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MULTIPLE SUPERNOVA EXPLOSIONS INSIDE A WIND-BLOWN BUBBLE

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ABSTRACT

We calculate the evolution of multiple supernova (SN) explosions inside a pre-exiting bubble blown up by winds from massive stars, using one-dimensional hydrodynamic simulations including radiative cooling and thermal conduction effects. First, the development of the wind bubble driven by collective winds from multiple stars during the main sequence is calculated. Then multiple SN explosion is loaded at the center of the bubble and the evolution of the SN remnant is followed for 10^6 years. We find the size and mass of the SN-driven shell depend on the structure of the pre-existing wind bubble as well as the total SN explosion energy. Most of the explosion energy is lost via radiative cooling, while about 10% remains as kinetic energy and less than 10% as thermal energy of the expanding bubble shell. Thus the photoionization and heating by diffuse radiation emitted by the shock heated gas is the most dominant form of SN feedback into the surrounding interstellar medium.

Key words : stars:early type — stars:winds — supernova remnants — galaxies:ISM

I. INTRODUCTION

Massive stars affect the evolution of the interstellar medium (ISM) of galaxies through radiative and mechanical energy injection and chemical enrichment. While these stars typically have stellar radiation luminosity of $10^4 \lesssim L_*/L_\odot \lesssim 10^6$, they inject the mechanical energy into the ISM as stellar winds with speed of $v_w \sim 1000 - 3000$ km s^{-1} and a mass loss rate of $\dot{M}_w \sim 10^{-7} - 10^{-6}$ M$_\odot$ yr^{-1}, corresponding to $100 \lesssim L_{\rm wind}/L_\odot \lesssim 3000$ during the main sequence (MS) stage (Chu *et al.* 2004; Smith 2006). In addition, most of massive stars ($M_* \gtrsim 8M_\odot$) explode as core-collapse supernovae (SNe) and deposit typically $E_{SN} \sim 10^{51}$ ergs in the form of kinetic energy of the ejecta. Such feedback effects of massive stars play a fundamental role in the formation and evolution of galaxies.

In this work, we estimate the amount of energy feedback of core-collapse SNe, including multiple detonation, into the surrounding ISM, using numerical hydrodynamic simulations. First, we calculate the evolution of bubble structures driven by stellar winds from multiple stars ($N_{star} = 1-50$) during the MS stage. We then load multiple SN explosion at the center of the wind bubble created in the first step, and follow the evolution of the supernova remnant inside the pre-existing bubble. Quantitative feedback efficiency parameters, e_{th}, e_{kin}, e_{rad}, for the thermal, kinetic and radiation energy, respectively, are calculated.

An Eulerian hydrodynamics code for the ideal gas in 1D spherical geometry, implemented with radiative cooling and thermal conduction, is employed (Ryu *et al.* 1993). We adopt the non-equilibrium radiative cooling rate for optically thin gas of a solar-metalicity (Sutherland & Dopita 1993). Classical Spitzer conduction for a fully ionized gas (Spitzer 1962) is supplemented by the saturated heat transport in the limit of large temperature gradient (Cowie & Mckee 1977).

II. WIND BUBBLE STRUCTURES

We first consider the development of a wind bubble to study the pre-supernova circumstellar environment. Massive early-type stars emit a steady stellar wind with constant terminal velocity V_w and mass-loss rate $\dot{M}_w = dM_w/dt$. We assume that the progenitor stars have an initial mass $15M_\odot$ and spends $\Delta t_w = 4\times10^6 yr$ in the MS phase. The MS wind is characterized with a mass-loss rate, $\dot{M}_w = 2.5 \times 10^{-7}$ M$_\odot$ yr^{-1}, and wind velocity, $V_w = 2000$ km s^{-1} (Smith 2006). Here we consider only the MS wind stage. We select the number of stars, $N_{star} = 1, 5, 10, 30$ and 50, because a typical OB association contains 10-100 early-type stars (Tomisaka & Ikeuchi 1986; Tenorio-Tagle *et al.* 1990). The density of the ambient ISM is $n_{H,0} = 1$ cm^{-3} and $\rho_0 = (2.34 \times 10^{-24}$g). The ambient medium is assumed to be photoionized at $T_{\rm min} = 10^4$K. Therefore, its sound speed is $c_s = 14$ km s^{-1} and the pressure is $P_{ISM} = 2.3 \times 10^{-12}$erg cm^{-3}.

