SEQUENTIAL EXPLOSIONS OF SUPERNOVAE IN AN OB ASSOCIATION AND FORMATION OF A SUPERBUBBLE

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Abstract. From the standpoint of view that the early type stars are formed sequentially at an OB association, it is expected that the supernova explosions will also occur sequentially. We study the expansion law of a supernova remnant, which is formed by sequential explosions of supernovae. The superbubbles and supershells with the radii $200 \sim 1000$ pc are naturally explained by this model. Assuming that the sequential explosion of supernovae occurs at every OB association, we deduce the star formation rate in our Galaxy.

1. Introduction

From the X-ray data of HEAO-1, Cash *et al.* (1980) have indicated a prominent ring structure in the Cygnus region. The ring diameter is estimated to be $d \simeq 450$ pc, assuming the distance as $D \simeq 2$ kpc. Because of its large size, this X-ray emitting ring is named as a superbubble. Along the ring edge, two extended X-ray sources are confirmed, i.e., Cyg X-6 (Coleman *et al.*, 1971) and Cyg X-7 (Davidsen *et al.*, 1977). From the observed spectrum and emission measure, the temperature and the density of X-ray emitting gas are estimated as $T_x \simeq 2 \times 10^6$ K and $n_x \simeq 0.02$ cm^{-3}, respectively (Cash *et al.*, 1980). The X-ray ring has been found to coincide precisely with the ring-like distributions of Hα filaments (Ikhsanov, 1960; Dickel *et al.*, 1969) and of H I shell GS081-05-37 listed by Heiles (1979). These evidences suggest that all the H I, Hα and X-ray features may be common in origin. It is to be noted that the Cygnus OB2 association is situated in the center of this complex.

Moreover, two other similar objects are reported in the Gum nebula (Reynolds, 1976) and in the Orion-Eridanus constellation (Reynolds and Ogden, 1979; Cowie *et al.*, 1979). As summarized in Table I, these three are characterized by a large-scale extention of X-ray and/or Hα rings, as well as H I loops. It is indicated that these objects clearly associate with the OB associations. We consider that these objects are originated in the activities of OB associations and call them as superbubbles.

On the other hand, Heiles (1979) has examined the large-scale distributions of H I gas, and indicated that the H I gas does not distribute uniformly but does fragmentally as sheet-like or filamentary clouds, which constitute ridges or shells as a whole. He has divided these shells into two groups as expanding shells and stationary shells, and extremely huge ones he named as supershells. The expanding supershells expand systematically with the velocity $V \simeq 20$ km s^{-1}, and

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TABLE I

Observed results of three candidates of superbubbles. d and E_0 denote, respectively, the diameter and the estimated ejection energy.

Object	X-ray	Hα	H I	d(pc)	E_0(erg)
Cygnus superbubble	Yes $T \sim 2 \times 10^6$ K	Yes	Yes	450	$10^{52.4 \sim 54}$ [a]
Gum nebula	No	Yes	Yes	250	5×10^{51} [b]
Orion-Eridanus	Yes $T \sim (2 \sim 3) \times 10^6$ K	Yes	Yes	280	3×10^{52} [c]

[a] Cash *et al.* (1980), [b] Reynolds (1976), [c] Reynolds and Ogden (1979).

their radii range from 100 pc to 1 kpc. Their kinetic energies are estimated to be $10^{52.4} \sim 10^{54}$ erg. The stationary supershells do not show the systematic velocity in H I ridges, and their radii are about $10 \sim 800$ pc. If a stationary supershell is formed by a point explosion, the energy necessary for this extension is estimated as $10^{49} \sim 10^{53}$ erg (Heiles, 1979). It is to be noticed that several H I shells clearly correlate with OB associations, especially the supershell GS 081-05-37 is situated in the Cygnus OB2 association and coincides with the shell of the Cygnus superbubble.

Recently, it is pointed out that a considerable fraction of interstellar space is occupied by a hot, tenuous gas by the observations of diffuse X-ray background (Tanaka and Bleeker, 1977; Hayakawa *et al.*, 1978) and of O VI absorption lines (Jenkins, 1978). As the origin of this hot gas, either supernova explosions (Cox and Smith, 1974; McKee and Ostriker, 1977) or strong stellar winds of early type stars (Castor *et al.*, 1975; Weaver *et al.*, 1977) are suggested.

