Triggered Star Formation in a Turbulent ISM
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NANTEN observations of triggered star formation: from H II regions to galaxy collisions

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Abstract. In this contribution, we will overview the NANTEN observations of molecular clouds faced to H II regions, supershells, and interacting galaxies, which demonstrate that star/molecular cloud formation is being triggered by young OB associations, supershells, and collisions between galaxies. The large volume filling factor of explosive events like supernovae, ultraviolet radiation fields and stellar winds of massive stars suggest that most of the interstellar medium has been agitated by such strong impacts and triggered star formation is a common event at all scales from small molecular clouds to large galaxy-galaxy mergers. The consequence is the increase of star formation efficiency in many cases, and that more massive stars or clusters of more member stars tend to be formed by triggering than in spontaneous star formation.

Keywords. stars: formation, ISM: bubbles, ISM: clouds, radio lines: ISM, Magellanic Clouds

1. Introduction

The basic process of star formation is gravitational collapse of an interstellar cloud core that mainly consists of molecular hydrogen. This collapse can be accelerated if the core is exposed to high external pressure. High pressure can be caused by the various reasons; ultraviolet photons or stellar winds of OB stars, supernovae, large relative motions between clouds, the galactic density waves and dynamical interactions between galaxies. Most of these actions enhance the star formation efficiency, and influence the evolution of galaxies.

2. Triggering by H II regions

The OB associations are formed in giant molecular clouds of typically 10^5 $M_\odot$ and UV photons of OB stars produce regions of fully ionized hydrogen, H II regions. The H II regions drive the ionization-shock front to compress the molecular clouds into post-shock layers that become gravitationally unstable to form dense fragments. The density increase so-induced should lead to more efficient cooling of the molecular gas since the radiative cooling rate is proportional to $(\text{density})^2$ and these fragments likely lead to star formation when the gravity overcomes the internal pressure. Cloud-cloud collisions in the arm or molecular outflows may also work in triggering to some minor effect. The prevailing occurrence and time-wise persistence make H II regions as important in triggering, although. It has been known that OB associations as well as H II regions and molecular clouds are organized in a galactic spiral pattern, although it is not clear if the spiral arms are enhancing star formation efficiency. We shall focus on the interface between H II regions and molecular clouds to see how triggering is working under the

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effects of H II regions. A survey for dense molecular gas interacting with H II regions has been made towards 23 southern H II regions within 4 kpc of the sun over 40% of the galactic longitude, from $l = 230°$ to $l = 20°$, including the galactic center (Yamaguchi *et al.* 1999). This study detected 57 molecular clouds of density around 10^3 cm^{-3} whose average mass is about 1,000 $M_\odot$. They show broad velocity dispersion of 5-10 km s^{-1} typical of interacting clouds and the clouds are forming stars as represented by more than 120 associated protostellar FIR sources.

This dataset was used to estimate how star formation is different between the molecular gas interacting with H II regions and the rest of the molecular cloud. The interacting region in a cloud was chosen by dividing the cloud into the two regions; the region adjacent to the H II regions, the interacting region, and the rest. This analysis for the 57 clouds leads to findings that the number of protostellar sources is by a factor of 2 increased in the interacting regions compared to the rest, and that these sources tend to be ten times more luminous than those in the rest. These differences are likely caused by the effects of the H II regions, and cannot be ascribed to the molecular properties since the molecular column density and mass are not significantly different between the both regions. The FIR luminosity of the protostellar sources is significantly enhanced in the interacting regions than in the remaining; e.g., the average FIR luminosity is $\sim 10^4$ $L_\odot$ and $\sim 10^3$ $L_\odot$ for the interacting regions and for the rest, respectively, at a cloud mass of $\sim$10 $M_\odot$. Star formation efficiency defined as a ratio between the formed stars and the combined total mass of the clouds and stars is then estimated to be a factor of 3.5 enhanced in the interacting regions if typical stellar mass-to-luminosity relation is assumed. The total star formation rate is 4 $M_\odot$/yr over the Galaxy (e.g., McKee & Williams 1997). The H II-triggered star formation may account for about 10-30% of this value after corrected for low-mass stars by using a Salpeter IMF. Enhanced massive star formation towards H II regions in fact appears consistent with the flatter initial mass function of galactic OB associations within 2 kpc of the sun for the high-mass part of the IMF (Massey *et al.* 1995).

