DYNAMICAL EXPANSION OF IONIZATION AND DISSOCIATION FRONT AROUND A MASSIVE STAR: A STARBURST MECHANISM

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ABSTRACT

We quantitatively examine the significance of star formation triggered in the swept-up shell around an expanding \(\text{H} \, \! \upiota\) region. If the swept-up molecular gas is sufficiently massive, new OB stars massive enough to repeat the triggering process will form in the shell. We determine the lower limit (\(M_{\text{thr}}\)) for the mass of the star that sweeps up the molecular gas, where at least one new star with mass \(M_* \geq M_{\text{thr}}\) forms after shell fragmentation. To calculate the threshold stellar mass \(M_{\text{thr}}\), we examine how massive molecular shells can form around various central stars, by performing detailed numerical radiation hydrodynamics calculations. The mass of the photodissociated gas is generally larger than the mass of the photonized gas. However, the swept-up molecular mass exceeds the photodissociated mass with a higher mass star of \(M_* \geq 20 M_\odot\). The accumulated molecular mass generally increases with the stellar mass, and amounts to \(10^{-4} - 10^3 M_\odot\) for \(M_* \geq 20 M_\odot\) with an ambient density of \(n \sim 10^2\) cm\(^{-3}\). The threshold stellar mass is \(M_{\text{thr}} \sim 18 M_\odot\) with a star formation efficiency of \(\epsilon \sim 0.1\) and \(n \sim 10^2\) cm\(^{-3}\). We examine the generality of this mode of runaway triggering for different sets of parameters and find that \(M_{\text{thr}} \sim 15 - 20 M_\odot\) in various situations. If the ambient density is too high or the star formation efficiency is too low, the triggering is not runaway, but a single event.

Subject headings: circumstellar matter — \(\text{H} \, \! \upiota\) regions — ISM: molecules — stars: formation

1. INTRODUCTION

In galaxies, most of the stars are born in localized active star-forming regions or starburst regions. Clustered star formation is the dominant mode in these regions (e.g., Evans 1999; Lada & Lada 2003), and several star clusters, including OB stars, form over a few Myr from the parental giant molecular cloud (Williams & McKee 1997). The newly born massive stars promptly emit UV (\(h\nu > 13.6\) eV) and far-UV (FUV; 11 eV \(\leq h\nu < 13.6\) eV) radiation, and radiative feedback by these photons occurs much earlier than supernova explosions. The UV and FUV radiation from massive stars has two competing effects on the parental molecular cloud. One is the negative feedback effect on star formation activity. The parental molecular cloud is ionized and heated up by UV radiation, and nearby star formation is quenched (e.g., Whitworth 1979; Franco et al. 1994; Williams & McKee 1997; Matzner 2002). Diaz-Miller et al. (1998) have shown that photodissociation by FUV photons is more significant than photoionization by UV photons. The other is the positive feedback effect. The next star formation is triggered in the compressed dense layer around the \(\text{H} \, \! \upiota\) region (collect-and-collapse scenario; e.g., Elmegreen & Lada 1977; Elmegreen 1989). Recent observations have provided dramatic snapshots of this triggering process (e.g., Deharveng et al. 2003, 2005; Zavagno et al. 2006). Kato et al. (2005) have observed details of the starburst regions and suggested that the propagating star formation is important on the scale of the clouds. The character of star formation depends on which feedback effect dominates the cloud in the order.

In our previous papers (Hosokawa & Inutsuka 2005 and 2006, hereafter Papers I and II) we have studied the time evolution of the \(\text{H} \, \! \upiota\) region, photodissociation region (PDR), and swept-up shell, performing detailed numerical calculations. We have shown that molecular gas is accumulated around the \(\text{H} \, \! \upiota\) region and that gravitational fragmentation of the shell is expected in many cases with a homogeneous molecular ambient medium. This suggests that the expanding \(\text{H} \, \! \upiota\) region is an efficient trigger of star formation in the cloud. In this Letter, we examine the net feedback effect of the expanding \(\text{H} \, \! \upiota\) region and PDR around a massive star.

