DYNAMICAL EXPANSION OF IONIZATION AND DISSOCIATION FRONTS AROUND A MASSIVE STAR. I.
A MODE OF TRIGGERED STAR FORMATION

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Received 2004 November 3; accepted 2005 January 5

ABSTRACT

We analyze the dynamical expansion of the H II region and outer photodissociation region (PDR) around a massive star by solving the UV and FUV radiation transfer and the thermal and chemical processes in a time-dependent hydrodynamics code. We focus on the physical structure of the shell swept up by the shock front (SF) preceding the ionization front (IF). After the IF reaches the initial Strömgren radius, the SF emerges in front of the IF and is geometrically thin shell bounded by the IF and SF is formed. The gas density inside the shell is about $10^3 - 10^2$ times as high as the ambient gas density. Initially, the dissociation fronts (DFs) expands faster than the IF, and the PDR is formed outside the H II region. Thereafter, the IF and SF gradually overtake the preceding DFs, and eventually the DFs are taken into the shell. The chemical composition within the shell is initially atomic, but hydrogen and carbon monoxide molecules are gradually formed. This is partly because the IF and SF overtake the DFs and the SF enters the molecular region, and partly because the reformation timescales of the molecules become shorter than the dynamical timescale. The gas shell becomes dominated by the molecular gas by the time of gravitational fragmentation, which agrees with some recent observations. A simple estimation of the star formation rate in the shell shows that these processes contribute significantly to the star formation rate in our Galaxy.

Subject heading: circumstellar matter — H II regions — ISM: molecules — stars: formation

1. INTRODUCTION

As the H II region expands around a massive star, the shock front (SF) emerges preceding the ionization front (IF). This SF sweeps up the ambient gas, and the gas shell is formed at the edge of the H II region. Many authors have studied the scenario in which the shell becomes unstable and the next star formation is triggered around the H II region (the “collect and collapse” model; see, e.g., Elmegreen & Lada 1977; Whitworth et al. 1994; Elmegreen 1998 and references therein). Recently, Deharveng et al. (2003, hereafter DV03) observed the fragmented molecular shell around the classical H II region Sh 104 and showed that young stars (a cluster) are formed in the core of one fragment. They argue that this is evidence for the collect and collapse model. Now we can refine the theory of the evolution of the shell and compare it with this detailed observation. Especially, we can focus on the amount of fragmented molecular gas that DV03 observed. The SF initially emerges in front of the IF, where sufficient FUV photons to dissociate molecules are available. Therefore, it is not clear whether or not the SF can gather the molecular gas in the shell, as observation seems to indicate.

Roger & Dewdney (1992) and Diaz-Miller et al. (1998) studied the time-dependent expansion of H II regions and photodissociation regions (PDRs) by solving the radiative transfer of UV and FUV photons. Although these works do not include hydrodynamics, they have shown that the IF gradually overtakes the dissociation front (DF), and this means that the IF and preceding SF gradually enter the molecular region. Numerical study of the hydrodynamic expansion of the IF has been carried out since the 1960s (e.g., Mathews 1965; Lasker 1966; Tenorio-Tagle 1976, 1979; Franco et al. 1990). These works successfully show the various dynamical aspects of the expansion in both homogeneous and inhomogeneous ambient medium. However, these do not include the outer PDR and the thermal processes dominant in the PDR.

We perform a time-dependent calculation including the IF, the DF, and the shell, the study of which has been very limited. We solve the UV and FUV radiation transfer and hydrodynamics numerically to investigate the structure and evolution of the shell and PDR as well as the H II region. Since the compression rate behind the SF depends on the thermal processes, we include the thermal processes that dominate in either the H II region or PDR. In this paper, we consider the simple situation in which there is one massive star within the homogeneous ambient medium, which can be compared with Sh 104 as observed by DV03. The detailed quantitative aspects of the evolution will be given in a subsequent paper (T. Hosokawa & S. Inutsuka 2005, in preparation).

