Evolution of a Superbubble Driven by Sequential Supernova Explosions in a Plane-Stratified Gas Distribution

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Abstract

The evolution of a superbubble driven by sequential explosions of supernovae in an OB association is studied. We especially focus on the effect of the plane-stratified gas distribution in the direction perpendicular to the galactic disk. It is shown that the superbubble asymmetrically expands with respect to the parallel and perpendicular directions to the disk. In the case that the density on the disk plane, $n_0$, is $\sim 1 \text{ cm}^{-3}$, it is found that the cooled shell surrounds the hot cavity like an egg shape. On the other hand, in a low-density disk with $n_0 \sim 0.1 \text{ cm}^{-3}$, a cooled wall is formed only on the disk plane side of the bubble and the hot gas flows up to the halo region. This corresponds to the H I worms pointed out by Heiles (1984; A&A 38.155.014). We can show that the hot gas which is pushed up maintains the galactic hot gaseous halo.

Key words: Galactic structure; Interstellar matter; Superbubbles; Supernova remnants.

1. Introduction

In recent years, there has been increasing interest in studying active events in the interstellar medium such as superbubbles supershells. Superbubbles are observed simultaneously at several wavelengths, i.e., X-ray, UV, H$\alpha$, and H I 21-cm emissions. They have common characteristics that the X-ray emitting hot gas ($T \sim 2 \times 10^6 \text{ K}$) is surrounded by an H I shell, whose diameter reaches 250–450 pc. Three examples in the solar neighborhood have been reported: Cygnus superbubble (Cash et al. 1980), Orion-Eridanus region (Reynolds and Ogden 1979; Cowie et al. 1979), and Gum Nebula (Reynolds 1976). If we consider them as supernova remnants (SNRs), extremely large explosion energy is necessary ($\gtrsim 5 \times 10^{51} \text{ erg}$) due to their large size.

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Observed results are summarized in a paper by Tomisaka et al. (1981).

On the other hand, from the photographic representation of the galactic plane H\textsc{i} survey data, many H\textsc{i} shells have been found (Heiles 1979; Hu 1981). Heiles (1979) pointed out that there exist many supershells whose diameters reach 100 pc–l kpc. Further, Heiles (1984) reported recently that the spatial filtering applied to H\textsc{i} survey data reveals "worms" of gas-wiggly filaments which tend to run perpendicular to the galactic plane. He considered these "worms" of gas really shells with open tops.

On the origin of the superbubbles/supershells, several theories have been proposed. Because all examples of superbubbles contain OB associations in them, the energy source can be attributed to the OB associations. The kinetic energy is released from massive stars in an OB association in the form of stellar winds and supernova explosions (Bruhweiler et al. 1980; Tomisaka et al. 1981). Another model is based on the collision of high-velocity clouds with the galactic disk (Tenorio-Tagle 1981). Tenorio-Tagle (1981) argued that a large fraction of the kinetic energy of the high-velocity clouds ($10^{47}$–$10^{48}$ erg) is transferred to the ambient medium during the collision. The transferred energy maintains the required large energy to form superbubbles with $\geq 5 \times 10^{41}$ erg.

Based on the former model, Tomisaka et al. (1981; hereafter referred to as Paper I) have investigated the expansion law of the superbubble formed by sequential explosions of supernovae in an OB association. We summarize their results briefly. They assumed that the interval of supernova explosions is constant as $\Delta \tau$ and the superbubble expands into a homogeneous ambient medium. The expansion law of the shock front formed by sequential supernova explosions is obtained as follows:

$$ r_s = 64.3 n_s^{-0.29} t_s^{0.43} \text{ pc} \quad \text{(for } \Delta \tau = 2 \times 10^6 \text{ yr}) , $$  

where $n_s$ and $t_s$ represent the ambient density and the elapsed time in units of $10^6$ yr. The maximum radius of a superbubble for equation (1) is expressed as

$$ r_{\text{max}} = 164 n_s^{-0.46} \text{ pc} \quad \text{at} \quad t_{\text{max}} = 8.33 \times 10^6 n_s^{-0.46} \text{ yr} , $$

where we assume that at the final time the expansion speed of the shell, $dr_s/dt$, is slowed down to the random velocity of interstellar clouds $\approx 8$ km s$^{-1}$. With use of this equation, 12 stationary shells out of 15 and 3 expanding shells out of 9, which have the highest confidence level in Heiles's (1979) lists, are explained as the consequence of sequential explosions of supernovae in an OB association.

Even in the interstellar medium (ISM) whose density, $n_s$, is equal to 1 cm$^{-3}$, it is found that the superbubble expands and reaches $\approx 300$ pc in diameter, which is comparable to the scale height of the gas distribution in the direction perpendicular to the disk. Then, the effect of the density distribution should be important to the evolution. But the above one-dimensional calculations cannot include it. Therefore, taking the density distribution into account, we study the evolution of superbubbles in the plane-stratified ISM in the present paper.

