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Triggered star formation associated with HII regions

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Abstract. There are two known mechanisms of triggered star formation associated with HII regions. One is the collect-and-collapse process of the shell accumulated around an expanding HII region, and the other is radiation-driven implosion (RDI) of bright-rimmed clouds (BRCs) originated from pre-existing cloud clumps. They are very briefly reviewed first. We then present the main results of our recent observations on the RDI star formation in BRCs. Finally, a third possible mechanism of triggering is suggested, which is attributed to the formation of elephant trunk-like structures due to hydrodynamical instability of ionization/shock fronts.

Keywords : stars: formation – ISM: HII regions – infrared: ISM – hydrodynamics

1. Introduction — Effects of massive stars on star formation

OB stars are so energetic that they can affect their surroundings in various ways. The agents are intense UV radiation, strong wind, and supernova explosion. Here we consider mainly the effects of UV radiation on star formation, which can be either constructive or destructive depending on the situation. As for the mechanisms with which it works constructively, two modes have so far been proposed: *collect-and-collapse* and *radiation-driven implosion* (RDI). The former is of larger size in space (∼10 pc) and of longer timescale (∼a few Myr), whereas the latter is of smaller size in space (∼1 pc) and of shorter timescale (∼0.5 Myr).

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2. Collect-and-collapse

Blaauw (1964) noticed that OB associations are often composed of some subgroups which are spatially aligned in an age sequence. Based on this fact, Elmegreen and Lada (1977) advocated the hypothesis of *Sequential Star Formation*. In this scenario, pressure-driven expansion of an HII region collects a dense shell between the ionization front (IF) and shock front (SF). In due time it becomes gravitationally unstable and collapses to form massive condensations, which give birth to OB stars. Hence the whole process is called collect-and-collpse and it can repeat itself, forming subgroups in an OB association. Since then, various analytic and numerical calculations were carried out under this scenario. Recent analytic calculations include those by Whitworth et al. (1994) and their results were basically confirmed by the SPH simulations by Dale, Bonnell and Whitworth (2007). Detailed numerical calculations with special attention on the physical structure of the swept-up shell were carried out by Hosokawa and Inutsuka (2005, 2006), which showed that the shell is 10-100 times denser than the ambient cloud with 0.02 - 0.2 pc in thickness and $\sim 10^4$ $M_\odot$ in mass, and that it becomes gravitationally unstable in $\sim$0.7 Myr.

This collect-and-collapse scenario is probably viable in relatively uniform molecular clouds. However, it has never been convincingly confirmed for many years. Recently, the Deharveng group (Deharveng et al. 2005, Pomares et al. 2009 and references therein) presented first persuasive examples. They paid attention to HII regions of simple morphology. In 17 such HII regions they found in the *MSX* A-band, a ring of dust emission (which means the presence of very dense gas in PDR), harboring *MSX* point sources (which imply embedded clusters or massive stars). Very interestingly, the ring-like clouds surrounding them are composed of regularly-spaced massive fragments. This point is important because regular spacing rules out the possibility that they are pre-existing clumps of the molecular cloud.

3. Radiation-driven implosion

Prominent dark structures found in HII regions are variously called "*elephant trunks*", "*cometary globules*", "*bright-rimmed clouds* (BRCs)", "*pillars*" and so forth. Typically they are $\sim$0.1 pc in size, 10^5-10^6 cm^{-3} in density and 0.3-100 $M_\odot$ in mass. As for their origin, Rayleigh-Taylor instability on the boundary of expanding HII regions was proposed first (e.g., Spitzer 1954), but Pottasch (1958) pointed out disagreements between the predictions of the theory and the morphologies of elephant trunks. In mid-1960s Axford (1964) investigated the stability of weak D-type IFs, explicitly taking into account the effect of diffuse UV radiation caused by recombinations to the ground state of hydrogen atoms. He claimed that weak D-type IFs, which correspond to the major part of the evolution of HII regions, are stable against the growth of length scales larger than 0.2 pc, so hydrodynamical instability could not be the origin of elephant trunks. Given the fact that molecular radio observations showed the clumpiness of molecular clouds, elephant trunks or BRCs have since usually been considered as remnant cloud clumps left over in expanding HII regions.

