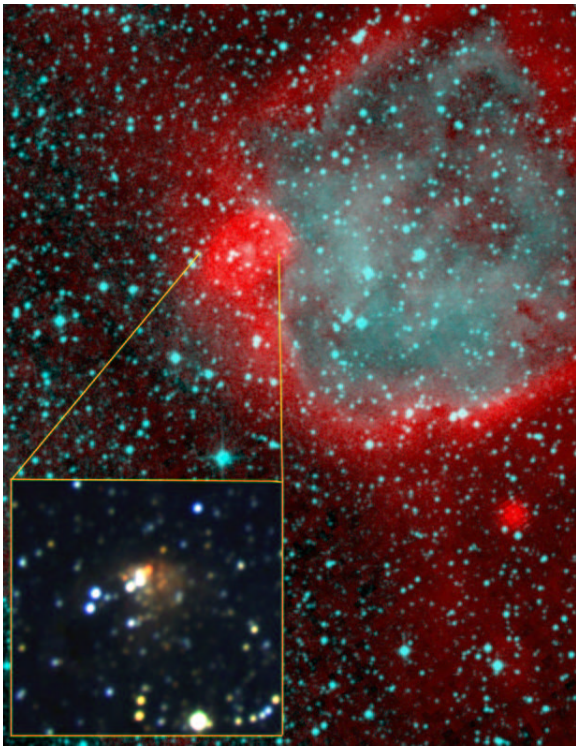

Fig. 1. Sh 104. Background: color composition of the DSS2-red frame (turquoise, showing the Hα emission of the ionized gas) and the *MSX* band-A frame (red, showing the emission of the PAHs in the PDR). Insert: JHK observations of the young cluster observed in the direction of the PDR (Porras et al. 2003; J is blue, H is green and K is red). NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

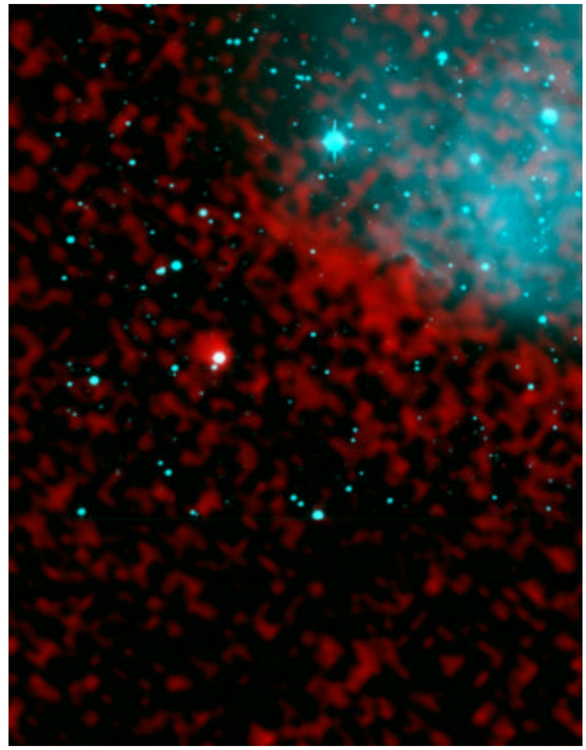

Fig. 2. Sh 217. Background: Color composition of an Hα frame (turquoise) and of the *MSX* band A frame (red). The Hα frame of the H II region has been obtained at the 120 cm telescope of the Observatoire de Haute Provence (France). Insert: JHK observations of the cluster observed at the periphery of Sh 217 (obtained at the 2.1 m telescope of the San Pedro Mártir Observatory, México). NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

3.2. *A Few Examples*

We have selected a number of H II regions based on the following criteria: (i) a simple morphology (circular ionized region surrounded by an annular PDR, as seen in Fig. 1); this specific configuration may help to disentangle the various protagonists of star formation along the line of sight. (ii) the presence, at the border of the ionized region, in the direction of the PDR, of bright IR sources that may represent second-generation massive stars or clusters.