The H\textsc{i} "worms" (Heiles 1984) appear as walls of a funnel, in which the hot gas heated by shock front flows upward to the halo region. The gaseous hot corona

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around our Galaxy has been observed by the IUE satellite (Savage and de Boer 1979). It should be studied carefully how the hot gas in the halo region is supplied from the galactic disk. We investigate the condition for forming the funnel or "worm" and heating the halo by the sequential explosions of supernovae.

The plan of this paper is as follows: In section 2, the model and numerical procedure are presented. The evolution may be much different between the OB association at high altitude and that at low altitude. Further, the consequence depends sensitively upon the density of ISM. We show numerical results for various altitudes of an OB association and interstellar densities in section 3. Section 4 is devoted to the discussion on the rate at which the hot gas is supplied to the halo and on the expansion law of the asymmetrical superbubbles.

2. Model and Numerical Procedure

Based on the model that the energy source of superbubbles consists of OB associations, the supernova rate in an OB association is one of the most important parameters. We begin with an estimation of the supernova explosion rate. It has been estimated as \( S_{\text{OB}} = 1/\Delta t \sim (1-5) \times 10^{-6} \text{ yr}^{-1} \) from the supernova rate in our Galaxy under the assumption that all of the type II supernovae originate in massive stars (Paper I). Further, Cowie et al. (1981) have derived the explosion rate in an OB association by using the number of early-type stars within the association as \( S_{\text{OB}} \sim 10^{-6} - 10^{-5} \text{ yr}^{-1} \). These two estimates agree with each other. Calculating the time variation of the supernova rate, using Salpeter's (1955) initial mass function and data on stellar lifetime calculation (Stothers and Chin 1979), we find that the supernova rate is nearly constant (variation within \( \approx 12\% \)) up to \( \sim 10^7 \text{ yr} \), at which the star with \( 10M_\odot \) ends its life. Therefore, we assume \( S_{\text{OB}} = 5 \times 10^{-6} \text{ yr}^{-1} \) constant throughout.

The kinetic luminosity inferred from the above supernova explosion rate is expressed as

\[
L_{\text{SN}} = S_{\text{OB}} E_{\text{SN}} \approx 1.6 \times 10^{85} \left(2 \times 10^5 \frac{\text{yr}}{\Delta t} E_{\text{SN}} / 10^{51} \text{ erg} \right) \text{ erg s}^{-1},
\]

in terms of the energy of a supernova explosion \( E_{\text{SN}} \). On the other hand, the total stellar wind luminosity emitted from early-type stars in an OB association has been estimated by Bruhweiler et al. (1980) for a typical one (Sco OB1) as

\[
L_w = N_{<B0} \frac{1}{2} \dot{M} V_w^2
\approx 3.5 \times 10^{37} \left( \frac{N_{<B0}}{28} \right) \left( \frac{\dot{M}}{10^{-6} M_\odot \text{ yr}^{-1}} \right) \left( \frac{V_w}{2 \times 10^8 \text{ km s}^{-1}} \right)^2 \text{ erg s}^{-1},
\]

where \( N_{<B0}, \dot{M}, \) and \( V_w \) represent, respectively, the number of stars earlier than B0 in an OB association, the average mass-loss rate, and the average wind velocity for stars earlier than B0.

When the supernova explosion rate is as high as \( 5 \times 10^{-6} \text{ yr}^{-1} \), the kinetic luminosity of supernova explosions predominates over that of the stellar wind. We take, therefore, in the present paper, \( S_{\text{OB}} = 5 \times 10^{-6} \text{ yr}^{-1} \), and ignore the effect of stellar
winds from OB stars. Although stars belonging to an OB association spread over \( \approx 20 \) pc, we assume for simplicity that explosions occur at the same point.

Next, we model the density distribution perpendicular to the galactic disk. We employ the hydrostatic equilibrium model of ISM derived by Fuchs and Thielheim (1979), who assumed that the ISM consists of two components: interstellar clouds and intercloud medium. The gas density \( n(z) \), where \( z \) is the coordinate perpendicular to the plane, is expressed as

\[
n(z) = n_0 \left\{ \theta \exp\left[ -\frac{V(z)}{\sigma_{10}^2} \right] + (1 - \theta) \exp\left[ -\frac{V(z)}{\sigma_C^2} \right] \right\},
\]

(5)

with the gravitational potential as

\[
V(z) = 68.6 \ln \left[ 1 + 0.9565 \sinh^2 \left( 0.758 \frac{z}{z_0} \right) \right] \quad \text{(km s}^{-1}\text{)}^2,
\]

(6)

where \( n_0, \theta, \sigma_{10}, \sigma_C, \) and \( z_0 \) represent the particle density at \( z=0 \) (central plane of the disk), the fraction of intercloud medium at \( z=0 \), the velocity dispersion of the intercloud medium, that of interstellar clouds, and the scale length of the potential. We adopt the values of these parameters as follows: \( \theta = 0.22, \sigma_{10} = 14.4 \) km s\(^{-1}\), \( \sigma_C = 7.1 \) km s\(^{-1}\), and \( z_0 = 124 \) pc according to Fuchs and Thielheim (1979). The density distribution is illustrated in figure 1. Although the distribution function (5) is based on the two-component ISM model, we assume that the gas is homogeneously distributed following equation (5), because the interstellar diffuse cloud will be evaporated when immersed in a hot cavity of the superbubble or struck by a shock front.