Detailed numerical calculations of the evolution of such clouds were carried out by Lefloch and Lazareff (1994). They showed that the evolution is divided into three phases; first a cloud undergoes a short *collapse phase* ($\sim 10^5$ yr) with the maximum compression, then bounces in the temporary *phase of re-expansions and re-compressions*, and finally settles into a long-lived *cometary phase* ($\sim 10^6$ yr). In recent years numerical simulations of the evolution of BRCs have been actively performed. Pavlakis et al. (2001) included the effect of diffuse UV radiation due to recombination. 3-D calculations with self-gravity implemented were made by Kessel-Deynet and Burkert (2003), by Miao et al. (2006, 2009), and by Gritschneder et al. (2009). The results are basically similar to those of Lafloch and Lazareff (1994), but the details differ. Very recently even magnetic field has been included in 3-D simulations by Henney et al. (2009).

Star formation in BRCs has long been suspected (e.g., Wootten et al. 1983). Clear evidence for it was provided by Sugitani and coworkers. Sugitani, Fukui and Ogura (1991) and Sugitani and Ogura (1994) compiled catalogs (the so-called *SFO Catalog*) of 44 BRCs in the northern sky and 45 BRCs in the southern sky, each associated with an IRAS point source of low dust temperature, respectively. Then, near-IR imaging observations by Sugitani, Tamura and Ogura (1995) indicated that BRCs are often associated with a small cluster of young stars showing not only an asymmetric spatial distribution with respect to the cloud but also a possible age gradient. Associated Hα emission stars show a very similar distribution (Ogura, Sugitani and Pickles 2002). Therefore Sugitani et al. (1995) advocated the hypothesis of "*small-scale sequential star formation*" (S^4F) that in a BRC star formation due to RDI starts closer to the exciting stars(s) and propagates successively outward in the HII region, as depicted in Fig. 1 of Ogura (2006).

Detailed observations of physical properties of BRCs in the SFO Catalog were made by a British group (Morgan et al. 2008, Urquhart, Morgan and Thompson 2009 and references therein) by means of sub-millimeter observations and radio continuum and CO/^{13}CO/C^{18}O line observations. They concluded that RDI is in progress in many (but not all) of SFO BRCs and that massive stars are being formed there, based on the high luminosity of the embedded sources (Urquhart et al. 2009). However, Valdettaro et al. (2008 and references therein) made extensive H_2O maser surveys of BRCs and claimed that the resulting low detection rate does not support the formation of massive stars.

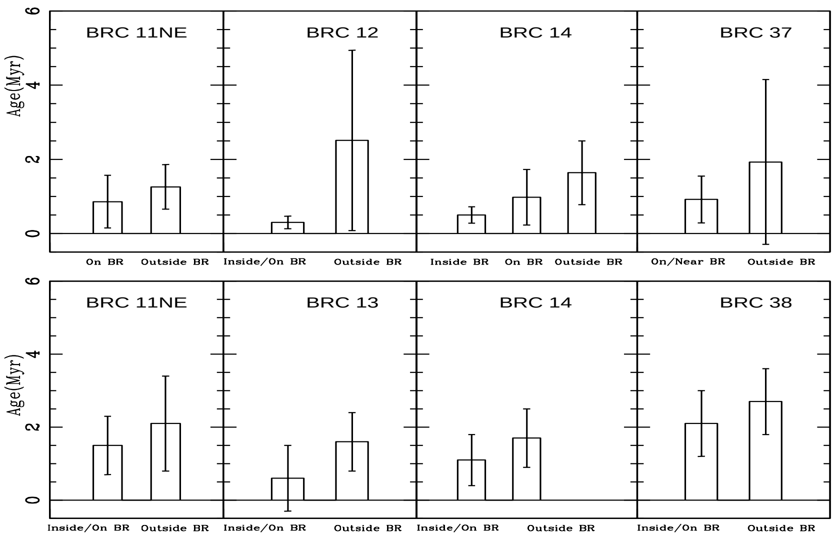

Figure 1. Histograms for the average ages of the groups of the stars according to their locations with respect to the bright rim of each BRC. Standard deviations are also shown. The upper panel is from the results in Paper I and the lower panel from Paper II.

