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Star formation associated with H II regions

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Abstract. Star formation associated with H II regions is briefly reviewed. Special emphasis is laid on our series of observational studies on bright-rimmed clouds (BRCs), in which we found a phenomenon called “small-scale sequential star formation.” In addition a new hypothesis is advocated on the two modes of star formation associated with H II regions, i.e., the cluster and dispersed modes. The former gives birth to a rich cluster and in the associated H II region BRCs are formed only at a later stage of its evolution in the peripheries. In the latter mode no clusters or only loose ones are formed, but BRCs can appear at earlier stages in inner part of the H II region. Presumably these modes depend on the initial density distribution of the natal molecular cloud.

Keywords : H II regions – ISM: globules – stars: formation – OB associations

1. Introduction – Bright-rimmed clouds

Bright-rimmed clouds (BRCs), or cometary globules, are small molecular clouds found in and around H II regions (H IIRs) and surrounded often on three sides by ionized gas. They are a sort of remnants of star formation activity associated with H IIRs, because they correspond to relatively dense clumps in the giant molecular cloud left unionized in the course of the expansion of the H IIR. But, at the same time, they are current sites of star formation. Theoretically, triggered star formation caused by the compression of the gas due to shock is expected to take place in such a configuration of the ionization front. This phenomenon is called radiation-driven implosion (RDI) and detailed model calculations were carried out by several authors (e.g., Bertoldi 1989; Lefloch and Lazareff 1994). Results of the molecular line and far-IR continuum observations of BRCs (Lefloch, Lazareff and Castets 1997; Thompson et al. 2004) are consistent with the RDI models.

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Actually, Herbig-Haro objects as signposts of recent star formation are sometimes found associated with BRCs. One of the best examples is HH 46/47 located in a periphery of the Gum Nebula (see, e.g., Stancke et al. 1999). IRAS point sources of low temperature, which are candidate young stellar objects (YSOs) are more often located near the head of BRCs. We compiled catalogues of altogether 90 BRCs associated with such IRAS point sources in Sigitani, Fukui and Ogura (1991) and Sugitani and Ogura (1994) using the Schmidt atlases for the northern and southern skies, respectively.

2. Small-scale sequential star formation hypothesis

For many of the BRCs in the above catalogues we carried out near-IR (*JHK*) imaging observations. The results for the northern sky were presented in Sugitani, Tamura and Ogura (1995). Briefly, we found that an elongated, small cluster or aggregate of YSOs are often associated with them. Interestingly, "redder" stars tend to be located more inside the BRC and closer to the IRAS source which corresponds to the reddest and lies at the innermost end of the aggregate, and "bluer" stars tend to lie more outside the cloud on the side of the O star(s) exciting the H II R. "Redder stars" by themselves may not straightforwardly mean younger stars but simply more deeply obscured objects. Still we consider that more deeply embedded stars are generally of younger age. Thus we speculate that in a BRC star formation due to RDI started closer to the exciting stars(s) and propagated successively outward in the H II R. This situation is schematically illustrated in Fig. 1 and is hypothesized as "small-scale sequential star formation (SSSSF)."

With the aim to strengthen the SSSSF hypothesis we made grism surveys of BRCs for Hα emission stars (Ogura, Sugitani and Pickles 2002). We used the University of Hawaii 2.2-m telescope combined with the grism spectrograph WFGS, and thanks to the superb seeing conditions ($\sim 0.7''$) atop Mauna Kea we reached the limiting magnitude of $R \sim 20$ and the limiting equivalent width (EW) of Hα detection of < 2 Å. The latter means that we are getting into the regime of weak-line T Tauri stars (TTSs). The targets were 24 and 4 BRCs with and without associated IRAS point sources, respectively, and altogether 460 Hα-emission stars and 12 Herbig-Haro objects have been detected in their vicinities. These objects are concentrated toward the head or just outside of BRCs on the side of the exciting star(s). Practically no follow-up observations have yet been done, but we believe that these Hα stars are mostly TTSs or Herbig Ae/Be stars. These results imply that RDI and SSSSF actually apply to BRCs. Also the large number of detected Hα-emission stars means that the star formation associated with BRCs is rather extensive, altogether roughly 50 stars per BRC, if we take into account the stars which formed previously but which already lost their Hα emission activity and those to form in the near future until the BRC is completely dispersed, and there are several BRCs in each H II R.

