Triggered Star Formation in a Turbulent ISM
Proceedings IAU Symposium No. 237, 2006
B. G. Elmegreen & J. Palouš, eds.

doi:10.1017/S1743921307001603

Triggered star formation in OB associations

W. P. Chen[1,2], H. T. Lee[1] and K. Sanchawala[1]

[1]Institute of Astronomy, National Central University, Chung-Li 32054, Taiwan
email: wchen@astro.ncu.edu.tw, eridan@astro.ncu.edu.tw, kaushar@outflows.astro.ncu.edu.tw

[2]Department of Physics, National Central University, Chung-Li 32054, Taiwan

Abstract. We present causal and positional evidence of triggered star formation in bright-rimmed clouds in OB associations, e.g., Ori OB1, and Lac OB1, by photoionization. The triggering process is seen also on a much larger scale in the Orion-Monoceros Complex by the Orion-Eridanus Superbubble. We also show how the positioning of young stellar groups surrounding the H II region associated with Trumpler 16 in Carina Nebula supports the triggering process of star formation by the collect-and-collapse scenario.

Keywords. stars: formation, stars: pre-main sequence, H II regions, ISM: clouds, ISM: bubbles, open clusters and associations: general

1. Introduction

A massive star has a profound influence on nearby molecular clouds. On the one hand, the stellar radiation and energetic wind could evaporate the clouds and henceforth terminate the star-forming processes. On the other hand, the massive star may provide "just the touch" to prompt the collapse of a molecular cloud which otherwise may not contract and fragment spontaneously. Except perhaps in an environment such as the nucleus of a starburst galaxy, for which triggering predominates the star formation process, triggering in most cases likely plays a constructive albeit auxiliary role. Other than providing additional push for cloud collapse, triggered star formation is self-sustaining (in time) and self-propagating (in space) in comparison to spontaneous cloud collapse.

The extent to which a massive star influences the starbirth in a cloud depends on the amount and proximity of the cloud material, and the positional configuration between the massive star and the cloud. If the massive star is born deep inside a cloud, which is often the case for a giant molecular cloud, the ionization fronts from the H II region created by the massive star push the cloud from within, forming a cavity. The gas and dust hence accumulate to a layer until the critical density is reached for gravitational collapse to form the next generation of stars. This is the so-called "collect-and-collapse" mechanism first proposed by Elmegreen & Lada (1977), and recently demonstrated observationally by Deharveng, Zavagno & Caplan (2005) and Zavagno *et al.* (2006). Any massive stars thus formed may subsequently break out their own cavities. Once a cavity forms, ionization now takes place on the surface of a remnant cloud. Alternatively, the massive star and neighboring clouds could initially be already oriented in this way. The UV photons from the massive star hence ionize the surface layer of the cloud, which illuminates as a bright rim seen prominently in an H-alpha image. The ionization fronts embracing the surface of the cloud then result in a shock compressing into the cloud to cause the dense clumps to collapse. This so-called "radiation-driven implosion" (RDI) process has been proposed to account for triggered star formation in bright-rimmed clouds near H II regions (Bertoldi 1989, Bertoldi & McKee 1990, Hester & Desch 2005). A massive star at the end of its life, with its Wolf-Rayet winds and supernova explosion, may create a superbubble which can