Each explosion of the type II supernova is assumed to release energy of \( E_{SN} = 10^{51} \) erg and eject a mass of \( M_{e0} = 10M_\odot \). Although the amount of the ejected mass is different for various masses of exploding stars, we assume it constant for simplicity.

Two other parameters are left unspecified, i.e., the height of the OB association, \( z_{OB} \), and the gas density at the central plane of the disk, \( n_0 \).

Having described our model, we proceed to the numerical procedure. The
Evolution of a Superbubble

The basic equations used in this investigation are hydrodynamical equations in the cylindrical coordinate system as

\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial z} (\rho v_r) + \frac{1}{r} \frac{\partial \rho}{\partial r} (r \rho v_r) = 0, \]  

\[ \frac{\partial p_z}{\partial t} + \frac{\partial}{\partial z} (p_z v_z) + \frac{1}{r} \frac{\partial}{\partial r} (r p_z v_r) = -\frac{\partial p}{\partial z} - \rho \frac{\partial V}{\partial z}, \]  

\[ \frac{\partial p_r}{\partial t} + \frac{\partial}{\partial z} (p_r v_z) + \frac{1}{r} \frac{\partial}{\partial r} (r p_r v_r) = -\frac{\partial p}{\partial r} - \rho \frac{\partial V}{\partial r}, \]  

\[ \frac{\partial e}{\partial t} + \frac{\partial}{\partial z} [(e+p)v_z] + \frac{1}{r} \frac{\partial}{\partial r} [r(e+p)v_r] = -\frac{\partial V}{\partial z} p_z - \frac{\partial V}{\partial r} p_r - \Lambda, \]

with

\[ e = \frac{p}{\gamma-1} + \frac{1}{2} \rho (v_z^2 + v_r^2), \]

\[ p_z = \rho v_z, \quad p_r = \rho v_r, \]

where \( e, (p_z, p_r), \) and \( \Lambda \) represent respectively the total energy, the linear momentum, and the radiative cooling rate per unit volume and the others have the usual meanings. The cooling function is taken from that of Raymond et al. (1976). We take here the adiabatic exponent as \( \gamma = 5/3. \)

We employ the two-dimensional MacCormack (1971) scheme as a numerical procedure, and the artificial viscosity of the third order (Lapidus 1967) is adopted in order to prevent the numerical instability. The number of numerical meshes in the z-direction is taken as 144 and in the r-direction as 72. The grid spacing can be variable and we take \( \Delta r = \Delta z = 5 \) pc in the case of \( n_0 = 1 \) cm\(^{-3} \) and \( \Delta r = \Delta z = 10 \) pc in the case of \( n_0 = 0.1 \) cm\(^{-3} \). The supernova explosion is initiated by depositing the energy \( E_{\text{SN}} \) at the center of an association at every \( \Delta t \). The energy is deposited as pure thermal energy in a small volume, which actually contains eight numerical cells \((2 \Delta r \times 4 \Delta z)\); this is the same as the method employed by Chevalier and Gardner (1974) and Bodenheimer et al. (1984).

The program was checked by running a model of an explosion \((E_{\text{SN}} = 10^{51} \text{ erg})\) in a uniform medium \((n_0 = 1 \text{ cm}^{-3})\). The remnant reaches the Sedov (1959) track by \( \approx 3 \times \) 10\(^4\) yr and moves to the radiative phase after \( \approx 5 \times \) 10\(^4\) yr. This result fits well that shown by Bodenheimer et al. (1984). The structure of the remnant in the adiabatic phase is compared with Sedov’s (1959) similarity solution. The pressures in the remnant agree with each other within \( \approx 8 \% \) error and especially those at the center of the remnant agree within \( \approx 2 \% \).

As the initial state, the ambient gas, whose density is taken as in equation (5), is set to be isothermal throughout the stratified medium as \( T = 100 \) K. Although this is not necessarily realistic, the evolution of a superbubble is hardly dependent on the gas temperature, as long as \( 10^3 \) K < \( T < 10^4 \) K.
Table 1. The adopted parameters and the final state.