On star formation in giant molecular clouds the following scenario is often mentioned (e.g., Herbig 1962, Strom 1985): it starts with quiet, stochastic formation of low-mass

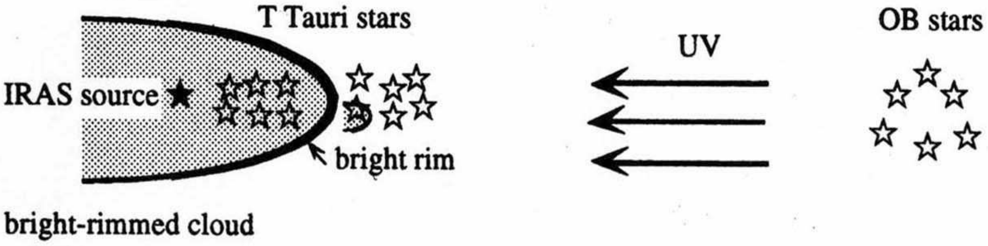

Figure 1. Schematic diagram of small-scale sequential star formation. A clump of remnant molecular cloud is surrounded by a curved ionization front (bright rim) and its head is compressed by the associated shock to give birth to stars (radiation-driven located). Then the bright rim recedes, leaving the young stars visible, and star formation again takes place at the new head of the BRC. This process repeats itself. As a result, we find an elongated aggregate of stars whose members are aligned according to an age sequence so that the oldest stars are localed closest to the exciting star(s) and the youngest, which actually is the IRAS source, lie at the other end deeply embedded in the BRC.

stars which lasts over a timescale of 10 Myr (we call it the "0-th stage star formation", but it is the most poorly established stage); then the full-dressed star formation takes place, giving birth not only to high-mass stars but also to a large number of low-mass stars (the "1st stage star formation"), among which OB stars brings about the dispersal of the cloud and the end of star formation. However in view of the above results of ours this last should be modified. In the course of the cloud dispersal star formation continues or even promoted by RDI in BRCs, which we call the "2nd-stage star formation," and it is rather extensive, as we saw above.

3. Importance of optical observations of low-mass stars in H II regions and OB associations

So far TTSs have been only poorly searched for in H IIRs and OB associations. It is simply due to observational difficulties. First, they are generally distant (∼1 kpc or more excepting the Orion region) compared to well-studied molecular clouds, such as those in Taurus, Ophiuchus, Chamaeleon etc., so TTSs there are too faint for previously conventional Schmidt surveys combined with objective prisms. So only brighter TTSs are known in OB associations or H IIRs (e.g., NGC 7000 etc., see Herbig and Bell 1988). In recent years, however, the advent of grism spectrographs combined with a CCD detector and mounted on a moderate-sized telescope have been drastically changing the situation, and now, as our above attempt shows, fainter TTSs in OB associations up to a few kiloparsecs can be reached within our scope. Also powerful are the recent, deep near-IR (*JHK*) observations, which have been revealing a large number of embedded "class II" sources (e.g., Ojha et al. 2004a, 2004b).

The second difficulty lies in the fact that OB associations are spatially much extended. This makes a big challenge to both grism surveys and *JHK* photometry. Our survey is restricted to the peripheries of BRCs and so spatially very limited even for H IIRs; and OB associations are wider. Surveys covering far wider sky areas are needed in order to elucidate the whole star-formation history and its extent in H IIRs and OB associations. At present the best means to overcome this difficulty is multi-object fiber spectroscopy with a large telescope. This technique was extensively used in Upper Scorpius OB Association (Preibisch et al. 2002 and references therein).

Optical observations of low-mass stars in H IIRs and OB associations have the following significances:

(1) The major techniques to search for pre-main sequence stars are Hα emission star surveys with panoramic detectors, near-IR photometry to detect IR excesses, and X-ray surveys. However all of them are incomplete in the sense of overlooking some of genuine young stars and/or of picking up irrelevant interlopers. Hα-emission surveys cannot look into deeply embedded regions; also it misses week-line TTSs of low EWs (see, however, the second paragraph of Sect. 2). Near-IR photometry completely fails to detect week-line TTSs. Products of X-ray surveys contain a large number of irrelevant objects, such as AGNs, and need to be followed up. Thus it is desired that these techniques be complemented each other.