2. NUMERICAL METHODS

We use a one-dimensional spherically symmetrical numerical method. The numerical scheme for the hydrodynamics is based on the second-order Lagrangian Godunov method (see, e.g., van Leer 1979). We use the on-the-spot approximation for UV and FUV radiation transfer. We assume that all hydrogen molecules are in the ground vibrational level of $X^1\Sigma_g^+$ and that the ortho/para ratio is 3:1 (Diaz-Miller et al. 1998). For the Lyman-Werner bands to photodissociate the hydrogen molecule, we solve the frequency-dependent transfer using a representative set of lines. The UV and FUV photon luminosity of the central star is adopted from Diaz-Miller et al. (1998) in the case of $Z = 1 Z_\odot$. The main thermal processes included in the energy equation are UV/FUV heating (e.g., H photoionization, photoelectric heating) and radiative cooling (e.g., H recombination, Ly$\alpha$, O I (63.0 and 63.1 \mu m), O II (37.29 \mu m), C II (23.26 and 157.7 \mu m), H$_2$, and CO; see Hollenbach & McKee 1979, 1989; Koyama & Inutsuka 2000). Nonequilibrium reaction
equations are implicitly solved for the species of $e$, H, H$^+$, H$_2$, C$^+$, and CO. The ionization rate of O is assumed to be the same as that of H. We adopt the simple approximation for the dissociation process of the CO molecule given by Nelson & Langer (1997). The hydrodynamic, radiative transfer, energy, and reaction equations are combined following Tenorio-Tagle (1976). Dust extinction is included only outside the IF, and the dust temperature is calculated following Hollenbach et al. (1991). We have checked our numerical code with well-studied problems (e.g., Franco et al. 1990).

3. RESULTS OF THE NUMERICAL CALCULATION

In this paper, we consider one typical case where there is one massive star of $T_{\text{eff}} = 40,000$ K ($M = 41 M_\odot$) in the ambient medium. This corresponds to an O6 V star, which is the central star of Sh 104. The initial ambient number density of the hydrogen nucleon is unknown, and we adopt a typical value for a giant molecular cloud, $n_{H,0} = 10^3$ cm$^{-3}$ ($n_{H,0} = 500$ cm$^{-3}$). As in the standard picture (e.g., Spitzer 1978), the IF expands rapidly as a weak R-type front with a recombination timescale $t_{\text{rec}} \sim 100$ yr for $n_{H,0} = 10^3$ cm$^{-3}$ (formation phase). As the IF reaches the Strömgren radius $R_{\text{St}} = 0.56$ pc, the photoionization rate and the recombination rate in the H II region become equal and the H II region begins to expand owing to the pressure difference between the H II region and the outer PDR or molecular cloud. At this phase, the SF appears in front of the IF and the IF changes to a weak D-type front (expansion phase). The expansion law in this phase is given by

$$R_{\text{IF}}(t) = R_{\text{St}} \left(1 + \frac{7}{4} \frac{C_{H\ II}}{R_{\text{St}}} t\right)^{4/7}$$  \hspace{1cm} (1)

(e.g., Spitzer 1978), where $C_{H\ II}$ is the sound speed in the H II region. The dynamical timescale is now given by $t_{\text{dyn}} = R_{\text{St}} / C_{H\ II} \sim 10^5$ yr. Figure 1 shows the time evolution of the physical quantities of the gas in the expansion phase. The radius of Sh 104 is 4 pc, and the IF reaches this radius at $t = 0.7$ Myr in our calculation. For each snapshot, we can see the H II region ($T \sim 10^4$ K), the gas shell swept up by the SF ($n_{H,0} \sim 10^2-10^3$ cm$^{-3}$), the outer PDR ($T \sim 100$ K), and the outermost molecular cloud ($T \sim 10$ K). The SF emerges just in front of the IF. The density behind the SF significantly increases from the ambient value owing to line cooling, and the gas density within the shell is about 10–100 times as high as the ambient density. The more detailed inner structure of the shell is shown in Figure 3. The geometrical thickness of the shell, $h$, increases throughout the calculation, $h \sim 0.02$–0.2 pc. The PDR ($T \sim 100$ K) becomes narrow as the IF expands; that is, the IF gradually catches up with the preceding DFs (e.g., Roger & Dewdney 1992; Diaz-Miller et al. 1998). The top panel of Figure 2 represents the overtaking of the IF more clearly. The position of the SF is very close to that of the IF. As the system switches from the formation phase to the expansion phase, the timescale of the expansion of the IF suddenly becomes long up to $t_{\text{dyn}}$. Even in this phase, the preceding DFs continue to expand. Then the region between the IF and the DFs appears as a PDR. However, the DFs gradually slow down because the FUV flux at each DF decreases owing to geometrical dilution and dust extinction in the PDR. The IF expands because of the pressure difference between the H II region and the outer PDR, and the deceleration is slower according to equation (1).