<table>
<thead>
<tr>
<th>Case</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$z_{OB}$ (pc)</th>
<th>Age (Myr)</th>
<th>Size ($z_{np}$, $r$) (pc)</th>
<th>Energy ($E_{thr}$, $E_{kin}$) (10$^{52}$ erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>100</td>
<td>10.5</td>
<td>(488, 248)</td>
<td>(3.09, 2.83)</td>
</tr>
<tr>
<td>B*</td>
<td>1</td>
<td>100</td>
<td>4.5</td>
<td>(453, 248)</td>
<td>(16.4, 6.07)</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>0</td>
<td>10.5</td>
<td>(213, 218)</td>
<td>(1.21, 1.24)</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>200</td>
<td>7.5</td>
<td>(568, 263)</td>
<td>(3.33, 2.61)</td>
</tr>
<tr>
<td>E</td>
<td>0.1</td>
<td>100</td>
<td>5.5</td>
<td>(815, 335)</td>
<td>(4.53, 3.32)</td>
</tr>
<tr>
<td>F*</td>
<td>0.1</td>
<td>100</td>
<td>7.4</td>
<td>(975, 385)</td>
<td>(5.20, 4.03)</td>
</tr>
<tr>
<td>G</td>
<td>0.1</td>
<td>0</td>
<td>10.5</td>
<td>(955, 405)</td>
<td>(3.44, 2.85)</td>
</tr>
<tr>
<td>H</td>
<td>0.1</td>
<td>200</td>
<td>4.5</td>
<td>(915, 375)</td>
<td>(4.99, 3.37)</td>
</tr>
</tbody>
</table>

* Adiabatic bubble.
† With classical thermal conduction.

3. Results

We studied seven cases as summarized in table 1. First we describe the results in the case of $n_0=1$ cm$^{-3}$.

3.1. Cases of $n_0=1$ cm$^{-3}$

(a) $z_{OB}=100$ pc

The evolution of the superbubble in the case of $n_0=1$ cm$^{-3}$ and $z_{OB}=100$ pc (Case A) is shown in figure 2. After $t=1.5 \times 10^6$ yr have passed (figure 2a), the diameter of the superbubble reaches $\approx 200$ pc and the bubble expands almost spherically. (Numerical resolution causes at earlier times rather a square appearance of the remnant. This, however, here and in the test runs, soon approaches sphericity).

After that, the bubble departs from the spherical symmetry and the asymmetry between upward and downward directions grows apparently. Figure 2b shows the bubble at the age $t=4.5 \times 10^6$ yr. At that time the bubble is clearly egg-shaped, with an elongation factor $\varepsilon=(z_{up}-z_{OB})/(z_{OB}-z_{down})\approx 1.8$, where $z_{up}$ and $z_{down}$ represent respectively the heights of the shock front propagating upward and downward. A small projection at the upper z-axis is made numerically and has no physical meaning. We show sectional views along the z-axis ($r=0$) and along the line of $z=z_{OB}$ in figure 3. Upward and downward shock fronts are clearly shown as the points where the pressure (solid line) jumps to a higher value from the ambient value. The temperature in the shell (thickness $\approx 20-30$ pc) is lower than $10^4$ K. The bubble shows such a structure that the cooled dense shell surrounds the hot ($T \geq 10^6$ K) rarefied ($n \leq 10^{-3}$ cm$^{-3}$) gas (cavity), which is similar to that derived by one-dimensional simulation (Paper I). The density in the shell is not so high as ordinary supernova remnants (Chevalier 1974). This low compression is partly due to numerical resolution which smears out unresolved structures over several grid points. It is also due to low ram pressure by the inflowing matter at the shock front, which confines the matter to a thin shell. The latter is the same physical process as that in which the shell thickness becomes large at the latest stage of supernova remnants (Chevalier 1974). Further, the evolution
of the bubble is followed till $t \approx 10^7$ yr (figure 2c). At that time, the shell of the bubble reaches $z_{up} \approx 450$ pc, $z_{down} \approx -80$ pc, and $r \approx 250$ pc (in the $r$-direction), and the elongation factor attains $\varepsilon = 2.05$.

Next, to clarify the effect of radiative cooling to the evolution of a superbubble we compare the above result with the case without radiative cooling (Case B). We plot the profile of the bubble at $t = 4.5 \times 10^6$ yr in figure 4. It is shown that the adiabatic bubble expands twice as large as that in Case A in the linear extent, because there is no energy loss due to the radiative cooling in this case. We can see the pressure in the bubble is almost constant in contrast to figure 2. It is found that the clear distinction between the shell and the cavity in figure 2 is the consequence of the effective cooling at temperatures $10^5$ K $\leq T \leq 10^6$ K.

Radiative cooling plays an important role in the evolution of a superbubble. In fact almost all of its life is spent in the "isothermal expansion stage." That is the cool isothermal shell is pushed by the pressure in the cavity (Weaver et al. 1977) or it moves by conservation of its own momentum (Spitzer 1978).

The time variation of the height of the shell, $z_{up}$, is illustrated in figure 5 for Cases A–H, where the expansion law of the bubble expanding into the homogeneous medium (Paper I) is also shown for comparison. While $z_{up}$ in the homogeneous medium is expected as $\approx 300$ pc at $t = 10^7$ yr, actually it reaches $\approx 450$ pc in the present case. The difference comes from the fact that the shock front is decelerated only slowly because the shock propagates into the low-density medium. In addition, the expansion in the radial direction, which is indicated by the maximum radial distance of the shock front from the $z$-axis, agrees approximately with that derived in Paper I. We will turn back to the expansion law of the other cases and present empirical expansion laws in the following section.