(2) Compared to high-mass stars, low-mass stars are far easier to determine the ages. In particular, OB stars have no optically visible pre-main sequence stage, so only nuclear ages of the post-main sequence stage can be used, which are, however, difficult to determine for very young OB associations. Therefore we have to rely on low-mass stars in order to know the star formation history of high-mass star-forming regions.

(3) We can obtain better information on the kinematics of the region by observing numerous sharp absorption lines of low-mass stars, which high-mass stars lack.

(4) Young stars in H IIRs are exposed to strong UV radiation and stellar winds from OB stars. The evolution of their star/disk system in such violent environments is more typical than that in quiet conditions in T associations, because the major mode of star formation in the Galaxy is not in T associations but in OB associations. This is even more important in view of the fact that the solar system was born in such an environment (Hester et al. 2004).

4. Two modes of star formation associated with H II regions

We classify H IIRs into four categories according to association/non-association with a rich open cluster and with BRCs. (A) Those which contain a rich open cluster, sometimes optically visible and sometimes embedded and detectable only in IR, but which are not associated with any BRCs. Examples include the Orion Nebula (M42), NGC 2024, M17 etc. Presumably they are young H IIRs. (B) Those which harbour a rich cluster and have associated BRCs, examples being IC 1805, the Rosette Nebula (NGC 2244), the Lagoon Nebula (M8), M16, NGC 281 etc. In this case BRCs are found usually in their peripheries. Probably they are somewhat evolved H IIRs. (C) Those which are associated with BRCs but lack rich clusters inside them. Good examples include IC 1396, IC 1848, the H II region around λ Ori, NGC 2264, the Trifid Nebula (M20) etc. (D) Those which have neither a rich cluster nor practically any BRCs associated with them. Examples are S201, NGC 2175, IC 2177 (around Z CMa; only one BRC exists), and IC 5146 etc.; in addition most of small H IIRs belong to this type. Of course the above classification is more or less oversimplified and naturally there exist many H IIRs which fall between the four types. For example, one may claim that IC 1396 and NGC 2264 contain a cluster (in the former case, Tr 37), but the both are rather poor clusters. Probably a better example which lies between types B and C is the Rosette Nebula; the cluster NGC 2244 inside it is not very rich but relatively rich. Note that the morphology of H IIRs in the optical is sometimes affected by deep obscuration, especially in type A as mentioned above, other examples being IC 1795 and NGC 7538 (Ojha et al. 2004a and 2004b).

What are the factors that cause the above types of H IIRs. Undoubtedly evolution of H IIRs is of relevance. As mentioned earlier, BRCs correspond originally to relatively small clumps in the molecular cloud, which, as the H IIR expands, have been left unionized on account of their high density. Therefore type A seems to evolve to type B, and the predecessor of type C might be type D. Then, what makes the difference between types A and D?

In Figs. 2a1 - 2d3 we show the distribution of the associated cloud material for examples of the H IIR types, i.e., for type A: M42 (distance 460 pc), NGC 2024 (460 pc), and M17 (1300 pc) in Figs. 2a1-2a3; for types B: IC 1805 (1890 pc), NGC 2244 (1450 pc), and M8 (1330 pc) in Figs. 2b1-2b3; for type C: IC 1848 (2000 pc), NGC 2264 (670 pc), and IC 1396 (840 pc) in Figs. 2c1-2c3; and for type D: S201 (2000 pc), NGC 2175 (1630 pc), and IC 2177 (1120 pc) in Figs. 2d1-2d3, respectively. All of them are taken from the SFD 100μm map (Schlegel, Finkbeiner, and Davis 1998) on the NASA SkyView database (`http://skyview.gsfc.nasa.gov/`). The distances in the parentheses are adopted mainly from the WEBDA database at `http://obswww.unige.ch/webda` (Mermiliod 1995). From a comparison between the figures, in particular between Figs. 2a1-2a3 and 2d1-2d3 we see that the clouds associated with H IIRs of type A are more or less centrally condensed and those associated with the type B, C and D H IIRs are not. The fact that clouds associated with type D H IIRs are not centrally concentrated is noteworthy.

