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Star formation influenced by OB stars

Wen Ping Chen*
Graduate Institute of Astronomy, National Central University, Jhongli 32054, Taiwan

Abstract. Given proper conditions, a massive star can play a constructive role in producing next-generation stars, thereby sustaining the star formation activity in a giant molecular cloud. We outline here a few examples where such triggered starbirth takes place in the peripherals, and in the remnants, of a molecular cloud. A supernova shock would have an even greater influence, inducing star formation out to hundreds of parsecs.

Keywords : stars: formation, stars: pre-main-sequence, H II regions, ISM: clouds, ISM: bubbles

1. Triggered star formation by massive stars

The stellar radiation and powerful wind from a massive star are devastating to its nearby molecular clouds so as to terminate any subsequent star formation. Working at a distance, however, the expanding bubble created by a massive star inside a molecular cloud, given proper conditions, may sweep to compress the surrounding cloud material. When the collected gas and dust reaches the critical density and become gravitationally unstable, the cloud collapses to form next-generation stars. This ionization induced "collect-and-collapse" mechanism (Fig. 1; *top*) was first proposed by Elmegreen & Lada (1977), and later demonstrated observationally by Deharveng et al. (2005) and by Zavagno et al. (2006). Massive stars thus formed, may subsequently break out their own cavities. The cloud soon gets dispersed, and any remnant clouds are now exposed to the strong stellar ultraviolet radiation. At this stage, photoionization takes place on a side, i.e., at the surface of a remnant cloud, illuminated as a bright-rimmed cloud. The ionization leads to a shock propagating inwards

*e-mail: wchen@astro.ncu.edu.tw

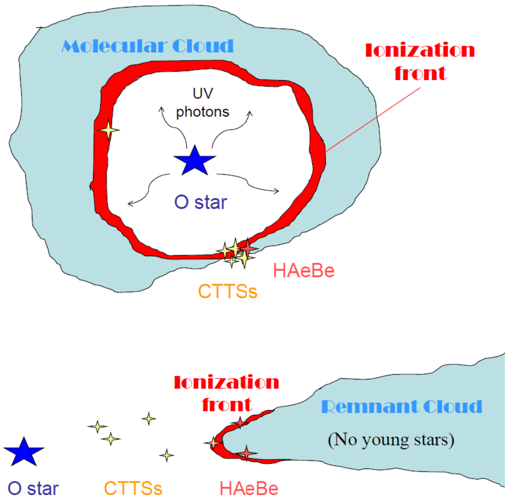

Figure 1. An illustration of a massive star to trigger star formation in a molecular cloud (*top*) from within a giant molecular cloud via the collect-and-collapse process, and (*bottom*) from a side of a remnant cloud via the radiation-driven implosion.

to compress a layer of dense clumps to collapse. This "radiation-driven implosion" mechanism (Fig. 1; *bottom*) has been proposed to account for the ongoing star formation seen in bright-rimmed clouds near H II regions (Sugitani et al. 1991; Bertoldi 1989; Hester & Desch 2005; Gandolfi et al. 2008). A massive star at the end of its life, with its Wolf-Rayet winds and supernova explosion, may create a superbubble which can have an impact on even larger scales, tens or perhaps hundreds of parsecs away (Lee & Chen 2009).

These kinds of triggering processes provide a perturbation to initiate a cloud collapse which otherwise might not have occurred spontaneously, thereby increasing the star formation efficiency of a molecular cloud. Yet, a massive star is known to be vastly destructive to the immediate environment so as to hamper any further star-forming activity. Here we report on a few examples to illustrate the working of triggered star formation in OB associations. These include the collect-and-collapse scenario in the vicinity of the massive star group in the Carina Nebula, and the radiation-driven implosion process in the remnant clouds in the Ori OB1 and Lac OB1 associations.

2. Examples of triggering in OB associations

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

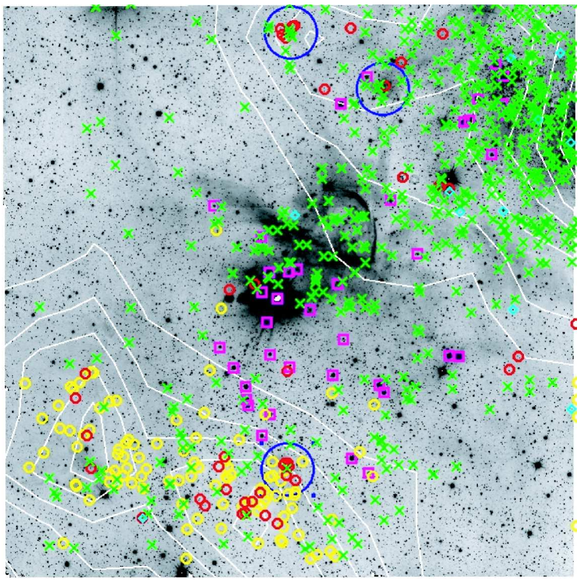

Figure 2. The mosaic K_s band image, $20' \times 20'$, centered on η Carinae. The class I (diamonds) and II (crosses) candidates are marked. Known OB stars are represented by squares, highly reddened sources (H-Ks > 2) by dark circles, and faint (Ks > 17 mag) sources by light circles. The white contours show the $^{12}CO(1-0)$ emission (Brooks et al. 1998), whereas the large blue circles indicate where mid-infrared MSX sources are (figure taken from Sanchawala et al. 2007b)

the dozen known star clusters in the region, Trumpler 14 and Trumpler 16 are centrally located and are the youngest and 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 luminous blue variable, η Carinae, which is considered to be the most massive star in our Galaxy (Massey & Johnson 1993). Sanchawala et al. (2007a) studied the *Chandra* X-ray sources and later with deep near-infrared imaging (Sanchawala et al. 2007b) identified numerous previously unknown embedded OB stars which, together with hundreds of candidate classical T Tauri stars, offer the most comprehensive census of the young stellar population in the Carina Nebula (see Fig. 2). This sample will be useful to diagnose the interplay of massive stars, low-mass young stars, and molecular clouds under turbulent conditions.