3. Triggering by supershells

OB stars trigger star formation when they are young and close to parental molecular gas over a time scale of 1 Myr. After this phase, the massive members whose mass is greater than 8 $M_\odot$ in an OB association evolve to a supernova which releases total energy of $\sim 10^{51}$ ergs at an explosion, and can be very effective in accelerating interstellar material at scales of 100–1000 pc. The accumulated mass due to the multiple blast waves and the pressure gradient of the hot gas from supernovae form a nearly spheroidal shell of dense interstellar matter that becomes gravitationally unstable to form stars in them (Palouš & Ehlerova 2000). A typical lifetime of a supershell is up to 30 Myrs, significantly longer than that of H II triggering and after that it may become difficult to identify a spherical shape with no further energy input. Supershell is not a separate phenomenon from H II-triggering phase but is a continuing process subsequent to it. The two phases can be even coexistent as in case of the OB associations in Orion. Figure 1 shows a large field in the Orion-Eridanus region including an extended supershell, the Orion-Eridanus superbubble, one of the typical supershells (superbubbles) in the solar vicinity. It is however to be noted that the role of these shells in triggering star formation was not clear until recently since the expanding gas is all of low density having gas column density of $\sim 10^{20}$ cm^{-2} that are not related to active star formation. The Orion-Eridanus superbubble either shows very little sign of triggered star formation except for a few small molecular clumps (e.g., Kun *et al.* 2001), making a sharp contrast to the active

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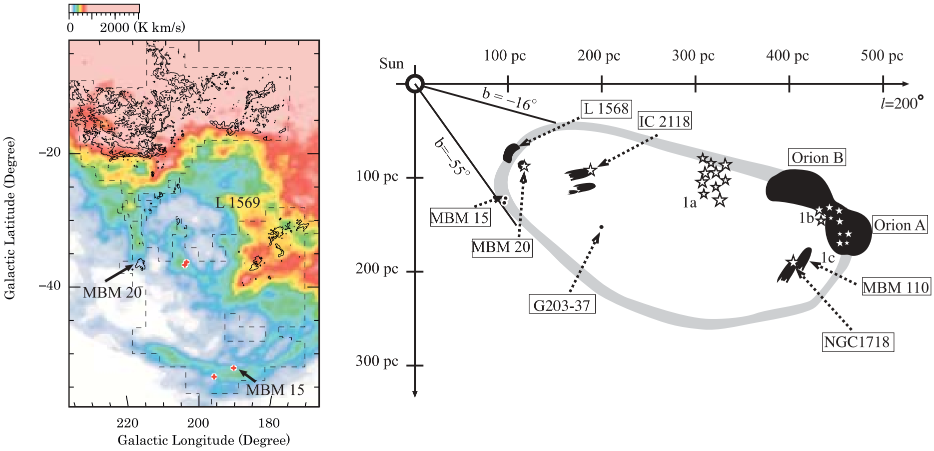

Figure 1. *Left*) The NANTEN ^{12}CO integrated intensity map (contour) and H I intensity map (pseudo-color) taken from Leiden/Dwingeloo Atlas of galactic neutral hydrogen (Hartmann & Burton 1997). *Right*) Schematic cross sections of the Orion-Eridanus superbubble. The x-axis indicates the Galactic plane, and the y-axis indicates the distance from the Galactic plane.

massive star formation in the Orion molecular clouds themselves where star formation is predominantly influenced by the H II regions.