Fig. 1 shows the structure of the wind bubble blown by a single star ($N_{star} = 1$). The contact discontinuity (CD) between the shocked wind and the shocked ISM is around 23 pc, while the location of the conduction front (CF) is around 12 pc. Near the CD, the gas density increases by more than two orders of magnitude, so the gas cools quickly down to the minimum temperature $T_{\rm min} = 10^4$K and forms a shell with

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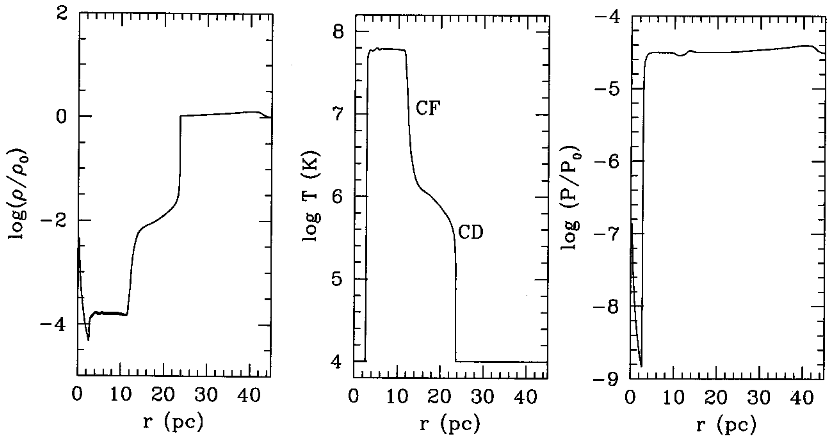

Fig. 1.— Gas density, temperature, and pressure profiles of the wind bubble driven by a single star at $t = 2.5 \times 10^6$ years. The density is given in units of $\rho_o = 2.34 \times 10^{-24}$g cm^{-3}, and the pressure in units of $P_o = 9.36 \times 10^{-8}$erg cm^{-3}.

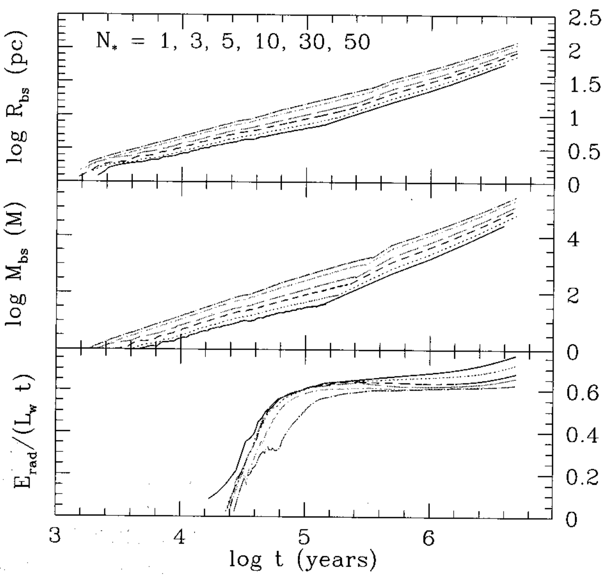

Fig. 2.— Outer radius (top panel) and mass (middle) of the wind-blown bubble shell, and the faction of energy lost due to radiative cooling (bottom) for the different number of stars, $N_{star} = 1$ (solid lines), 3 (dotted), 5 (dashed), 10 (long dashed), 30 (dot-dashed), and 50 (dot-long dashed) models.