A single supernova explosion releases the energy of the order 10^{51} erg, and the final radius of the remnant is given (Chevalier, 1974) as

$$R_{\mathrm{SNR}} = 84.5(E_{51}/n_a^{1.12})^{0.32}\ \mathrm{pc}, \tag{1}$$

where n_a is the number density of ambient gas and E_{51} is the explosion energy in units of 10^{51} erg. On the other hand, the expansion law of a stellar bubble formed by a strong stellar wind is given (Weaver *et al.*, 1977) as

$$R_B \simeq 27(L_{36}/n_a)^{1/5}\, t_6^{3/5}\ \mathrm{pc}, \tag{2}$$

where L_{36} is the wind energy in units of 10^{36} erg s^{-1} and t_6 is the age of a bubble in units of 10^6 yr. Such a strong stellar wind is now confirmed (Conti, 1978; McCray and Snow, 1979) for an O-star with the mass, say, $\sim 20\, M_\odot$, whose lifetime is $\sim 10^7$ yr. In this case, the final radius of a hot bubble is $R_B \sim 107\, (L_{36}/n_a)^{1/5}$ pc.

Although these two will be efficient for the formation of hot interstellar gas, it seems to be impossible to form superbubbles and supershells so long as we consider a single event of a supernova or a stellar wind at the ambient gas of

$n_a \gtrsim 0.1\ \mathrm{cm}^{-3}$. However, if we consider the fact that superbubbles are formed at the OB associations and that the sequential star formation model at the OB associations is proposed (Elmegreen and Lada, 1977; Herbst and Assousa, 1977), the following alternative idea will be involved. When an OB association is formed at the edge of a molecular cloud, the massive stars within it evolve quickly with emitting strong winds and explode as type II supernovae. Then, the shock waves are generated and compress the cloud. At the compressed region, a new OB association is formed. In this way, the star formation continues till the molecular cloud is completely exhausted. Under this sequential star formation model, a number of massive stars are formed together, and stellar winds and supernova explosions occur collectively. Therefore, we should examine the formation of the hot gas region based upon such a model that stellar winds and supernova explosions occur sequentially at an OB association. In the preceding paper (Tomisaka *et al.*, 1980), we have studied the expansion law of a supernova remnant (SNR) when its progenitor exploded within a hot bubble. In the present paper, extending this calculation to the case when the supernovae explode sequentially within a cavity of an SNR, we investigate the formation of hot superbubbles and supershells. Similar models are already proposed by Bruhweiler *et al.* (1980) and Kafatos *et al.* (1980), but their studies are insufficient because they did not examine the expansion law in detail. Moreover, we can estimate the star formation rate in our Galaxy by using the present results.

In Section 2, the model and the fundamental equations are summarized. In Section 3, numerical results are summarized. In Section 4, the discussions on the formation of superbubbles and supershells are given, as well as on the star formation rate in our Galaxy.

2. Model Setting and Fundamental Equations

A typical OB association contains $20 \sim 100$ early-type stars (Blaauw, 1964). In such an OB association, the stellar winds from many earlier stars than the B0 type and the sequential supernova events may occur with complexity. At present, we study the following simple model, and after then we discuss the general case for interactions among stellar winds and supernova explosions.

At first, a stellar wind of the most massive star in the OB association continues for $\tau_B \simeq 3 \times 10^6$ yr and produces a wind bubble. In this wind phase, we assume the mass loss rate to be $\dot{M}_W = 10^{-6}\, M_\odot\ \mathrm{yr}^{-1}$ and the wind velocity to be $V_W = 2 \times 10^3\ \mathrm{km\ s}^{-1}$. Therefore, the ejection rate of kinetic energy is $L_K = 1.3 \times 10^{36}\ \mathrm{erg\ s}^{-1}$.