4. Our recent studies to testify age sequence in BRC aggregates

As for the S^4F hypothesis, deep NIR photometry of BRC 14 by Matsuyanagi et al. (2006) revealed that three indicators of star formation show a clear trend from outside to inside of the rim, indicating that the YSOs located near the rim are younger than those located away from the rim. This result further strengthens the S^4F hypothesis, but unfortunately it is not quantitative. The best way to quantitatively testify the hypothesis is to derive the ages of the stars associated with BRCs and to compare them among different regions with respect to the bright rim. In the last few years we have been working in this direction.

Ogura et al. (2007, hereafter referred to as Paper I) and Chauhan et al. (2009, Paper II) undertook BVI_c photometry of BRC aggregates in four and five BRCs, respectively, using the Himalayan Chandra Telescope. JHK_s data collected from the 2MASS Catalog have also been used. The aggregate member stars have been selected from the Hα emission stars of Ogura et al (2002); stars with IR-excesses, which were picked up in the $(J-H)/(H-K_s)$ color-color diagrams (2CD), have been added in Paper II. For these stars interstellar reddening and extinction have been estimated from the same 2CD. Thus we have constructed reddening-corrected $V_0/(V-I_c)_0$ color-magnitude diagrams

(CMDs) for the above BRC aggregates. We estimated the ages of the stars individually from these CMDs and derived the average ages and average amounts of extinction for the location groups of the stars. The results are shown as histograms with standard deviations in Fig. 1. In these histograms we *always* find the trend that the stars inside or on the bright rim have younger ages than those outside it, which is exactly what is expected from the S^4F hypothesis. (In Paper II we observed BRC 27 as well, but it does not show this trend. We now consider that it is not a genine BRC because its rim is not actually bright.) So we would think the age sequence in BRC aggregates is now quantitatively established. However we also notice that the above results show large scatter, which makes them statistically weak. We suspect that the main reasons are the random motions of the stars and photometric errors; see the discussion in Paper I.

In Paper II we noticed the presence of a large number of scattered IR-excess stars inside HII regions (see Figures A2 to A5 of Paper II). No doubt some of these stars must be part of the central cluster, which formed as the stars of the first generation. As the second possibility we suspect that some of the others are the results of a series of RDI. If a BRC is relatively large, it may undergo multiple RDI events (Kessel-Deynet and Burkert 2003), each time receding outward and leaving a group of stars. Groups of IR-excess stars which are found aligned roughly linearly between the BRCs and the central O star(s) suggest this possibility. However we further suspest another possibility, which is discussed in the next section.

5. Dynamical instability of ionization/shock fronts – A third possible mechanism of triggering

Are BRC-like structures formed only by pre-existing clouds in expanding HII regions? Guiliani (1979) examined the stability of the IFs/SFs of HII regions and showed that there is a new instability which grows rapidly in an oscillatory manner (overstability). Vishniac (1983) generalized this instability to SN/wind bubble shells, and it is now called "*thin shell instability*" or "*Vishniac instability*". Its mechanism is simple, as shown, in Fig. 1 of Garcia-Segura and Franco (1996).

Sysoev (1997) reexamined the stability of D-type IFs analytically and showed that, contrary to the conclusion by Axford (1964), they are NOT stable even with the effect of recombination. This new result was confirmed by the numerical simulations of Williams (2002). Thus BRCs or elephant-trunk structures seem to be formed also via hydrodynamical instability without pre-existing molecular clumps. This was clearly shown in the numerical simulations (2-dimensional) of the evolution of HII regions by Garcia-Segura and Franco (1996); such structures appear in all of their models as HII regions expand.