The lower two panels of Figure 2 represent the time evolution of the column density of each region. The column density of the H II region gradually decreases because the number density decreases as $n_{H\ II} \propto R_{\text{IF}}^{-3/2}$ in the expansion phase, where $R_{\text{IF}}$ is the radius of the H II region. The column density of the gas shell, $\sigma$, increases. The ambient mass swept up by the time $t$ is proportional to $R_{\text{IF}}(t)^3$, and the mass within the H II region is $\propto n_{H\ II} R_{\text{IF}}(t)^3 \propto R_{\text{IF}}(t)^{3/2}$. Thus, most of the swept-up mass does not flow into the H II region but remains in the shell. The calculated mass of the H II region is 430 $M_\odot$, and the shell mass is 9000 $M_\odot$ at $t = 0.7$ Myr (including both the PDR and molecular region), which is in good agreement with observation (see DV03). The PDR initially spreads outside the shell, but H$_2$ and CO molecules are gradually accumulated from the outer side of the shell. The accumulation of the molecules already begins when each DF is still outside the SF. Therefore, the accumulation
is not simply explained by the fact that the IF and SF overtake the DFs and that the SF enters the molecular region. The gas density within the shell is so high that the reformation timescales of the molecules become sufficiently short. The reformation timescale of the hydrogen molecule is about $10^6$ yr for $n_H > 10^4$ cm$^{-3}$. The dynamical timescale is about $t_{\text{dyn}} \approx 10^5$ yr, and thus the reformation of $H_2$ on the grain surface is not important for the ambient number density. However, the reformation timescale in the gas shell, $\sim 10^4$–$10^5$ yr, is shorter than $t_{\text{dyn}}$, and therefore the formation of $H_2$ molecules is significant in the shell.

Figure 3 shows the detailed structure of the physical quantities and the chemical composition of the shell at $t = 0.3$ Myr. As this figure shows, the molecular fraction in the shell is higher than the value in the PDR outside the shell owing to the rapid reformation. As the $H\alpha$ region expands, the DFs are taken into the shell and the denser ($n_H > 10^4$ cm$^{-3}$) PDR is formed on the inner side of the shell. Once the molecules are reformed in the shell, the FUV radiation is consumed by the photodissociation of these molecules, which decelerates the expansion of the preceding DFs and accelerates the accumulation of the molecules. About 80% (55%) of the hydrogen (carbon) atoms within the shell exist as $H_2$ (CO) molecules at $t = 0.7$ Myr in our calculation. Figure 3 also shows other interesting features of the shell. The thermal pressure inside the shell is high and about constant at the value of the $H\alpha$ region. The gas temperature has a negative gradient from the inner side to the outer side of the shell.
shell, because the FUV radiation is attenuated owing to dust extinction through the shell and photoelectric heating decreases. Conversely, the gas density has a positive gradient to the outer side of the shell.

4. DISCUSSION

4.1. Dust in H II Region

In this section, we discuss the possible effect of dust grains in H II regions (e.g., Spitzer 1978). For example, the grains can be driven by the radiation pressure during the expansion of the H II region (e.g., Arthur et al. 2004). Arthur et al. (2004) have shown that small grains are destroyed by sublimation but that large graphite grains can exist close to the star. In contrast, the recent observation by Roger et al. (2004) found no far-infrared component correlated with the H II region Sh 170. Even in H II regions, photoelectric heating works at a level comparable to photoionization heating (Weingartner & Draine 2001) and is sensitive to the uncertain abundance of the small dust grains. If we adopt a dust absorption cross section in the H II region of $6 \times 10^{-22}$ cm$^2$ (H nucleon)$^{-1}$, which we adopt in the PDR and outer region, the radius of the H II region becomes slightly smaller, but the difference from the case without dust in the H II region is always less than 5%. The temperature in the PDR decreases by 10%–20% because of the attenuation of FUV photons by dust grains in the H II region. The gas density within the shell rises by a factor of 1.4–1.5. These changes in the shell, however, only slightly promote the accumulation of molecular gas. If we include the standard photoelectric heating rate and dust recombination cooling rate in the H II region (Bakes & Tielens 1994), the temperature near the central star in the H II region rises, but the temperature near the gas shell hardly changes. Therefore, the existence of dust grains does not significantly alter the results in this paper.

4.2. Fragmentation of the Shell

The triggered star formation scenario predicts that the shocked layer fragments and that these fragments collapse into stars of the second generation. Although the fragmentation of the shocked layer has been studied by many authors, it is still uncertain which instability actually occurs and which induces the next star formation. Here we assume that nongravitational instabilities (e.g., decelerating shock instability, DSI) themselves are not the essential ones for sequential star formation. Elmegreen (1989) showed that the gravitational instability couples with the DSI for the decelerating layer using linear analysis, but Mac Low & Norman (1993) pointed out that the DSI quickly saturates in the nonlinear phase.

However, Garcia-Segura & Franco (1996) showed that the DSI is strongly modified by the presence of the IF. The shell rapidly fragments and finger-like structures are formed in their two-dimensional calculation. Furthermore, the shadowing instability and corrugation instability of the IF were studied by Williams (1999, 2002), and these instabilities also can disturb the IF and the shell. Although these complexities are beyond the scope of this paper, it will be interesting to study the effect of these instabilities on the evolution of the DF and the postshock layer with two-dimensional or three-dimensional calculations in the future.