the inner boundary at CD and the outer boundary at $R_{bs} \approx 42pc$. The thickness of the shell is rather thick (*e.g.*, . $\Delta R \sim 0.45 R_{bs}$ for the bubble shown in Fig. 1) because the wind does not effectively push out the shell. The continuous injection of wind energy seems to be radiated away efficiently near the conduction front owing to fast radiative cooling aided by thermal conduction. For a spherical shell with inner radius, $R_{bs,i} = \alpha R_{bs}$, outer radius, R_{bs}, and uniform density, n_{shell}, the density can be derived from the condition that the shell mass is equal to the swept-up mass: $n_{shell}/n_{H,0} \approx (1-\alpha^3)^{-1}$. So the density enhancement factor is small for thick shells found in our simulations. For the bubble shell shown in Fig. 1, for example, $\alpha \approx 0.55$ and $n_{shell}/n_{H,0} \approx 1.2$, only slightly higher than the ambient density.

Top two panels of Fig. 2 show the evolution of R_{bs} and swept-up mass, $M_{bs} = (4\pi/3)R_{bs}^3\rho_0$, for the wind bubbles driven by multiple stars. For our models with $L_w = (3.17 \times 10^{35}\text{ergs}^{-1}\ N_{star})$ and $n_{H,0} = 1$ cm^{-3}, the radius and mass of wind-blown bubble shell can be approximated by

$$R_{bs} \approx (22\text{pc}) N_{star}^{0.18} \left(\frac{t}{10^6\text{yrs}}\right)^{0.4}, \quad (1)$$

$$M_{sw} \approx (1.6 \times 10^3\ \text{M}_\odot) N_{star}^{0.54} \left(\frac{t}{10^6\text{yrs}}\right)^{1.2}. \quad (2)$$

These relations are slightly different from what Weaver et al. (1977) derived through simplified numerical integrations.

Bottom panel of Fig. 2 shows the fraction of energy lost due to radiative cooling. The radiation energy is calculated as the energy lost from the simulation volume, $E_{rad}(t) = L_w \cdot t + E_{tot,i} - E_{tot}(t)$, where $E_{tot} = E_k + E_{th}$ is the total energy inside the simulation volume and $E_{tot,i}$ is its initial value. The energy loss due to radiative cooling is significant: about 60-80 % of the total wind energy is radiated away from typical wind bubbles.

III. MULTIPLE SUPERNOVA REMNANTS

Next we calculate the evolution of multiple supernova explosion detonated inside the wind bubble that is calculated in the previous step. So we take the final structure of the wind bubble data at $t = 4 \times 10^6$ yrs, as the initial circumstellar state of progenitor stars. Each SN explosion is characterized by the explosion energy, $E_{ej} = 10^{51}$erg, and the ejecta mass, $M_{ej} = 10\ \text{M}_\odot$. For a multiple explosion where N_{SN} supernovae detonate simultaneously, total explosion energy $E_{SN} = N_{SN}E_{ej}$. The SN ejecta is approximated by a uniform density core and an outer envelope with a steep power-law density profile ($\rho \propto r^{-n}$, $n = 10$), expanding freely with the radial velocity, $v = r/t$ (Chevalier & Liang, 1989).