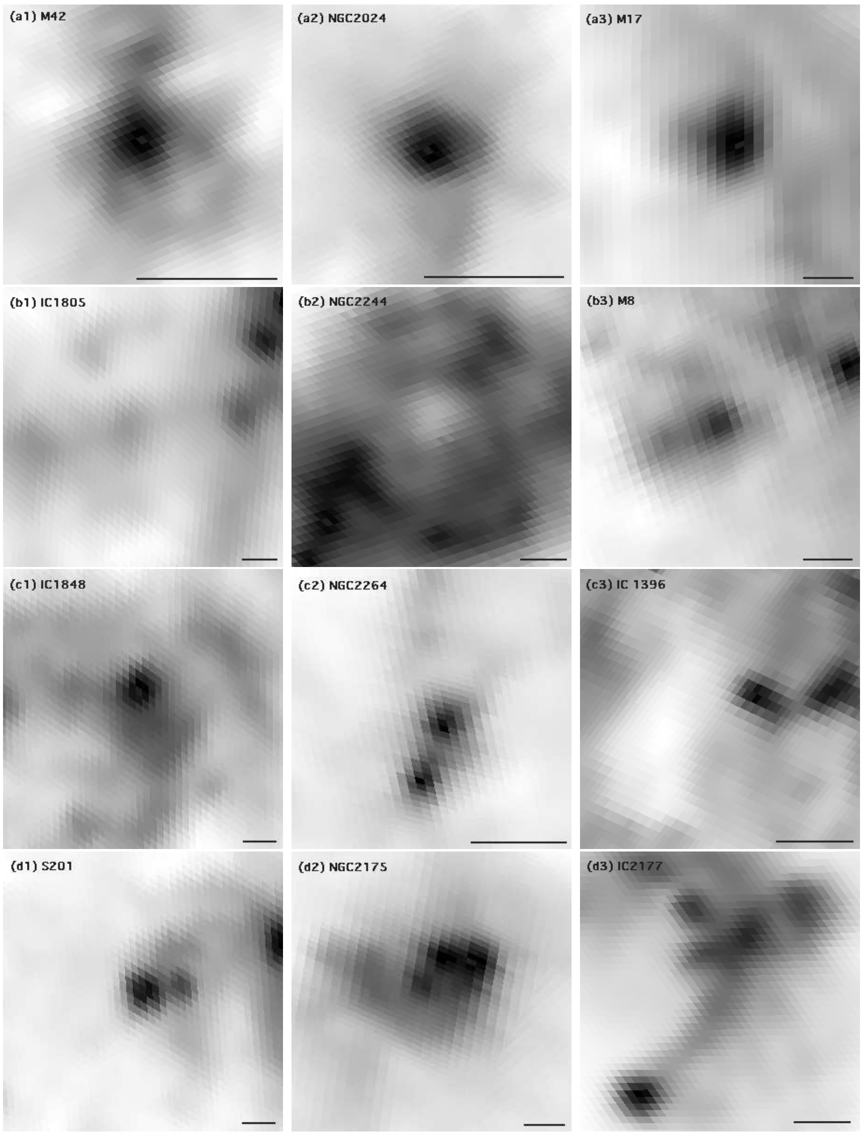

Figure 2. Distribution of the associated cloud material is shown for examples of the H II R types, i.e., type A (M42, NGC 2024, and M17) in Figs. 2a1-2a3, types B (IC 1805, NGC 2244, and M8) in Figs. 2b1-2b3, type C (IC 1848, NGC 2264, and IC 1396) in Fig.s 2c1-2c3, and type D (S201, NGC 2175, and IC 2177) in Figs. 2d1-2d3, respectively. All of them have been taken from the SFD 100μm map and are $90'$ by $90'$ wide with north up and east to the left. The bar at the bottom right in each figure corresponds to 10 parsec. The clouds associated with type A H IIRS are more or less centrally condensed, while those associated with the type B, C and D H IIRs generally are not. We suspect that H IIRs evolve from type A to B and from type D to C.

From the above considerations it seems that there are two modes of star formation associated with H IIRs and that they depend on the initial density distribution of the natal molecular cloud. One is the cluster mode which gives birth to a rich open cluster and the other is the dispersed mode which forms only a loose cluster or a less loose aggregate of stars. Presumably, the former takes place in centrally condensed, massive clouds, and BRSs develop only at a later stage of the evolution of the H IIR in its peripheral regions where density fluctuations exist. The latter arises in clumpy, dispersed clouds and BRCs can appear in relatively inner part of the H IIR and at earlier stages. Admittedly this hypothesis needs to be elaborated with more scrutiny.

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