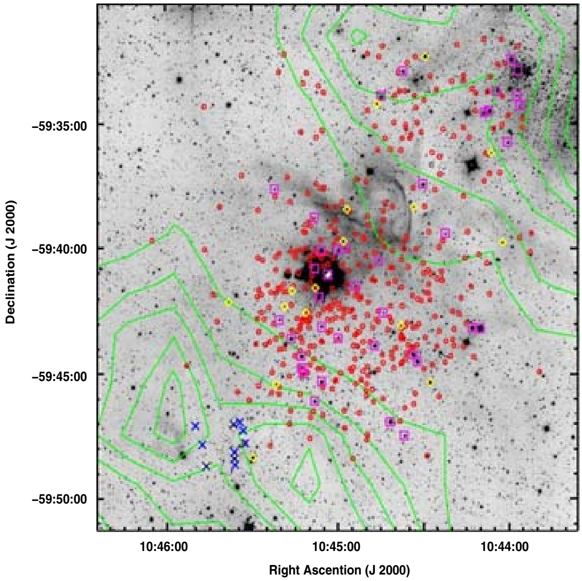

Figure 1. The *Chandra* sources overlaid on the mosaic K_s band image (Sanchawala *et al.* 2006) taken by the IRSF, centered on η Carinae, with the contours showing the $^{12}CO(1-0)$ emission (Brooks *et al.* 1998). Known OB stars are marked as boxes and the candidate OB stars are marked as diamonds. The stars of the embedded X-ray group to the south-east of Trumpler 16 are marked as crosses, whereas all other *Chandra* sources are marked as circles.

have an impact on even larger scales, tens or perhaps hundreds of parsecs away. Here we report on observations to illustrate triggered star formation by the collect-collapse-clear process and by the RDI mechanism in some OB associations.

2. Triggered star formation in Carina Nebula

The Carina Nebula is known to contain the largest number of early-type stars in the Milky Way, with a total of 64 O-type stars (Feinstein 1995). Among the dozen known star clusters in the region, Trumpler 14 and Trumpler 16 are centrally located and are the youngest and the most populous. These two clusters host 6 exceedingly rare main-sequence O3 stars. In particular Trumpler 16 contains a Wolf-Rayet star, HD 93162, and the famous luminous blue variable, η Carinae, which is arguably the most massive star in our Galaxy (Massey & Johnson 1993). The Carina Nebula therefore serves as a unique laboratory to study not only the massive star formation process, but also the interplay among massive stars, interstellar media and low-mass star formation.

Sanchawala *et al.* (2006) studied the X-ray sources detected by *Chandra* in the Carina Nebula (Fig. 1). Of the 454 X-ray sources, 38 coincide with known OB stars. Additionally, 16 anonymous stars have been found to have X-ray and near-infrared properties similar to those of the known OB stars. These candidate OB stars likely escaped earlier optical studies because of their excessive dust extinction. Close to 200 X-ray sources are candidate classical T Tauri stars (CTTSs), judged on the basis of their infrared colors. This sample represents the most comprehensive census of the young stellar population in the Carina Nebula so far and is useful for the study of the star-formation history in this turbulent environment.

In Fig. 1, in addition to Trumpler 16 near the center and Trumpler 14 to the north-west, there is an embedded group of 10 young stars to the south-east of Trumpler 16,

https://doi.org/10.1017/S1743921307001603 Published online by Cambridge University Press

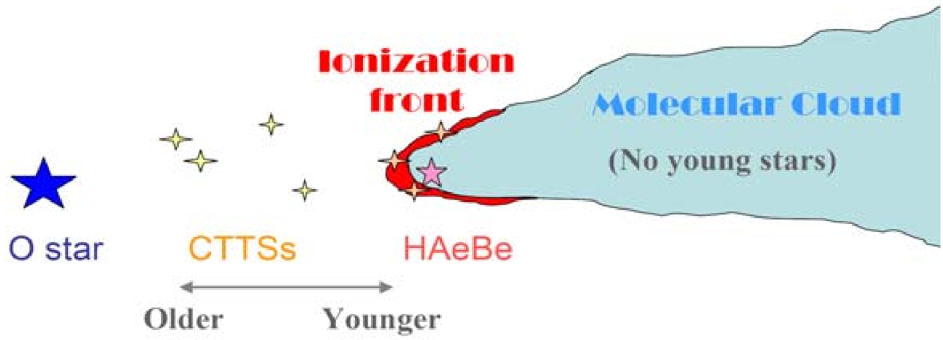

Figure 2. An illustration of a massive star to trigger star formation in a nearby molecular cloud.