2. A STARBURST MECHANISM

2.1. Triggering Threshold Condition

First, we focus on the positive feedback process for triggering star formation in the shell. Let us consider a situation where a dense molecular shell whose mass is \(M_{\text{shell}}\) forms around a massive star, and the subsequent star formation is triggered after fragmentation of the shell. The total number of newly born stars is calculated as

\[
N_* = \frac{M_{\text{shell}} \epsilon}{M_{\text{av}}},
\]

where \(\epsilon\) is the star formation efficiency (SFE) of the swept-up gas and \(M_{\text{av}}\) is the average stellar mass, which is defined as

\[
M_{\text{av}} = \frac{\int_0^\infty \phi(M)M\,dM}{\int_0^\infty \phi(M)dM},
\]

where \(\phi(M)\) is the initial mass function (IMF). Below, we use the IMF by Miller & Scalo (1979). The calculated value of \(M_{\text{av}}\) is about 0.6 \(M_\odot\). The mass of the swept-up molecular gas, \(M_{\text{shell}}\), generally depends on the ambient number density and mass of the central star (see Paper II). If \(M_{\text{shell}}\) is sufficiently large, another massive star as well as lower-mass stars will form in the shell. Another \(\text{H} \, \! \upiota\) region expands around this newly born massive star, and the triggering process will repeat. Furthermore, if the number of newborn stars is larger than that of the previous generation, this process causes runaway triggering or a burst of star formation.

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In order to examine the efficiency of this mode of triggering, we presume that the runaway triggering begins with a star more massive than the threshold stellar mass $M_{\text{thr}}$. A star of $M_{\text{thr}}$ produces a shell that barely generates just one star more massive than $M_{\text{thr}}$. If the triggering cycle begins with a star of $M_{\ast} > M_{\text{thr}}$, multiple stars of $M_{\ast} > M_{\text{thr}}$ form as “second generation” stars. The number of newborn stars increases as the triggering cycle advances, and the burst of star formation occurs. We represent the condition for runaway triggering with simple equations. The number of $M_{\ast} > M_{\text{thr}}$ stars born in the shell is

$$N_{\text{thr}} = f_{\text{thr}}N_{\ast},$$

where $f_{\text{thr}}$ is the number ratio of $M_{\ast} > M_{\text{thr}}$ stars, calculated as

$$f_{\text{thr}} \equiv \frac{\int_{M_{\text{thr}}}^{\infty} \phi(M) dM}{\int_0^{\infty} \phi(M) dM}.$$  

We can determine $M_{\text{thr}}$ from the triggering threshold condition, $N_{\text{thr}} = 1$. Combining this condition and equations (1) and (3), we obtain

$$M_{\text{sh},m} = \frac{M_{\ast}}{\epsilon f_{\text{thr}}}.$$  

Evaluating how $M_{\text{sh},m}$ depends on the stellar mass, we can calculate $M_{\text{thr}}$ for a given ambient number density and SFE by equation (5). If the molecular mass of the shell is smaller than $M_{\ast}/\epsilon f_{\text{thr}}$, triggering is not runaway, but only a single event. We examine $M_{\text{sh},m}$ with various stellar masses and ambient number densities based on numerical calculations.