At the time τ_B of wind phase, we consider the first supernova explodes at the center and after then the supernova explosions occur sequentially at a rate S_{OB}. This supernova rate in an individual OB association is estimated under the assumption that all of the type II supernovae originate in massive (early type) stars as follows: (1) The supernova explosion rate in our Galaxy is assumed to be $S_G \cong 1/20\ \text{yr}^{-1}$ (Tammann, 1977). (2) The type II supernovae consist of the fraction $f_{II} \simeq 1/2$ of the total supernovae (Tammann, 1977). Then, the rate of type II supernovae in our Galaxy becomes $S_G f_{II} \sim 1/40\ \text{yr}^{-1}$. (3) The fraction of early type stars which belong to OB association is asserted as $f_{OB} \simeq 0.5 \sim 0.9$ (Cowie *et al.*, 1979). (4) The number of OB associations within 1 kpc from the Sun is reported to be 11 by Blaauw (1964). Then, the total number of OB associations in our Galaxy would be $N_{OB} \simeq (20\ \text{kpc}/1\ \text{kpc})^2 \times 11 = 4400$ as a rough estimation. Thus, the supernova explosion will occur in an OB association at a rate of

$$S_{OB} \simeq S_G f_{II} f_{OB}/N_{OB} \simeq (2.8 \sim 5.1) \times 10^{-6}\ \text{yr}^{-1}. \tag{3}$$

Then, the mean time-interval between repeated supernova explosions becomes $\Delta\tau = S_{OB}^{-1} \simeq (2 \sim 4) \times 10^5$ yr, which is enough shorter than the time necessary for an expanding shell to be destructed. Since $20 \sim 100$ early type stars are contained in an OB association, this sequential supernova phase will continue $\Delta\tau \times (20 \sim 100) \simeq (4 \sim 40) \times 10^6$ yr. We assume that all supernovae eject the energy $E_0 = 10^{51}$ ergs and $\Delta M \simeq 3\ M_\odot$. The ejected mass ΔM by a supernova explosion depends upon the mass of precursor star. However, the expansion of a supernova remnant at a late stage is independent of the value of ΔM as it follows from the following discussion: since the swept mass at the shock front is much greater than ΔM, the reacceleration by the impact of the ejecta is negligibly small. This means that the increase of density at the shock front due to the ejecta is also negligibly small. Therefore, the radiative cooling at the shell is not affected by the supernova ejecta.

The above model is calculated under the assumption of spherical symmetry, that is, the explosions are thought to occur at the same point. This assumption is verified when the radius of expanding shock front is enough large in comparison with the distance between supernova explosion points. While the size of superbubble that we investigate is larger than 100 pc, the mean separation between stars in an OB association is smaller than 20 pc.

The basic equations used in this investigation are

$$\frac{d\rho}{dt} + \rho \nabla \boldsymbol{v} = 0\,, \tag{4}$$

$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla p\,, \tag{5}$$

$$\rho \frac{dU}{dt} = -n^2\Lambda + \frac{p}{\rho}\frac{d\rho}{dt} + \nabla(\kappa \nabla T)\,, \tag{6}$$

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + (\boldsymbol{v}\nabla)\,; \tag{7}$$

and an equation of state, where U is the specific internal energy, $n^2\Lambda$ is the radiative loss per unit volume and κ is the coefficient of thermal conductivity. We assume the thermal conductions to be the classical one as $\kappa = \kappa_0 T^{5/2}$,

$\kappa_0 = 0.6 \times 10^{-6}$ erg cm^{-1} s^{-1} deg$^{-7/2}$ (Spitzer, 1962). The others have usual meanings.

As the cooling function, we adopt the analytic expressions of those calculated by Raymond *et al.* (1976), and Dalgarno and McCray (1972): i.e.,

$$\Lambda(T) = \begin{cases} 3.16 \times 10^{-28} T^{0.875} \text{ erg cm}^3 \text{ s}^{-1} (10^2 \text{ K} < T \leq 10^4 \text{ K}), & (8) \\ 1.00 \times 10^{-24} T^{0.55} \text{ erg cm}^3 \text{ s}^{-1} (10^4 \text{ K} < T \leq 10^5 \text{ K}), & (9) \\ 6.20 \times 10^{-19} T^{-0.6} \text{ erg cm}^3 \text{ s}^{-1} (10^5 \text{ K} < T \leq 4 \times 10^7 \text{ K}), & (10) \\ 2.24 \times 10^{-27} T^{+0.5} \text{ erg cm}^3 \text{ s}^{-1} (4 \times 10^7 \text{ K} < T). & (11) \end{cases}$$