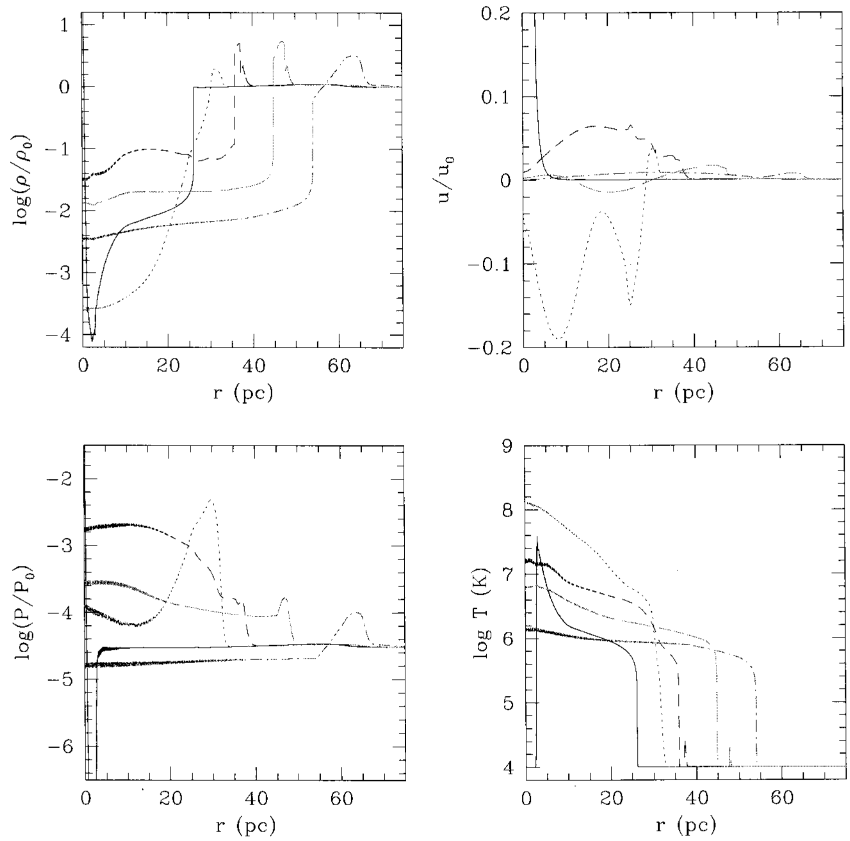

Fig. 3.— Evolution of the supernova remnant from a single SN detonated inside the pre-existing bubble shown in Fig. 1. Snap shots are shown at $t = 0$ (solid lines), 2. x 10^4 years (dotted), 9. x 10^4 years (dashed), 2.5 x 10^5 years (long dashed), and 9.5 x 10^5 years (dot-dashed). The normalization constants are : $\rho_o = 2.34 \times 10^{-24}$gcm^{-3}, $u_o = 2000$ km s^{-1}, and $P_o = 9.37 \times 10^{-8}$ergcm^{-3}.

Fig. 3 shows the radial profile of the SN remnant for the single SN case. Initially the wind termination shock is located at 3 pc and the hot cavity extends to 25 pc as seen in the black solid lines. The SN blast wave passes through the pressure barrier produced by the wind termination shock and travels quickly through the hot cavity. The forward shock first interacts with the bubble shell at $\sim 10^4$ years, pushing out the inner shell boundary and generating two secondary waves, i.e., a transmitted shock propagating outward into the bubble shell and a weak reflected compression wave moving inward into the ejecta. A reverse shock forms in the SN ejecta around 5 x 10^3 years and is reflected at the center around 7.5 x 10^3 years. Afterward it becomes a traveling compression wave, because the shock heated gas inside the cavity is hot. When this wave runs into the shell at $\sim 10^5$ years, the shell is heated for the second time. It travels in and out repeatedly by getting reflected both at the center and at the bubble shell, accelerating the shell outward.

Fig. 4 shows the evolution of the bubble properties for multiple SN models ($N_{SN} = 1, 3, 5$, and 10) inside a wind bubble generated by 10 massive stars. The radial position of the outermost shock, *i.e.*, outer boundary of the SN shell, increases as $R_{ss} \propto t^{0.6-0.8}$ before the arrival of the blast wave at the shell, and afterward it increases very slowly, $R_{ss} \propto t^{0.1-0.15}$. The size of SN-driven shells depends on both the SN explosion energy and the size of pre-existing wind bubbles. According to the numerical results shown in Fig. 4, for multiple SN explosions inside the wind-bubble driven by 10 stars, the radius and mass of the SN bubble shell can be approximated as R_{ss} and M_{ss} depends rather weakly on E_{SN},