(b) $z_{OB} = 0$ pc

Next we proceed to Case C, where the OB association is situated at the disk plane, $z_{OB} = 0$ pc. Because OB associations are observed almost near the disk plane, it is particularly interesting to investigate this case. We illustrate the bubble at $t = 10^7$ yr in figure 6. It is found that the size of the bubble is smaller than that in Case A and the asymmetry between the $z$-direction and the $r$-direction is much weaker than in the previous case.

This is a consequence of the fact that the density at the explosion site is high. Because of the high density at the explosion site, the expansion of the superbubble is dynamically suppressed and radiative cooling becomes effective in the dense matter. In other words, if the shock front propagates into the lower-density region at high altitude, both the deceleration due to the ambient matter and the radiative cooling at the post shock shell become inefficient and the bubble expands mainly upwards.

The diameter of the bubble reaches $\approx 250$ pc at $t = 3.5 \times 10^6$ yr due to $\sim 20$ supernova explosions and is comparable to the diameter of the superbubble in the Orion–Eridanus region and Gum Nebula.

We have shown two typical evolutions of the superbubble. The bubble driven by a low-altitude OB association is not seriously affected by the stratified density distribution. On the other hand, the bubble formed at $z_{OB} \geq 100$ pc expands asymmetrically, i.e., with elongation in the $z$-direction. Case D for $z_{OB} = 200$ pc, not illustrated,
Fig. 2. The evolution of the superbubbles in Case A \( (n_0 = 1 \text{ cm}^{-3} \) and \( z_{OB} = 100 \text{ pc} \). It shows the pressure contours in the cross section, where the contour levels (1–10) are written at the upper-right part of the panel. We also show the velocity fields by arrows, whose length is proportional to the absolute value of velocity. The scale of the arrow is presented in the fifth line at the upper-right corner. We show the bubbles at (a) \( t = 1.5 \times 10^6 \text{ yr} \), (b) \( t = 4.5 \times 10^6 \text{ yr} \), and (c) \( t = 9.5 \times 10^6 \text{ yr} \).

![Image of a diagram showing pressure and velocity contours]

Fig. 3. The sectional view along the z-axis \( (r=0) \) and along the line at \( z = z_{OB} \) at the stage of figure 2b for Case A.

![Image of a sectional view diagram]
Fig. 4. The same as in figure 2 but for the adiabatic bubble (without radiative cooling: Case B). The bubble at $t=4.5 \times 10^5$ yr, which is equal to the age of figure 2b, is shown. Comparing with figure 2b, we can see that radiative cooling has an important role to the evolution of a superbubble.

Fig. 5. The expansion law of the height of the shock front propagating upwardly, $z_{sp}$, for Cases A–H. Those for the bubbles expanding into the homogeneous medium with $n_0=1$ and $0.1 \text{ cm}^{-3}$ are shown for comparison.
Fig. 6. The same as in figure 2 but for Case C \( (z_{\text{OB}}=0 \text{ pc}) \) at \( 1.05 \times 10^7 \text{ yr} \). As is seen, the bubble is almost spherical in contrast to Case A.

shows an evolution similar to that of Case A.

3.2. Cases of \( n_0=0.1 \text{ cm}^{-3} \)

(a) \( z_{\text{OB}}=100 \text{ pc} \)

In this subsection, we describe the evolution of a superbubble in the low-density ambient medium with \( n_0=0.1 \text{ cm}^{-3} \). First, the result of Case E \( (z_{\text{OB}}=100 \text{ pc}) \) is presented.

At \( t=1.5 \times 10^6 \text{ yr} \), the bubble becomes elongated in the \( z \)-direction as \( z_{\text{up}} \approx 400 \text{ pc} \) and \( z_{\text{down}} \approx -100 \text{ pc} \). This trend increases more and more. The shock front reaches \( z_{\text{up}}=900 \text{ pc} \) at \( t=5.5 \times 10^6 \text{ yr} \). The structure at that time is shown in figure 7 and the sectional views along the \( z \)-axis and along the line of \( z=z_{\text{OB}} \) are presented in figure 8 (thick lines).

It is to be noticed that the cavity is not completely surrounded by the shell. In figure 8 (thick lines) we can see that the temperature in the upwardly moving shell
Fig. 7. The same as in figure 2 but for Case E (v_0=0.1 cm^{-1} and Z_{obs}=100 pc) at t=3.5 \times 10^5 yr. The shell is seen only in the lower part of the bubble (z \leq 200 pc). The upper part, where radiative cooling is inefficient, resembles the structure of the adiabatic bubble (figure 4).