2.2. Mass of the Molecular Shell versus Mass of the Central Star

In order to evaluate the threshold stellar mass $M_{\text{thr}}$ for the burst of star formation, we examine how the shell mass $M_{\text{sh},m}$ changes with the mass of the massive star and the ambient molecular gas density. Even if the shell forms around the H II region, the accumulated gas is exposed to FUV radiation from the central star. Unless the FUV radiation is blocked, almost no cold molecular gas accumulates in the shell. Therefore, we should carefully estimate the mass of the cold molecular gas in the shell, which is available for the next star formation episode. For this purpose, we have calculated the time evolution of the H II region, PDR, and swept-up shell around various central stars in the homogeneous molecular medium (see Paper I for the details). In this subsection, we focus on the fiducial case with $n_{\text{H}} = 100$ cm$^{-3}$ ($\rho_{\text{H}} = 50$ cm$^{-3}$). If the FUV radiation is efficiently shielded in the shell, the accumulated molecular mass $M_{\text{sh},m}$ increases as the H II region expands. However, $M_{\text{sh},m}$ is actually limited by the following two factors. First, the expanding shell finally dissolves due to the turbulent motion of the ambient medium. Ubiquitous supersonic turbulent motions in molecular clouds have been recognized by the observed broad emission line width. The corresponding velocity dispersion increases with the length scale as $\sigma \propto L^{1/3}$, and $\sigma \approx 2$ km s$^{-1}$ at $L \approx 10$ pc. We define the dissolving velocity, $v_{\text{dlv}} \sim$ several km s$^{-1}$, and the shell dissolves at the time $t_{\text{dilv}}$, when the shell velocity becomes less than $v_{\text{dlv}}$. Second, OB stars evolve to the Wolf-Rayet phase after the main-sequence phase, and finally explode as supernovae. Although the Wolf-Rayet winds and supernova explosions must cause the dynamical expansion of bubbles, we do not consider the evolution after the main-sequence lifetime $t_{\text{MS}}$. We evaluate the mass of the molecular gas in the shell at the termination time of the shell, $t_{\text{dilv}}$, and the main-sequence lifetime of the central star, $t_{\text{MS}}$, respectively. The termination time of the shell is the smaller of $t_{\text{dilv}}$ and $t_{\text{MS}}$. The dotted line indicates the time when the gravitationally unstable region appears in the shell. The dots and open circles indicate the calculated values in each model. Middle: Mass of molecular hydrogen accumulated in the shell (solid line), neutral hydrogen in the PDR (dot-dashed line), and ionized hydrogen in the H II region (dotted line) for various central stars at the termination time. Bottom: Relative fraction of these three masses presented in the middle panel. In each panel, a positive feedback effect is expected in the unshaded mass range, while negative is expected in the shaded range.
and terminates earlier. The main-sequence lifetime \( t_{\text{MS}} \) is shorter for a higher mass star, and the expansion is limited by \( t_{\text{MS}} \) for \( M_\ast \geq 30 \, M_\odot \).

The middle panel of Figure 1 presents the mass of the swept-up molecular gas at the termination time. This panel shows that \( M_{\text{sh, m}} \) increases with the stellar mass, which verifies the triggering threshold condition. The molecular mass amounts to \( M_{\text{sh, m}} \sim 10^5 - 10^6 \, M_\odot \) for massive central stars of \( M_\ast \geq 20 \, M_\odot \). In these cases, the \( \text{H} \, \text{ii} \) region expands to 10–20 pc by the termination of the shell. With a central star of \( M_\ast \leq 20 \, M_\odot \), the accumulated molecular mass is significantly small. The shell dissolves before the accumulation of the molecular gas with a lower mass star. To clarify the dominant feedback effect, we also plot the masses of the photodissociated and photoionized gas around the star at the same time. With higher mass stars of \( M_\ast \geq 20 \, M_\odot \), the accumulated molecular mass is much larger than both the ionized and photodissociated masses. Therefore, such massive stars have a positive feedback effect on the clouds. With lower mass stars of \( M_\ast \leq 20 \, M_\odot \), on the other hand, the photodissociated mass is much larger than the ionized and accumulated molecular masses. In these cases, the net feedback effect is negative and photodissociation by FUV photons is the dominant negative process, as argued by Diaz-Miller et al. (1998). The bottom panel of Figure 1 presents the masses multiplied by the population of exciting stars. When higher mass stars of \( M_\ast \geq 20 \, M_\odot \) are formed in the cloud, the positive feedback effect can dominate, despite a large number of lower mass stars. Whether the net feedback effect is negative or positive depends on the mass of the most massive star in the cloud; it is positive for \( M_\ast \geq 20 \, M_\odot \), and vice versa in the current fiducial case.