The equation of state is $p = k\rho T/\mu H$ and $U = kT/(\gamma - 1)\mu H$, γ and μ being the adiabatic exponent ($\gamma = 5/3$) and the mean molecular weight ($\mu = 0.62$), respectively, and k and H being the Boltzmann constant and the proton mass. The equations are written in finite-difference form, and the spatial division is 50 to 200 meshes with equal size. An Eulerian code of the beam scheme is adopted from one written by Hirayama (1978). The other is the same as usual numerical calculations of spherical supernova remnants (e.g., Chevalier, 1974).

In the case of supernova explosion, the energy E_0 and the mass ΔM were deposited at the innermost cell as heat at every $\Delta\tau$. In the case of a stellar wind, the energy of $L_K\,\Delta t$, the mass of $\dot{M}_W\,\Delta t$, and the momentum of $\dot{M}_W\,V\,\Delta t$ were deposited at the innermost cell for every time step Δt.

We have studied two cases of supernova explosion rate, namely, lower rate $\Delta\tau = 10^6$ yr and higher one $\Delta\tau = 2 \times 10^5$ yr, and three cases of ambient matter, namely, ($n_a = 1.0$ cm^{-3}, $T_a = 10^4$ K), ($n_a = 10^{-1}$ cm^{-3}, $T_a = 10^4$ K) and ($n_a = 10^{-2}$ cm^{-3}, $T_a = 10^4$ K). We summarize the supernova explosion rate and the ambient density in Table II.

3. Numerical Results

3.1. Wind phase

The structures of the wind bubbles agree with the analytical ones by Weaver *et al.* (1977). Innermost region bounded by inward-facing shock is dominated by a stellar wind, outside it, there is a shocked wind region and outermost region is a cooled H I shell consisting of swept up interstellar material. The calculated expansion law of this bubble is approximated as

$$R_B = 18.5 n_a^{-0.29} t_6^{0.49} \text{ pc}, \qquad (12)$$

$$= 18.5\,(L_K/L_0)^{0.22} n_a^{-0.29} t_6^{0.49} \text{ pc}, \qquad (13)$$

where $L_0 = 1.3 \times 10^{36}$ erg s^{-1}. Equation (13) is derived from Equation (12) by use of the scaling law by Chevalier (1974), in which the energy scales as λ^{-2} and the time as λ^{-1} in varying the density as $n \to n\lambda^{-1}$. Therefore, we scale L as $L\lambda^{-1}$, and can determine the power index of L_K in Equation (13).

TABLE II

Summary of the numerical results. E_K and MV are the kinetic energy and momentum of expanding shell, respectively.

Case	n_a(cm^{-3})	t_6(yr)	R_s(pc)	V_s(km s^{-1})	E_K(erg)	MV(g cm s^{-1})
A	1.0	0	32	(16.0)		
		1.0	53	10.3	1.25×10^{49}	2.5×10^{43}
$\Delta\tau = 10^6$ yr		2.0	63	4.9	1.0×10^{49}	2.7×10^{43}
B	0.1	0	60	7.3	2.0×10^{48}	5.6×10^{42}
		1.0	105	21.0	5.8×10^{49}	5.5×10^{43}
		2.0	130	19.3	9.1×10^{49}	9.1×10^{43}
		3.0	147	17.7	1.1×10^{50}	1.2×10^{44}
$\Delta\tau = 10^6$ yr		10.1[a]	235	8.0	—	—
C	0.01	0	120	17.6	6.8×10^{48}	7.8×10^{42}
		1.0	190	41.9	1.5×10^{50}	6.1×10^{43}
		2.0	240	19.3	1.9×10^{50}	1.0×10^{44}
$\Delta\tau = 10^6$ yr		25.6[a]	602	8.0	—	—
D	1.0	0	32			
		0.5	50	27.2	1.3×10^{50}	7.9×10^{43}
		1.0	64	20.0	1.5×10^{50}	1.2×10^{44}
$\Delta\tau = 2 \times 10^5$ yr		8.83[a]	164	8.0	—	—
E	0.1	0	60	7.3	2.0×10^{48}	5.6×10^{42}
		0.5	93	57.3	2.8×10^{50}	9.2×10^{43}
		1.0	119	40.8	3.4×10^{50}	1.5×10^{44}
		1.7	149	35.3	4.9×10^{50}	2.5×10^{44}
$\Delta\tau = 2 \times 10^5$ yr		25.5[a]	474	8.0	—	—
F	0.01	0	120	17.6	6.8×10^{48}	7.8×10^{42}
		0.5	173	92.7	3.1×10^{50}	7.2×10^{43}
		1.0	215	87.3	6.5×10^{50}	1.5×10^{44}
		1.5	255	70.0	8.2×10^{50}	2.2×10^{44}
		2.0	289	66.5	9.5×10^{50}	2.9×10^{44}
$\Delta\tau = 2 \times 10^5$ yr		73.4[a]	1345	8.0	—	—