Fig. 8. The same as in figure 3, but for Cases E and F at t=3.5 \times 10^5 yr. Thick lines represent the density (solid line) and the temperature (dashed line) for Case E. Thin lines represent those for the conductive bubble (Case F).
exceeds $10^6$ K. On the other hand, the downwardly moving shell is cooled below $10^5$ K. The shell exists only in the lower side, $z \leq 500$ pc. The upper part of the bubble shows a structure similar to the adiabatic bubble (figure 4). That is, the temperature varies only gradually and the pressure is almost constant inside the shock front. The density at that high altitude is so low as $n(z=500$ pc)$\approx 5 \times 10^{-3}$ cm$^{-3}$ that the cooling time ($\approx n^{-1}$) is longer than the expansion time. Therefore, radiative cooling becomes less efficient at that high altitude. This is a distinct contrast to the case of $n_e=1$ cm$^{-3}$, in which a shell-cavity structure is seen in all simulated cases ($0$ pc $\leq z_{ob} \leq 200$ pc). When the bubble expands higher in the z-direction, the deceleration becomes weaker and the shell expands still more; this is a positive feedback, which enhances the large scale deformation in comparison with the case of $n_e=1$ cm$^{-3}$ and $z_{ob}=100$ pc.

(b) Effect of thermal conduction

We describe here the effect of thermal conduction on the evolution of the superbubbles. We add the term of heat transport to the right-hand side of equation (10) as

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial z}[(e+p)v_z] + \frac{1}{r} \frac{\partial}{\partial r}[r(e+p)v_r] = -\frac{\partial V}{\partial z} p_x \frac{\partial V}{\partial r} p_r - \Lambda + \frac{\partial}{\partial z} \left( \kappa \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \kappa \frac{\partial T}{\partial r} \right), \tag{13}$$

where $\kappa$ represents the coefficient of thermal conductivity and we assume the classical conduction with $\kappa=6 \times 10^{-7} T^{2.5}$ erg cm$^{-1}$ s$^{-1}$ (Spitzer 1962).

In case F we include thermal conduction. Thermal conduction plays an important role in the hot rarefied medium. The temperature in the cavity becomes constant due to the rapid heat transport. Further, the temperature becomes lower and the density becomes higher in comparison with the nonconductive case, because the thermal energy is transferred from the hot cavity to the cooled shell and a part of the shell is evaporated by the heat flow. The sectional views of the bubble at $t=5.5 \times 10^8$ yr are also illustrated in figure 8 with thin lines. The temperature and density in the cavity are $T_{max} \sim 10^{6.5} - 10^{7.5}$ K and $n_{max} \sim (0.5-1) \times 10^{-3}$ cm$^{-3}$ (thin lines) compared with those in Case E, $T_{max} \sim 10^7.5$ K and $n_{max} \sim 5 \times 10^{-5}$ cm$^{-3}$ (thick lines). Although the structure in the cavity is different from Case E, the dynamical behavior such as the expansion law of the shell (figure 5) and the content of the thermal energy in the superbubble (table 1) are only slightly altered, even when we include the effect of thermal conduction. Therefore, we do not pursue further the effect of thermal conduction for other cases.

(c) $z_{ob}=0$ pc

As seen in the preceding section, the bubble is found to be almost spherical in the case of $z_{ob}=0$ pc and $n_e=1$ cm$^{-3}$. Is the evolution different in the case of $n_e=0.1$ cm$^{-3}$?

Before the epoch when the radius of the shock front reaches 200 pc ($t=1.5 \times 10^8$ yr; figure 9a), the bubble expands almost spherically. After that, the bubble becomes an elongated shape. At $t=4.5 \times 10^8$ yr (figure 9b), $z_{up}$ attains $\approx 400$ pc and a shell-cavity structure appears. The upper part of the bubble becomes similar to the adia-
Fig. 9. The same as in figure 2 but for Case G ($n_0=0.1 \text{ cm}^{-3}$ and $z_{OB}=0 \text{ pc}$) at (a) $t=1.5 \times 10^6 \text{ yr}$, (b) $t=4.5 \times 10^6 \text{ yr}$, and (c) $t=1.05 \times 10^7 \text{ yr}$. It is clearly seen that the spherical bubble is deformed to a funnel shape.
batic bubble, subsequently. We illustrate the bubble at $t \approx 10^7$ yr in figure 9c. It is found that the structure at this stage becomes like a duct flow and the shell is seen only in the lower part ($z \leq 500$ pc) like a cylindrical wall. The final structure of the superbubble is characterized by a funnel-like structure, i.e., the hot gas flows upward in the cylindrical pipe.

The bubble in Case E (figure 7) also seems to become this funnel-like structure. In Case H (not illustrated), a cooled shell is formed in the lower part, $z \leq 600$ pc and the upper part of the bubble shows an adiabatic bubble structure.

Summarizing the results of $n_0 = 0.1$ cm$^{-3}$ cases, a cooled shell is formed partially only below $z \leq 500$ pc and the hot gas is easily pushed up to $z > 1$ kpc.