In addition to the known star clusters, there is an embedded group of some 10 young stars to the south-east of Trumpler 16, 'sandwiched' between two cloud peaks (Sanchawala et al. 2007a). 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 in between the north-west and south-east cloud complexes, and so has Trumpler 14 to a less extent. The newly identified

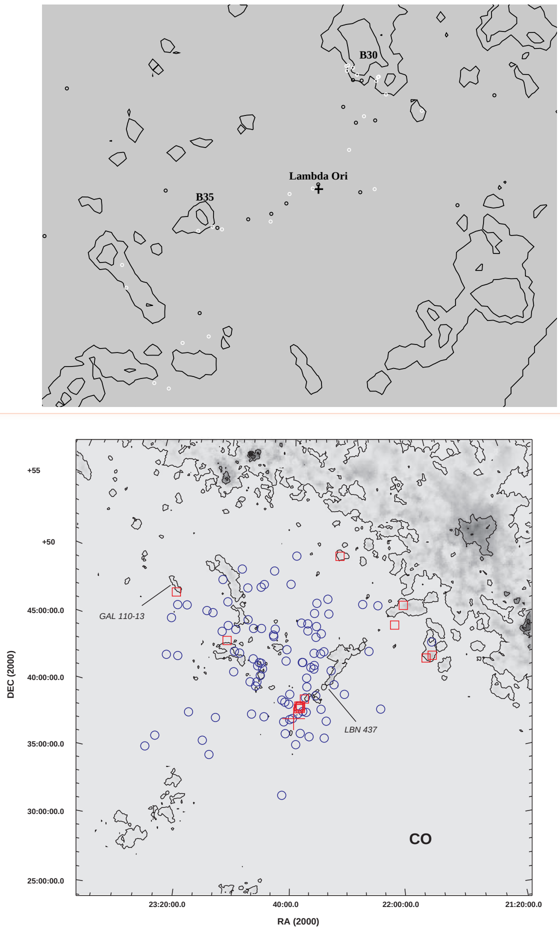

Figure 3. (*top*) Young stars appear to line up between the massive star (marked by an asterisk), and remnant clouds in Ori OB1 (Lee et al. 2005, with the young stars presented by circles), and (*bottom*) in Lac OB1 (Lee & Chen 2007; Chen & Lee 2008, young stars by squares; circles are *Hipparcos* OB members by de Zeeuw et al. 1999).

group suffers a large amount of reddening and is also situated between clouds, 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.

There are ample examples about the radiation-driven implosion process around bright-rimmed clouds. Such a process would have left several telltale

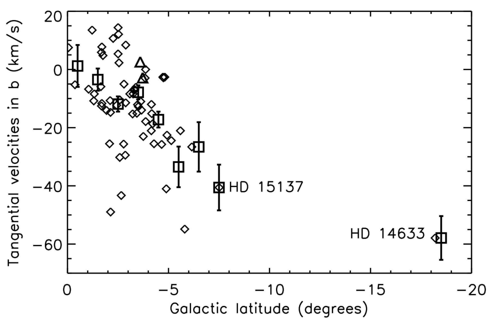

Figure 4. Proper motions along the Galactic latitude for young stars in the Per OB1 association (figure taken from Lee & Lim 2008).

imprints (Chen et al. 2007): (1) The remnant cloud is extended toward, or pointing to, the massive star. (2) The young stellar groupings are roughly lined up between the remnant clouds and the luminous star, (3) Next-generation stars closer to the cloud, i.e., formed later in the sequence, are younger in age, with the youngest distributed at the interacting bright rim of the cloud, and (4) No young stars exist far inside the cloud. 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.

In a series of papers, Lee et al. (2005), Lee & Chen (2007), and Lee & Lim (2008) have developed an effective set of criteria based on the Two Micron All Sky Survey (2MASS) colors to select young stars in star-forming regions. 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 triggered formation of low- and intermediate-mass stars. Fig. 3 shows an example near λ Ori, and another one in Lacertai OB1, where triggered star formation is evident. Furthermore, there is a tendency for the Herbig Ae/Be stars to reside deeper in the cloud, indicating that more massive stars, when prompted to form, favor denser environments where the photoevaporation effect is reduced. On the other hand, when a dense core closer to the ionization layer (i.e. current cloud surface) collapses, the accretion process has to compete with photoevaporation, leading to formation of a less massive star.

The Perseus OB1 offers a particularly interesting case for sequential star formation. This OB association contains the famous h and χ double cluster. At a distance of 2.34 kpc (Slesnick et al. 2002), Per OB1 is located some 300–380 pc above the Galactic plane, compared with the typical height of less than 100 pc for Galactic star-forming regions. Young stars in Per OB1 show a clear differential motion along the Galactic latitude (Fig. 4), suggesting a triggering formation sequence (Lee & Lim 2008).

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 to one molecular cloud to another (Lee & Chen 2009). A sequence of such events ("relay star formation") could spread the star formation out to tens or even hundreds of parsec away. The threshold of how a massive star plays a constructive role in star formation is yet to be worked out quantitatively. Except perhaps in the nucleus of a starburst galaxy, where sequential star formation prevails, triggering in the context of molecular cloud environments most likely plays only an auxiliary role. Still, triggered star formation provides an additional, and in some cases, alternative way to form stars. The process is self-sustaining (in time) and self-propagating (in space), so may have extensive influence in comparison to spontaneous cloud collapse alone.

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