[a] Extrapolated final time when the expansion velocity becomes equal to the random velocity of intersteller clouds, 8 km s^{-1}.

This result should be compared with the expansion law derived by Steigman *et al.* (1975)

$$R_B = 17.2(L_{36}/n_a)^{1/4}(V_W/10^3 \text{ km s}^{-1})^{-1/4} t_6^{1/2} \text{ pc}, \tag{14}$$

under the assumption that the expanding shell will be driven directly by the momentum of stellar wind.

3.2. Supernova explosion phase

After the first supernova exploded, the shock front overtakes the expanding shell, which is formed by a stellar wind, and the shell expansion is accelerated. The structure of hot region is different from the one of an ordinary SNR before $t \lesssim 5 \times 10^5$ yr because the shock front does not reach the cooled shell.

In Figure 1, we illustrate the time variations of radii of expanding fronts. Here, the time is measured from the epoch when the first supernova exploded. From these results, the expansion law of shock front is expressed as:

Case A ($n_a = 1\ \mathrm{cm}^{-3}$, $\Delta\tau = 10^6$ yr)

$$R_s = 54.0 t_6^{0.25}\ \mathrm{pc}, \tag{15}$$

Case B ($n_a = 10^{-1}\ \mathrm{cm}^{-3}$, $\Delta\tau = 10^6$ yr),

Case C ($n_a = 10^{-2}\ \mathrm{cm}^{-3}$, $\Delta\tau = 10^6$ yr)

$$R_s = 55.7 n_a^{-0.26} t_6^{0.35}\ \mathrm{pc} \tag{16}$$

and

Case D ($n_a = 1\ \mathrm{cm}^{-3}$, $\Delta\tau = 2 \times 10^5$ yr),

Case E ($n_a = 10^{-1}\ \mathrm{cm}^{-3}$, $\Delta\tau = 2 \times 10^5$ yr),

Case F ($n_a = 10^{-2}\ \mathrm{cm}^{-3}$, $\Delta\tau = 2 \times 10^5$ yr)

$$R_s = 64.3 n_a^{-0.26} t_6^{0.43}\ \mathrm{pc}. \tag{17}$$

These analytical expressions of expansion laws well approximate the numerical results for the snowplow phase of shell expansion. In the case of a single supernova explosion, the expansion law at the snowplow phase is given by the momentum conservation as $R_s \propto t^{1/4}$ (Spitzer, 1968). This corresponds to the result