2.3. Threshold Stellar Mass for Starburst

Using the calculated \( M_{\text{sh, m}} \) for various central stars, we determine the threshold stellar mass \( M_{\text{thr}} \) for the burst of star formation. For example, in the fiducial case with \( n_\text{H} = 100 \, \text{cm}^{-3} \) and \( v_{\text{div}} = 2 \, \text{km s}^{-1} \), the threshold mass calculated by equation (4) is \( M_{\text{thr}} \sim 18 \, M_\odot \) with \( \epsilon = 0.1 \). This means that only a star more massive than \( 18 \, M_\odot \) can generate a shell massive enough so as to produce at least one star as massive as the original star. Note that the threshold mass is comparable to the stellar mass over which the character of feedback changes from negative to positive. In this case with \( M_\ast \geq 20 \, M_\odot \), therefore, the net feedback effect is positive, and strong enough to cause runaway triggering.

We have examined the possibility of runaway triggering by calculating \( M_{\text{thr}} \) with different parameters (Fig. 2). For example, \( M_{\text{sh, m}} \) increases with decreasing SFE. This is because the more massive molecular shell is needed to compensate for the lower SFE. With \( \epsilon = 0.03 \) in the fiducial case, we obtain \( M_{\text{thr}} \sim 21 \, M_\odot \). If the SFE is as low as \( \epsilon \leq 0.01 \), however, equation (4) is not satisfied with any \( M_{\text{thr}} \). This is because the increase in \( M_{\text{sh, m}} \) grows saturated at about \( \sim 10^5 \, M_\odot \) as the mass of the central star increases (see Fig. 1). Although the net feedback effect is positive with \( M_\ast \geq 20 \, M_\odot \), triggering is not runaway, but only a single event.

The threshold stellar mass also increases with the higher ambient density. In the denser ambient medium, the size of the \( \text{H} \, \text{ii} \) region shrinks as \( R_\ast \propto n_\text{H}^{-0.7} \). The total swept-up mass at the termination time also becomes smaller following the scaling relation, \( M_{\text{sh}} \propto n_\text{H}^{-0.7} \), with the same central star. With the higher ambient density, therefore, \( M_{\text{th}} \) increases to produce the mass-

![Figure 2](image-url)

**Fig. 2**—Threshold stellar masses \( M_{\text{th}} \) for the runaway triggering with different parameters. The horizontal axis is the ambient number density, and the different symbols denote different sets of dissolving velocity \( v_{\text{div}} \) and star formation efficiency \( \epsilon \). Some symbols disappear at higher ambient densities, which means that the triggering threshold condition (eq. [5]) is not satisfied with the corresponding set of parameters. In these cases, triggering is not runaway, but a single event.

sive shell, which enables runaway triggering. Since the increase in \( M_{\text{sh, m}} \) becomes saturated for the higher mass stars, runaway triggering becomes impossible unless the SFE is very high in the denser ambient medium. With \( n_\text{H} = 10^3 \, \text{cm}^{-3} \) and \( v_{\text{div}} = 2 \, \text{km s}^{-1} \), for example, an SFE as high as \( \epsilon \sim 0.3 \) is needed for runaway triggering.

Finally, the higher dissolving velocity reduces the significance of triggering. The expanding shell dissolves earlier with higher \( v_{\text{div}} \), and the \( \text{H} \, \text{ii} \) region sweeps up only the smaller region. Furthermore, the molecular fraction in the shell is preferentially reduced with higher \( v_{\text{div}} \). During the dynamical expansion of the \( \text{H} \, \text{ii} \) region, the column density of the shell, \( N_{\text{sh}} \), increases as \( N_{\text{sh}} \sim R_\ast R_{\text{in}}(t)/3 \). Therefore, a smaller \( \text{H} \, \text{ii} \) region has a shell with lower column density, although the incident FUV radiation is strong owing to the poor geometrical dilution. Since the FUV radiation shielding is inefficient, it is hard for molecules to accumulate in the shell. With \( v_{\text{div}} = 4 \, \text{km s}^{-1} \) and \( \epsilon = 0.3 \), for example, runaway triggering is possible only with a low ambient density of \( n_\text{H} \approx 10^{1.5} \, \text{cm}^{-3} \).