4. Discussion

4.1. Heating of Halo by Superbubbles

As is shown in the preceding section, in the case of $n_0 = 0.1$ cm$^{-3}$ the superbubble reaches the height of $z_{up} \geq 1$ kpc and the hot gas in the cavity can flow freely upwards, because the cooled shell is formed only at low altitude. In the case of $n_0 = 1$ cm$^{-3}$, the outflow of hot gas from the disk is considered inefficient, because (1) the cooled shell surrounds the hot cavity, (2) the shock front expands only up to $z_{up} \sim 500$ pc, and (3) the volume fraction occupied with superbubbles is small. In contrast, the outflow of hot gas is probably more active in the case of $n_0 = 0.1$ cm$^{-3}$.

We investigate the possibility that the hot gas in the halo region, which is observed by absorption lines in the UV wavelength region (Savage and de Boer 1979), is supplied by the elongated superbubbles.

The outflow of heated gas from the galactic disk (wind) has been studied by many authors (Chevalier and Oegerle 1979; Bregman 1980; Habe and Ikeuchi 1980, hereafter referred to as HI). HI have shown that depending upon the temperature and density in the galactic disk whose half thickness is taken as 250 pc, there can be three types of hot gaseous haloes: the wind type, bound type, and cooled type.

First, we estimate the formation rate of OB associations in the Galaxy. Assuming that all type II supernovae originate in massive stars, the formation rate of OB associations is estimated as follows: (1) The explosion rate of type II supernovae is assumed to be $r_{II} \approx 0.01$ yr$^{-1}$ (Tammann 1977). (2) The fraction of early-type stars belonging to OB associations is asserted as $f_{OB} \approx 0.5-0.9$ (Cowie et al. 1979). (3) The total number of supernovae exploding in an OB association is estimated as $N \sim 100$ (Bruhweiler et al. 1980). Thus, the OB association is to be formed at a rate of

$$r_{OB} \approx \frac{r_{II} f_{OB}}{N} \sim 9 \times 10^{-8} \left( \frac{r_{II}}{0.01 \text{ yr}^{-1}} \right) \left( \frac{N}{100} \right)^{-1} \left( \frac{f_{OB}}{0.9} \right) \text{ yr}^{-1}. \tag{14}$$

Next, we should see how much fraction of the interstellar volume is occupied with superbubbles. Assuming that the superbubble forms a funnel with radius $R(t) \propto t^p$, the probability that an arbitrary point in the disk is inside a superbubble with the radius smaller than $R(t)$ is given by
\[ Q = \frac{S}{1 + 2\eta} \pi R(t)^2 \ t, \]  

(15)

where \( S \) represents the formation rate of superbubbles per unit surface. If all the OB associations show the activity of superbubble formation, the porosity \( Q \) is expressed by using the result that \( R(t) \) is well approximated by the expansion law of the superbubble in a homogeneous medium as in equation (1),

\[ Q = \frac{1}{1 + 2\eta} \left( \frac{R(t)}{R_0} \right)^2 t \]

\[ \approx 0.48 \left[ \frac{n(z_{OB})}{0.1 \text{ cm}^{-3}} \right]^{-0.52} \left( \frac{t}{10^7 \text{ yr}} \right)^{1.66} \left( \frac{R_G}{10 \text{ kpc}} \right)^{-0.7} \left( \frac{r_H}{0.01 \text{ yr}^{-1}} \right) \left( \frac{N}{100} \right)^{-1} \left( \frac{f_{OB}}{0.9} \right), \]  

(16)

where \( R_0 \) represents the radius of the disk in which OB associations are predominantly distributed and we take \( S = r_{OB}/(\pi R_0^2) \). This shows that a large fraction of the interstellar space is occupied by superbubbles in the case of \( n_0 = 0.1 \text{ cm}^{-3} \). In contrast, in the case of \( n_0 = 1 \text{ cm}^{-3} \) \( Q \) is no more than \( \approx 0.14 \) even when we overestimated the porosity in such a way that with \( n_0 = 1 \text{ cm}^{-3} \) the bubble actually does not form a funnel.

The density and temperature of the hot matter supplied to the halo are estimated by those of the gas in the cavity of the superbubble. In Case E, the density and temperature in the cavity are, respectively, \( n_{av} \sim 5 \times 10^{-5} \text{ cm}^{-3} \) and \( T_{av} \sim 10^7 \text{ K} \). The temperature far exceeds the critical temperature, \( T_c \) above which the gas can escape from the galaxy getting over the gravitational potential well:

\[ T_c = \frac{\gamma - 1}{\gamma} \frac{\mu m_p}{K} |\Phi(r, z=0)| \sim 2 \times 10^6 \text{ K} \]  

(17)

where \( \Phi \) represents the effective gravitational potential including the centrifugal force. Further the radiative cooling is ineffective in such rarefied gas \( (5 \times 10^{-5} \text{ cm}^{-3}) \). Therefore, the gas halo which is formed by the superbubbles will be a wind-type halo (HI). This is, however, an underestimation of the density in the cavity, because engulfed clouds and the dense shell are evaporated due to the effect of thermal conduction. We can see that in Case F, where the classical thermal conduction is included, \( n_{av} \sim (0.5-1) \times 10^{-5} \text{ cm}^{-3} \) and \( T_{av} \sim 10^6-10^6-10^7 \text{ K} \). When the gas flows out to the halo, it also forms the wind-type halo but the wind will be trapped if the massive halo is considered (HI).