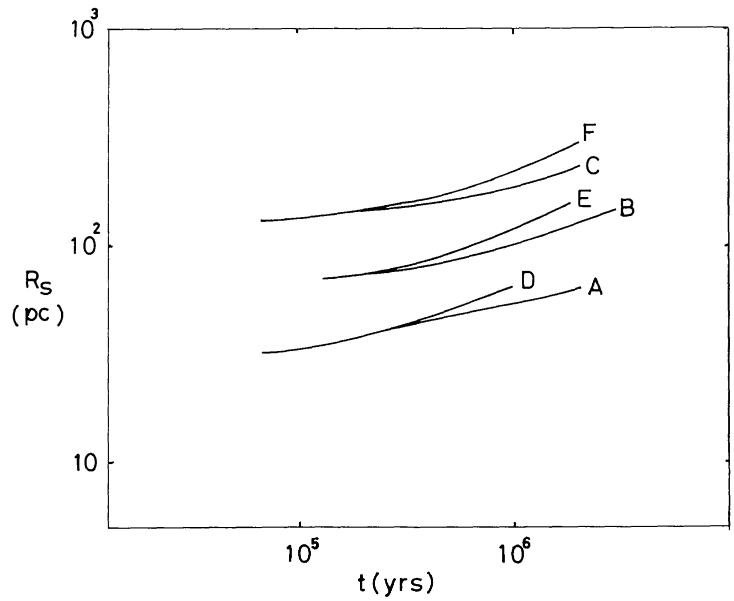

Fig. 1. The expansion laws of superbubbles for respective Cases A ~ F. The time is measured from the epoch when the first supernova exploded.

of Case A. When the pressure of the hot cavity $p_{\rm in}$ is predominant in comparison with that of ambient gas p_a, we must consider the pressure-driven expansion of shock front as $R_s \propto t^{2/7}$ (McKee and Ostriker, 1977). Moreover, the momentum injection to the shell due to the sequential supernova explosions accelerates the shell expansion further as $R_s \propto t^{1/3}$ in Equation (16). With decreasing the time interval $\Delta\tau$ of supernova explosions, the structure and evolution of a superbubble become similar to those for the continuous injection of energy (McCray and Snow, 1979). If we compare Equation (13) with (17), the result of sequential supernova explosion for $\Delta\tau = 2 \times 10^5$ yr nearly corresponds to the wind model of $L_K = 1.8 \times 10^{38}$ erg s^{-1}, while the energy release rate is $E_0/\Delta\tau \simeq 1.67 \times 10^{38}$ erg s^{-1}. These two results well agree. Therefore, we can expect the expansion law of the shell will be the same as that of stellar wind with the energy emitting rate $L_K \simeq E_0/\Delta\tau$ if $\Delta\tau \lesssim 10^5$ yr.

3.3. Final radius of a superbubble

By extrapolating the expansion laws (15) ~ (17) to the time when the expansion velocity of the shell $V_s = dR_s/dt$ becomes equal to the random velocity of interstellar clouds 8 km s^{-1} (Spitzer, 1968), we can obtain the radius and the age of the final phase of a superbubble as

$$R_c = 62 \text{ pc}, \tag{18}$$

$$t_c = 1.8 \times 10^6 \text{ yr}, \tag{19}$$

for Case A;

$$R_c = 91.5 n_a^{-0.40} \text{ pc}, \tag{20}$$

$$t_c = 3.96 \times 10^6 n_a^{-0.40} \text{ yr}, \tag{21}$$

for Cases B and C; and

$$R_c = 164 n_a^{-0.46} \text{ pc}, \tag{22}$$

$$t_c = 8.33 \times 10^6 n_a^{-0.46} \text{ yr}, \tag{23}$$

for Cases D, E and F. These are summarized in Table II.

As is seen, the superbubble observed at the Cygnus region is well explained when either $\Delta\tau = 2 \times 10^5$ yr and $n_a \leq 0.5$ cm^{-3} or $\Delta\tau = 10^6$ yr and $n_a \leq 0.1$ cm^{-3}. On the other hand, the smaller superbubbles at the Gum nebula and Orion-Eridanus region are reproduced even if $n_a = 1.0$ cm^{-3} when $\Delta\tau = 2 \times 10^5$ yr. As an example, we illustrate in Figure 2 the calculated structure of a superbubble for the case $\Delta\tau = 2 \times 10^5$ yr and $n_a = 0.1$ cm^{-3}. This result well reproduces the size and the temperature of X-ray emitting gas at the Orion-Eridanus region. Since the time after the first supernova explosion is ~1.8×10^6 yr, the total number of supernovae exploded there is 9.