3. DISCUSSION AND CONCLUSIONS

In this Letter we suggest a possible mode of self-propagating star formation in molecular clouds, which should be examined in further studies. Although we have adopted a homogeneous ambient density, for example, real clouds show clumpy structure with a turbulent velocity field. Recently, Mellema et al. (2006) have calculated the dynamical expansion of the \( \text{H} \, \text{ii} \) region in turbulent molecular clouds. They have shown that a clumpy medium leads to an irregular ionization front. The radial position of the ionization front approximately agrees with that in the homogeneous medium on average with the mean density, but significantly depends on the radial direction. More theoretical studies and multidimensional numerical simulations of the deformation and fragmentation processes of the swept-up shell are needed. Observational estimation of the SFE in the shell might be interesting and useful for the present model. The stellar wind from massive stars is another omission in
our evaluation. The expanding wind-driven bubble can modify the dynamics of the ISM around massive stars. When the bubble pressure is much higher than the ambient pressure, the time evolution of the bubble size and pressure is given by

\[ R_b(t) = \left( \frac{125}{154\pi} \right)^{1/5} L_w^{1/5} \rho_0^{-1/5} t^{3/5}, \quad (6) \]

\[ P_b(t) = \frac{7}{(3850\pi)^{2/5}} L_w^{2/5} \rho_0^{1/2} t^{-4/5}, \quad (7) \]

where \( L_w \) is the wind mechanical luminosity (Weaver et al. 1984). If \( n_\perp \), the bubble is confined by the ambient \( \mathrm{H}\) \( \perp \) pressure before reaching the initial Strömgren radius. The numerical value of \( f_\perp \) can be estimated by \( f_\perp = 0.8 \times (S_{10} / 10^{19} \text{ cm}^{-2} \text{ s}^{-1})^{1/5} \rho_0^{1/5} \) (Abbott 1982). With a number density of \( n_\perp = 100 \text{ cm}^{-3} \), \( f_\perp \sim 0.4 \) for a 20 \( M_\odot \) star and \( f_\perp \sim 1.5 \) for a 50 \( M_\odot \) star. Therefore, the stellar wind only slightly increases the initial pressure of the \( \mathrm{H}\) \( \perp \) region with a star of \( M_* \sim 50 M_\odot \). The effect of the wind-driven bubble becomes significant with a very massive star (\( \sim 100 M_\odot \)), with highly clustered massive stars, or in higher density media. When a wind-driven bubble dominates the dynamics, the bubble sweeps up the larger region at higher velocity than the expansion only due to the \( \mathrm{H}\) \( \perp \) region overpressure. This situation may even promote the positive feedback effect and should be separately studied in detail.

Finally, we summarize the results. First, we have formulated the conditions for the positive feedback process by which triggered star formation continues in the swept-up shell. The threshold stellar mass \( M_{thr} \) is defined as the mass of the central star that sweeps up the molecular gas in the shell, where at least one new star with mass \( M_* = M_{thr} \) forms after shell fragmentation. In order to evaluate \( M_{thr} \), we have calculated how massive molecular shells can form around various central stars. In the fiducial case with \( n_\perp = 100 \text{ cm}^{-3} \) and \( v_{\text{dis}} = 2 \text{ km s}^{-1} \), the swept-up molecular mass increases with stellar mass and amounts to \( M_{sh,m} \sim 10^{7} – 10^{8} M_\odot \) with a massive star of \( M_* \sim 20 M_\odot \). We have also calculated the photoionized and photodissociated masses to clarify the net feedback effect. The negative effect of photodissociation is important with lower mass stars of \( M_* \lesssim 10 M_\odot \), but is dominated by the positive effect with higher mass stars. We have calculated the threshold mass as \( M_{thr} \sim 18 M_\odot \) in the fiducial case with \( \epsilon = 0.1 \). We have also calculated \( M_{thr} \) with different parameters and examined the generality of runaway triggering. We have found \( M_{thr} \sim 15 – 20 M_\odot \) in various situations. The triggering process is only a single event with a higher ambient density, higher dissolving velocity, or lower SFE.

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