Finally, we show the supply rate of thermal energy and that of mass to the halo. In Case G, the thermal energy which is sustained in the super-bubble or -funnel reaches \( E_{th} \sim 3 \times 10^{51} \text{ erg} \) after \( t = 10^7 \text{ yr} \) have passed. More fraction of the input energy is left in Cases E and H, because the radiative cooling is less effective.

The supply rate of the thermal energy to the halo will be

\[ \dot{E} \sim 9 \times 10^{38} \left( \frac{E_{th}}{3 \times 10^{51} \text{ erg}} \right) \left( \frac{r_{OB}}{9 \times 10^{-5} \text{ yr}^{-1}} \right) \text{ erg s}^{-1}. \]  

(18)

The mass-loss rate associated with the thermal energy supply becomes
\[ \dot{M} = \frac{2 \dot{E} \mu m_p}{3kT_{\text{eqv}}} \sim 0.22 \left( \frac{\dot{E}}{9 \times 10^{50} \text{ erg s}^{-1}} \right) \left( \frac{\mu}{0.61} \right) \left( \frac{T_{\text{eqv}}}{10^5 \text{ K}} \right)^{-1} M_\odot \text{ yr}^{-1}. \] (19)

Compared with the numerical result by HI in the case that \( (T, n) = (10^4.4 \text{ K}, 10^{-8} \text{ cm}^{-3}) \), the mass-loss rate derived here is 1/4 of that derived by HI \( (\approx 1 M_\odot \text{ yr}^{-1}) \). This is because HI assumed that the whole disk is occupied with such a hot gas. We have shown that the hot gas heated by the superbubble is pushed up through the funnel, even if the gas disk is not wholly occupied by the hot rarefied gas.

4.2. Expansion Law of Superbubbles

In this subsection, we derive an empirical expansion law of superbubbles from the numerical results. The expansion law of bubbles in a homogeneous medium is expressed as in equation (1). The evolution of the superbubble is similar to that of the stellar-wind bubble, when we consider the time span much longer than \( \Delta t \), because it is considered that the energy is released at a constant rate. Although several methods to solve this problem have been proposed as the similarity solution (Weaver et al. 1977) and the Laumbach–Probstein method (Sakashita and Hanami 1986), the effect of radiative cooling is, however, not fully included in them. Therefore, we attempt to obtain an empirical relation by using the numerical results.

The maximum radius of the bubble, which is reached at \( z \approx z_{\text{OB}} \), is well expressed by replacing \( n_a \) by \( n(z_{\text{OB}}) \) in equation (1). On the other hand, in the upward \( z \)-direction the shock front expands faster than that of equation (1), because it expands to the lower density region.

We found that the expansion law for \( z_{\text{up}} \) is well expressed in the following way: We replace \( n_a \) in equation (1) by the density in front of the shock wave propagating lower upward, i.e.,

\[ z_{\text{up}} = z_{\text{OB}} + r_s[n_a = n(z_{\text{up}})] = z_{\text{OB}} + 64.3[n(z_{\text{up}})]^{-0.28} \left( \frac{t}{10^5 \text{ yr}} \right)^{0.43} \text{ pc}. \] (20)

In comparison with the numerical result of the expansion law (figure 5), this empirical relation reproduces numerical results within the 2% error for \( t < t_{\text{crit}} \). The critical age, \( t_{\text{crit}} \), after which this empirical expansion law breaks down, is of the order of \( >10^7 \text{ yr} \) (Cases A and D), \( \approx 2 \times 10^6 \text{ yr} \) (Case G), \( 3 \times 10^6 \text{ yr} \) (Case E), or \( 4 \times 10^6 \text{ yr} \) (Case H). If we used equation (20) even after \( t_{\text{crit}} \), the shock front would be accelerated to blow out within a finite age, \( 6.8 \times 10^4, 5.3 \times 10^5, \) and \( 4 \times 10^6 \text{ yr} \) for Cases G, E, and H, respectively. We did not see actually such blowout in the numerical simulations.

We found that the critical age, \( t_{\text{crit}} \), is determined from the following condition:

\[ \left( \frac{\partial \ln z_{\text{up}}}{\partial \ln t} \right)_{t=t_{\text{crit}}} \approx 1. \] (21)

This means that equation (20) is suitable for the expansion law during the deceleration phase of the shock front propagating upward \( (\partial \ln z_{\text{up}}/\partial \ln t < 1; t < t_{\text{crit}}) \). As the structure of the bubble changes when the shock varies from deceleration to accelera-

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