A recent discovery of the Carina Flare is the first case which exhibits massive star formation triggered by a supershell in the Galaxy (Fukui *et al.* 1999, Dawson *et al.* 2006). Triggering in the Carina Flare naturally invokes a question, how the star formation efficiency of supershells is significant all over the Galaxy. Many supershells appear not triggering star formation. The previous sample may be biased towards low density features, a natural consequence of the past extensive usage of the H I data, Hα emission and the FIR dust emission. We need to observe dense molecular gas that is directly connected to on-going star formation over a reasonable large height (z) coverage in order to better understand the impact of supershells. Subsequently, a first attempt to search for molecular supershells in higher resolution with NANTEN has revealed 9 shells including the Carina Flare, 7 of which are new discoveries, where the identification was made primarily based on the arm-like morphology of the molecular gas. Their radius ranges from 50 pc to 230 pc, with ages between 2×10^6 yrs to 1×10^7 yrs (Matsunaga *et al.* 2001). The area covered corresponds to 1/5 of the galactic disk within a distance of $\sim$4 kpc. The 8 molecular supershells are positionally well correlated with galactic spiral arms at a frequency of about $\sim$0.4 kpc^{-2} in the galactic disk. The association with the spiral arms is as expected from the relation with OB associations, while the frequency may be somewhat smaller than expected, implying that only a fraction of OB associations surrounded by rich H I envelope may be able to form molecular supershells. The total mass included in these molecular supershells at z above 150 pc, $\sim 10^6 M_\odot$, is very small, less than 1%, compared to 15% of the molecular mass included in the disk of the surveyed area, suggesting that only a small fraction of the high z gas can be identified morphologically as a supershell, probably because the arc-like shape of a supershell is soon lost after $\sim$10 Myrs due to differential rotation etc. It is also to be noted that the identification of associated stars becomes very difficult at distances larger than 2 kpc near the galactic plane, making it hard to study second-generation stars of triggered formation. More insights into the role of supershells are to be obtained in the nearby galaxies which are not heavily obscured. In the Large Magellanic Cloud (LMC) having

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no clear strong spiral patterns the super(giant) shells may be more important in forming clouds and stars (Fukui 2006, Kawamura *et al.* 2006).

The other relevant aspect is the role of shells in formation of very massive stars and/or rich stellar clusters; The η Carina cluster is where unusually massive stars in the Milky Way may have been formed under triggering of a supershell. η Carina is located just at the same distance and at the same longitude of the Carina Flare. Considering that η Carina cluster is 3-5$\times 10^6$ yrs old, it is suggested that triggering by the Carina Flare shell may have played a role to form this cluster by effectively collecting gas over a large volume into a small space which was never possible without the action of a supershell. Similarly, the 30 Doradus region in the LMC is well known for its outstanding nature of a massive and rich stellar cluster R136 and is apparently sandwiched by two super giant shells (LMC2 and LMC3). These suggest that super(giant) shells may play a role in the formation of very massive stars and the richest clusters in the system.

4. Triggering by galaxy collisions

Galaxy-galaxy interactions or collisions between galaxies can significantly enhance the rates of star formation. Recently, we found the molecular clouds in the nearest and brightest tidal structure: the Magellanic Bridge (Mizuno *et al.* 2006). We suggest that CO clouds are formed *after* the tidal encounter, rather than being extracted from the SMC. This is supported by the small typical lifetime of CO clouds which is as short as $\sim 10^7$ yrs, and much less than the estimated 200 Myr age of the Bridge itself. These observations have shown that not only is star formation on-going within the Bridge, but that it is quite widespread throughout its kilo-parsec length. Further efforts to probe the spatial extents of the CO emission regions, and to better establish association/cluster properties and star formation will be extremely valuable. The Magellanic Bridge provides an outstanding opportunity to probe the weakly-understood process of star formation in the interacting system, it is difficult to study to a useful level of detail at distant galaxies.

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