'sandwiched' between two cloud peaks (Sanchawala *et al.* 2006). One sees immediately the general paucity of massive stars with respect to molecular clouds; namely Trumpler 16 itself has cast out a cavity and lies between the north-west and south-east cloud complexes, and so has Trumpler 14 to a less extent. The newly identified group suffers a large amount of reddening and also is situated between cloud peaks, apparently in the initial stage to expel the gas. There seems a general tendency for the X-ray sources (i.e., young stars) to be either intervening between clouds or located near the cloud surfaces facing Trumpler 16. The morphology of young stellar groups and molecular clouds peripheral to an H II region (i.e., Trumpler 16 here) fits closely the description of the collect-and-collapse mechanism for massive star formation.

3. Triggered star formation in Orion OB1, near λ Ori, and Lac OB1

An RDI triggering process would leave several imprints that can be diagnosed observationally (Fig. 2): (1) The remnant cloud is extended toward, or pointing to, the massive stars. (2) The young stellar groupings are roughly lined up between the remnant clouds and the luminous star, (3) Stars closer to the cloud, formed later in the sequence, are younger in age, with the youngest distributed at the interacting region, i.e., along the bright rim of a cloud, and (4) No young stars exist far inside the cloud, i.e., leading the ionization front. In particular, the temporal and positional signposts, (3) and (4), are in distinct contrast to the case of spontaneous star formation by a global cloud collapse, which would lead to starbirth spreading throughout the cloud.

Lee *et al.* (2005) and Lee & Chen (2006a) developed an empirical set of criteria, based on the Two Micron All Sky Survey (2MASS) colors, to select CTTSs and Herbig Ae/Be (HAeBe) stars in star-forming regions. The selection criteria prove very effective as follow-up spectroscopy showed that most candidates associated with nebulosity were indeed young stars, but otherwise were carbon stars or M giants. With the sensitivity of 2MASS, young stars within ~ 1 kpc can be readily recognized. In Ori OB1, λ Ori, and Lac OB1 there is compelling evidence of RDI triggering to form low- and intermediate-mass stars. Fig. 3 shows an example near λ Ori. Analysis of 2MASS colors shows the young stars to be progressively younger toward the clouds, with the youngest near the cloud rim. Furthermore, there is a tendency for HAeBe stars to reside deeper into the cloud, indicating that more massive stars, when prompted to form, appear to favor denser environments where photoevaporation effect is reduced. On the other hand, when a dense core near the ionization layer (i.e., current cloud surface) collapses, the accretion process

https://doi.org/10.1017/S1743921307001603 Published online by Cambridge University Press

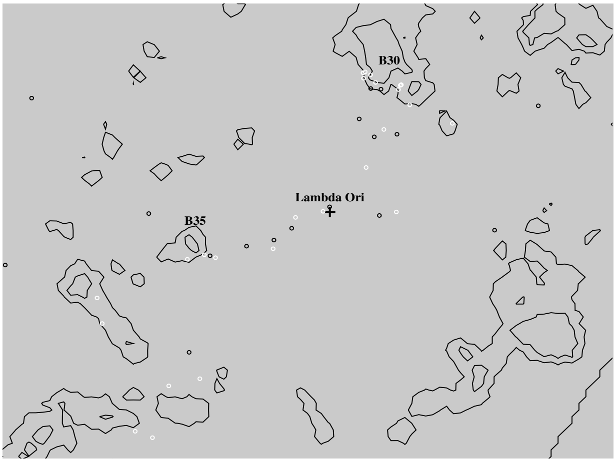

Figure 3. The CTTSs appear to line up between λ Ori and remnant clouds, with the clouds roughly pointing to λ Ori (Lee *et al.* 2005).

has to compete with the mass loss arising from photoevaporation, leading to formation of a less massive star or even substellar objects (Whitworth & Zinnecker 2004). Eventually the remnant cloud would be dispersed completely, and stars of different masses remain in the same volume. On a larger scale, the Wolf-Rayet winds and supernova explosion of a massive star would create a superbubble ramping on one molecular cloud to another (Lee & Chen 2006b). A sequence of such events ("relay star formation") could spread the star formation out to tens or even hundreds of parsec away. Note that the CTTS sample traces only recent star formation, and the bright-rimmed clouds present convenient snapshots to show how triggering leads to formation of low- and intermediate-mass stars once an O star is formed. These processes do not preclude stars formed in earlier epochs, with whatever mechanisms and masses, which already exist in a region.