Whalen and Norman (2008) obtained similar results in their 3-D simulations. There are other possibilities to form BRCs or elephant-trunks, such as shadowing instability (Williams 1999). Mellema et al. (2006) showed that filamentary density structures of the underlying medium, resulting from turbulence, produce HII regions of highly irregular shapes.

In the *Spitzer* images of IC 1848 shown in Koenig et al. (2008), in particular Figs 2 and 4, we see a wealth of intricate structures (including known BRCs) on its boundaries. We suspect that many of them may have been caused by the above effects, in particular, by hydrodynamical instability of the IFs, and may possibly give birth to stars of the next generation.

References

Axford W.I., 1964, ApJ, 140, 112
Blaauw A.A., 1964, Ann. Rev. Astron. Astropys., 2, 213
Chauhan N., Pandey A.K., Ogura K., et al., 2009, MNRAS, 396, 964 (Paper II)
Dale J.E., Bonnell I.A., & Whitworth A.P., 2007, MNRAS, 375, 1291
Deharveng L., Zavagno A., & Caplan J., 2005, A&A, 433, 565
Elmegreen B.G, & Lada C.J., 1977, ApJ, 214, 725
Garcia-Segura G., & Franco J., 1996, ApJ, 469, 171
Giuliani J.L., 1979, ApJ, 233, 280
Gritschneder M., Naab T., Burkert A., et al., 2009, MNRAS, 393, 21
Henney W.J., Arthur S.J., De Colle F., & Mellema G., 2009, MNRAS, 398, 157
Hosokawa T., & Inutsuka S., 2005, ApJ, 623, 917
Hosokawa T., & Inutsuka S., 2006, ApJ, 646, 240
Kessel-Deynet O., & Burkert A., 2003, MNRAS, 338, 545
Koenig X.P., Allen L.E., Gutermuth R.A., et al., 2008, ApJ, 688, 1142
Lefloch B., & Lazareff B., 1994, A&A, 289, 559
Matsuyanagi I., Itoh Y., Sugitani K., et al., 2006, PASJ, 58, L29
Mellema G., Arthur S.J., Henney W.J., et al., 2006, ApJ, 647, 397
Miao J., White G.J., Nelson R., et al., 2006, MNRAS, 369, 143
Miao J., White G.J., Thompson M.A., & Nelson R.P., 2009, ApJ, 692, 382
Morgan L.K., Thompson M.A., Urquhart J.S., & White G.J., 2008, A&A, 477, 557
Ogura K., 2006, BASI, 34, 111
Ogura K., Chauhan N., Pandey A.K., et al., 2007, PASJ, 59, 199 (Paper I)
Ogura K., Sugitani K., & Pickles A., 2002, AJ, 123, 2597
Pavlakis K.G., Williams R.J.R., Dyson J.E., et al., 2001, A&A, 369, 263
Pomares M., Zavagno A., Deharveng L., et al., 2009, A&A, 494, 987
Pottasch S., 1958, Bul. Astron. Inst. Netherlands, 14, 29
Spitzer L., 1954, ApJ, 120, 1
Sugitani K., Fukui Y., & Ogura K., 1991, ApJS, 77, 59
Sugitani K., & Ogura K., 1994, ApJS, 92, 163
Sugitani K., Tamura M., & Ogura K., 1995, ApJ, 455, L39
Sysoev N.E., 1997, Astronomy Letters, 23, 409
Urquhart J.S., Morgan L.K., & Thompson M.A., 2009, A&A, 497, 789
Valdettaro R., Migenes V., Trinidad M.A., et al., 2008, ApJ, 675, 1352

Vishniac E.T., 1983, ApJ, 274, 152
Whalen D.J., & Norman M.L., 2008, ApJ, 672, 287
Whitworth A.P., Bhattal A.S., Chapman S.J., et al., 1994, MNRAS, 268, 291
Williams R.J.R., 1999, MNRAS, 310, 789
Williams R.J.R., 2002, MNRAS, 331, 693
Wootten A., Sargent A., Knap G., & Huggins P.J., 1983, ApJ, 269, 147