Elmegreen & Elmegreen (1978), Miyama et al. (1987), Lubow & Pringle (1993), and Nagai et al. (1998) have studied the stability of the dense gas layer and show that the earliest gravitational instability occurs with a wavelength comparable to the layer thickness and that the growth rate is $\sim (G\rho)^{-1/2}$. The calculated shell suffers from this instability, and the shaded region in Figure 2 represents the unstable region, where $t > (G\rho)^{-1/2}$. Although the mass scale at the maximum growth rate is comparatively small, $\sim \sigma t^2 \sim 1 M_\odot$, larger mass scale perturbation gradually develops in turn. As mentioned above, the gas density is higher in the outer part of the shell, and thus the unstable region extends from the outer edge to the inner part of the shell. By the age of Sh 104, 0.7 Myr, the outer part of the shell dominated by CO molecules becomes unstable. Therefore, dense molecular fragments are formed around H II regions and triggered star formation may occur in their cores, as DV03 shows.

4.3. The Role of This Triggering Process

Even if the molecular gas is successfully gathered around the H II region and triggered star formation actually occurs, its impact on global star formation is still uncertain. However, we can show its significance with a simple argument. In our galaxy, most of stars are formed in clusters (e.g., Evans 1999), and thus the feedback effects from massive stars are ubiquitous for global star formation. If every massive star gathers the molecular gas $M_{\text{sh}}$ on average and triggered star formation occurs within the shell, the induced star formation rate $SFR_{\text{H II}}$ is estimated as

$$SFR_{\text{H II}} \sim SFR_0 \left( \frac{M_{\text{av}}}{0.6 M_\odot} \right)^{-1} \left[ \frac{f (>20 M_\odot)}{0.0006} \right] \left( \frac{M_{\text{sh}}}{10^4 M_\odot} \right) \left( \frac{\epsilon}{0.1} \right),$$

where $SFR_0$ is the current total star formation rate in our galaxy, $M_{\text{av}}$ is the average stellar mass, $f (>20 M_\odot)$ is the number fraction of massive stars that create relatively large H II regions ($>20 M_\odot$), and $\epsilon$ is the star formation efficiency for the swept-up gas. The normalization values of $M_{\text{av}} \sim 0.6 M_\odot$ and $f (>20 M_\odot) \sim 0.0006$ are calculated with the initial mass function given by Miller & Scalo (1979). Equation (2) shows that if the average mass of the gas shell is $\sim 10^4 M_\odot$, this triggering process even alone can sustain the current Galactic star formation rate. In our calculation, molecular gas of $\sim 10^4 M_\odot$ is accumulated around one massive star owing to the expansion of the H II region by the time of $t \sim 1$ Myr. Therefore, this mode of triggered star formation should be an important process. The efficiency of triggering should depend on the physical conditions of the parent cloud, ambient density structure, and so on. For example, many H II regions show “blister-like” or “champagne flow” features (Tenorio-Tagle 1979). In these cases, the IF rapidly erodes the parental cloud and only a part of the swept-up mass remains within the shell, which might result in smaller $M_{\text{sh}}$ (e.g., Whitworth 1979; Franco et al. 1994). More realistic estimation including such cases will be explored in T. Hosokawa & S. Inutsuka (2005, in preparation).

5. CONCLUSION

We have calculated the dynamical expansion of the H II region and PDR around a massive star, focusing on the dense gas shell around the H II region. Our results are summarized as follows:

1. A dense gas shell is formed just in front of the IF, and this shell is initially atomic but gradually dominated by molecules. This is partly because the IF and SF overtakes the preceding DFs and the SF enters the molecular region, and partly because the reformation timescale within the shell becomes shorter than the dynamical time because of the high density of the shell.

2. The calculation successfully reproduces the observed properties of Sh 104. The mass of the shell and H II region and the location of the IF at $t \sim 0.7$ Myr agree with observation. Gravitational instability occurs after the gas shell is dominated by molecular gas. By the time of $t \sim 0.7$ Myr, a gravitationally...
unstable molecular shell is formed around the H\textsuperscript{ii} region, as observation shows.

3. In our calculation, a molecular gas shell of the order of $\sim 10^4 M_{\odot}$ is formed in 1 Myr around one massive star. With simple estimations, we show that the triggering process owing to the expansion of H\textsuperscript{ii} regions is important in the context of Galactic star formation.

We thank G. Tenorio-Tagle and Pepe Franco for the useful discussion at the international workshop "Gravitational Collapse: From Massive Stars to Planets" (Ensenada, 2003 December 8–12). We also greatly appreciate the helpful comments of Pepe as the referee of this paper. T. H. is supported in part by research fellowships of the Japan Society for the Promotion of Science for Young Scientists.

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