$$R_{ss} \approx (85\mathrm{pc}) N_{SN}^{0.1}, \quad (3)$$

$$M_{ss} \approx (10^{4.8}\ \mathrm{M}_\odot) N_{SN}^{0.3}. \quad (4)$$

Lower three panels of Fig. 4 show how the different energy changes in time. Again the evolution of E_{th}, E_k, and E_{rad} indicates the complex thermalization history via shocks. The first major episode of radiative cooling occurs when the SN blast wave first hits the wind bubble at $t \sim 10^{4.5}$ years. When the compression wave generated by the reverse shock runs into the shell at $t \sim 10^{5.4}$ years, the shell is heated and compressed, leading to the second episode of rapid cooling. For the models considered here, about 80-90 % of E_{SN} is lost via radiative cooling within 10^6 years, while only 10 % remains as thermal energy and $\lesssim$10 % as kinetic energy.

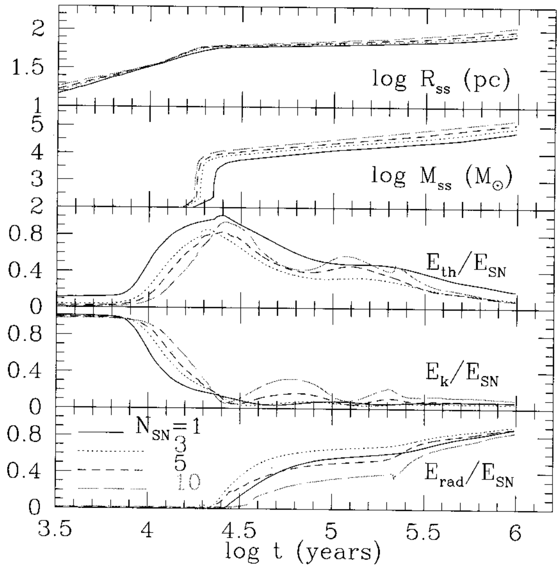

Fig. 4.— Radial position of the outer shock wave, swept-up mass of the SN-driven shell, thermal energy, kinetic energy, and the energy lost due to radiative cooling (from top to bottom, respectively) for the different number of supernovae, N_{SN}= 1 (solid lines), 3 (dotted), 5 (dashed), and 10 (long dashed) are shown.

IV. SUMMARY

We study multiple supernova (SN) explosions inside a pre-existing cavity blown up by stellar winds from massive progenitor stars during the main sequence stage through numerical hydrodynamic simulations. The growth of a bubble blown up by collective winds from an association of young massive stars is calculated first and then the evolution of the remnant from multiple SN explosion is followed. The evolution of such supernova remnants inside a wind bubble is much more complex than that in a uniform interstellar medium. It depends on the structure and size of the pre-existing bubble as well as the total explosion energy, $E_{SN} = N_{SN} \cdot 10^{51}$ ergs. At the termination time of the simulations ($t_f = 10^6$ years), the outer shock radius is $R_{ss} \approx 67$ pc for a single SN inside a bubble blown by one massive star. For multiple SN explosions inside a bubble produced by 10 massive stars, the size and mass of the shell increase rather weakly with the total explosion energy as $R_{ss} \approx (85\text{pc})N_{SN}^{0.1}$ and a mass of $M_{ss} \approx (10^{4.8}\ \mathrm{M}_\odot)N_{SN}^{0.3}$.

Kinetic energy of the SN is transfered to thermal energy via various shocks. About 20-60 % of the explosion energy is radiated away after the SN shock hits the wind bubble shell, and then 20-40 % is lost after the compression wave crushes into the shell later. Although the final energy budget at the termination time of our simulations depends on both the wind bubble structure and E_{SN}, in most cases the feedback efficiencies can be approximated as follows: $e_{rad} = E_{rad}/E_{SN} \approx 0.8-0.9$, $e_{th} = E_{th}/E_{SN} \sim 0.1$ and $e_k = E_k/E_{SN} \lesssim 0.1$. Consequently, it is obvious that the photoionization and heating is the most dominant form of SN feedback into the ISM. That should be implemented in a physically correct prescription for SN feedback in numerical simulations of galaxy formation.

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