Acknowledgements

We acknowledge the grant NSC94-2112-M-008-017 from the National Science Council of Taiwan to support this research.

References

Bertoldi, F. 1989, *ApJ*, 346, 735
Bertoldi, F. & McKee, C. F. 1990, *ApJ*, 354, 529
Brooks, K., Whiteoak, J. B. & Storey, J. W. V. 1998, *PASA*, 15, 202
Deharveng, L., Zavagno, A. & Caplan, J. 2005, *A & A*, 433, 565
Elmegreen, B. G. & Lada, C. J. 1977, *ApJ*, 214, 725
Feinstein, A. 1995, *Rev. Mexicana AyA*, 2, 57
Hester, J. J. & Desch, S. J. 2005, in: A. N. Krot *et al.* (eds.), *Chondrites and the Protoplanetary Disk* (ASP-CS) 341, 107
Lee, H.-T., Chen, W. P., Zhang, Z. W. & Hu, J. Y. 2005, *ApJ*, 624, 808
Lee, H. T. & Chen, W. P. 2006, *ApJ*, in press, astro-ph/0509315
Lee, H. T. & Chen, W. P. 2006, *AJ*, in press, astro-ph/0608216
Massey, P. & Johnson, J. 1993, *AJ*, 105, 980
Sanchawala, K., *et al.* 2006, *ApJ*, in press, astro-ph/0603043
Whitworth, A. P. & Zinnecker, H. 2004, *A & A*, 427, 299
Zavagno, A., Deharveng, L., Comerón, F., Brand, J., Massi, F., Caplan, J. & Russeil, D. 2006 *A & A*, 446, 171

Discussion

Zinnecker: You suggested radiative driven implosion works over tens of parsecs, but have you really shown this? By implication, have you really proven that ionisation fronts can sweep across whole molecular clouds and trigger star formation on tens of parsecs?

Chen: Triggering by a superbubble from stellar winds or a supernova explosion can have a longer range influence, over tens of parsecs, as we witness in the Orion OB1 association. The RDI works only on nearby clouds, but triggering can be self-propagating, so a sequence of such processes can still go further than just a few parsecs.

Toth: What is the typical mass of the bright rimmed clouds? Do you see any relation between cloud mass and star forming activity?

Chen: Measurements of some BRCs suggest $\sim 20-30$ $M_{\odot}$. But this is not really relevant because star formation takes place only near the interacting layer (i.e., the bright rim) of a cloud.

Deharveng: Sequential star formation near bright rims at the border of HII regions is also observed at small scales (see for example the observations by the group of Sugitani, which show Hα emission line stars in front of the bright rim – in the direction of the ionised region – then near IR objects near the BR's surface, and then mid-IR sources more deeply embedded inside the BR).

Chen: Indeed these results have been reported earlier. The use of the 2MASS enables us to study the triggering process on larger distance scales. There has been ambiguity of the configuration you raised. For example, photoevaporation of cloud material and circumstellar disks — instead of triggering — would result in a "cleaned" population toward the massive star, and a "being cleaned" population near a BRC's surface, just as observed. Our studies provide some age discrimination of star groups away or near a BRC, in terms of IR colors and presence of forbidden lines in a star's spectrum. Although this is still ambiguous because photoevaporation of the circumstellar disk would again produce the same outcome, we also found a genuine lack of NIR YSOs inside a BRC (rather than due to dust extinction), which cannot be circumvented in a spontaneous scenario.