Sh 104 is a low density H II region, at about 4 kpc, excited by a O6V star. It is almost spherical with, however, a shell structure, which may indicate that this region is in the "champagne" phase. Fig. 1 shows that the H II region is surrounded by an annular PDR containing dust. An *MSX* "point source" is observed in the direction of the ring; it is also an *IRAS* point source, with a luminosity of about $3\times10^4 L_\odot$. Near-IR observations of this region (2MASS Survey and Porras, Cruz-González, & Salas 2003) show a deeply embedded cluster in the direction of the *MSX* point source. This cluster ionizes an ultracompact (UC) H II region. The molecular material associated with Sh 104 has been observed with the IRAM 30 m telescope in 2002 September. Molecular material, observed in CO (2–1), completely surrounds the ionized gas. Four double condensations, observed in CS (3–2), are present at the border of the H II region; one of these is observed in the direction of the cluster and its associated UC H II region. It is most probably the remainder of the molecular core that formed the cluster.

Sh 217 and Sh 219 are two low density H II regions, apparently circular, surrounded by a half-ring seen in *MSX* band-A emission (Fig. 2, Deharveng et al. 2002). In each region an *MSX* point source is observed in the direction of the ring. This corresponds to a deeply embedded cluster (visual extinction $\geq$ 20 mag). These clusters ionize UC H II regions. The cluster associated with Sh 219 is elongated along the ionization front, and contains an Hα emission star. A wide and massive ring of low-density atomic hydrogen surrounds these H II regions. The distribution of the molecular material associated with these regions is not known.

Several similar H II regions (satisfying our selection criteria) have been found, and are under study in the near IR.

3.3. *Where to Search for Young Clusters*

Young clusters are observed at the periphery of H II regions. They are young, as they are still deeply embedded, and they are not dispersed. The probability that the exciting stars of the evolved H II regions formed in the associated clusters, and were subsquently ejected from these clusters, is non-zero; but the probability that, being ejected, they form an H II region with a radius just equal to the cluster-to-exciting-star distance is very low. Thus, the clusters observed at the periphery of these H II regions are most probably second-generation clusters.

These clusters contain massive stars, as they are associated with UC H II regions. If we assume a standard Initial Mass Function, and a star-formation efficiency of 30%, the estimated mass of the molecular cores forming these clusters should be $\geq 350\, M_\odot$.

All the clusters are observed in the direction of the PDR where they probably formed.

4. CONCLUSIONS

The "collect and collapse" model works, at least in its basic principle. The three clusters observed at the periphery of the H II regions Sh 104, Sh 217, and Sh 219 are most probably second-generation clusters formed in the decelerating, shocked, neutral layers surrounding the H II regions, as these layers became gravitationally unstable. They are still observed in the direction of the layers where they formed, which, according to the models (Elmegreen 1998), indicates that they result from instabilities on the long timescale; these instabilities are the only ones susceptible to form massive objects.

Many details are still obscure and need to be addressed. For example, the H II regions seem much too young (dynamical age) for the fragmentation to have taken place in the shocked layer; if these regions are better represented by a champagne model, they are much older, but then the collect and collapse model must be modified. The structure of the PDR of these regions needs to be clarified; what is the location, with respect to the dense molecular material necessary to form stars, of the low-H I component observed at the periphery of Sh 217 and Sh 219?

REFERENCES

Bonnell, I. A. 2001, in ASP Conf. Ser., 267, Hot Star Workshop III: The Earliest Stages of Massive Star Formation, ed. P. A. Crowther (San Francisco: ASP), 193

Deharveng, L., Zavagno, A., Salas, L., Porras, A., Caplan, J., & Cruz-González, I. 2003, A&A, submitted

Dobashi, K., et al. 2001, PASJ, 53, 85

Dyson, J. E., & Williams, D. A. 1980, The Physics of the Interstellar Medium (Manchester: Manchester Univ. Press)

Egan, M. P., et al. 1999, The Midcourse Space Experiment Point Source Catalog Version 1.2 Explanatory Guide, AFRL-VS-TR-1999-1522, Air Force Research Laboratory

Elmegreen, B. G. 1998, in ASP Conf. Ser., 148, Origins, eds. C. E. E. Woodward, J. M. Shull, & H. A. Tronson (San Francisco: ASP), 150

Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725

Maeder A., & Behrend R. 2001, in ASP Conf. Ser., 267, Hot Star Workshop III: The Earliest Stages of Massive Star Formation, ed. Paul A. Crowther (San Francisco: ASP), 179

Porras, A., Cruz-González, I., & Salas, L. 2003, ApJ, submitted

Whitworth, A. P., Bhattal, A. S., Chapman S. J., Disney, M. J., & Turner, J. A. 1994, MNRAS 268, 291

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