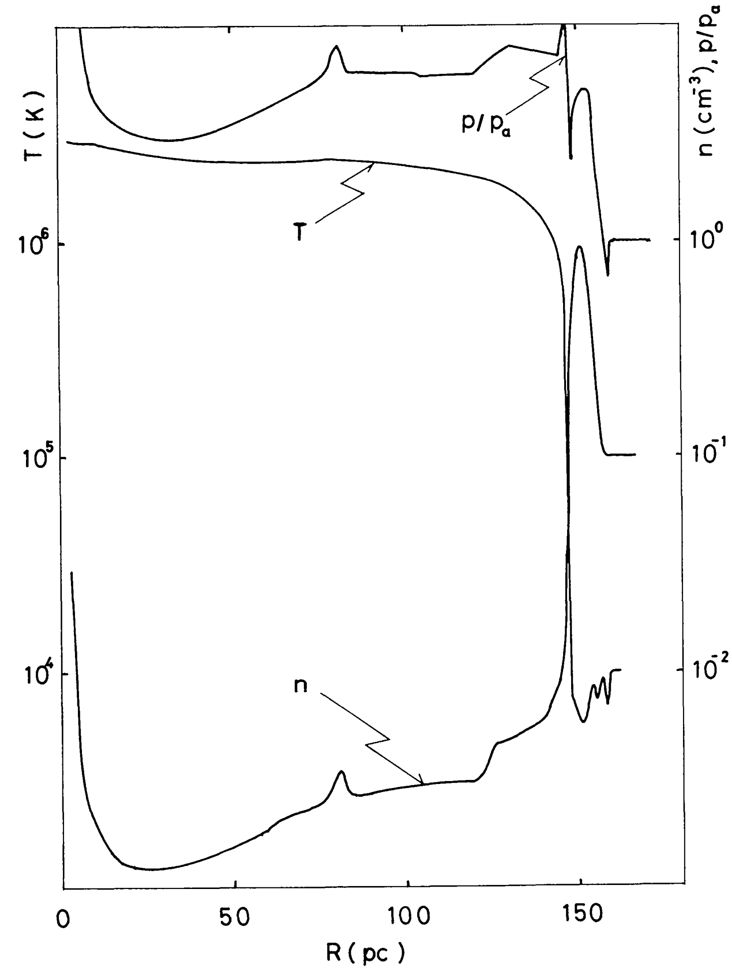

Fig. 2. The calculated structure of a superbubble for the case $\Delta\tau = 2 \times 10^5$ yr and $n_a = 0.1$ cm^{-3}. The time after the first supernova explosion is $\sim 1.8 \times 10^6$ yr.

4. Discussion

4.1. Supershells

In the previous section, we assume the final stage of a superbubble to be the time when $V_s = \mathrm{d}R_s/\mathrm{d}t$ is equal to the one-dimensional rms velocity of interstellar clouds. We should consider that at this stage the shell of a superbubble will be broken into fragments (clouds). These fragments will expand with the outward momentum until the swept-up interstellar medium becomes comparable to the mass of respective fragment. Then, each fragment will move away further about the distance

$$l \simeq (4\pi r n_s/3)/n_a \simeq N_H/n_a\,, \tag{24}$$

where r, n_s and N_H are the radius of a fragment, its density and its column density, respectively. We assume N_H to be equal to the average column density in observations of supershells as $N_H \simeq 10^{20}\,\mathrm{cm}^{-2}$ (Heiles, 1979), so that we obtain $l \simeq 30/n_a$ pc. In Figure 3, we plot the final radii of SNRs versus the ambient gas density n_a, in such a way that the curves (I), (II) and (III) show, respectively, R_{SNR} in Equation (1), R_c in (22) and $(R_c + l)$ in (22) and (24). As is seen, the H I shells and supershells pointed out by Heiles (1979) are well reproduced by the model considered in the present paper.

4.2. Variety of models

As is indicated in Section 1, the stellar winds and supernova explosions would occur with complexity in an OB association. Besides the calculated model, there may be several possibilities in the formation of superbubbles. (Case 1) The stellar winds from a number of O, B stars contribute simultaneously and produce a large bubble. We assume the number of O, B stars is n_{OB} and the n_g generations of groups of O, B stars are formed due to the sequential star formation. In this case, we may replace L_K by $n_{\mathrm{OB}} L_K$ and t by $n_g \tau_B$ in Equation (13). Then, the bubble

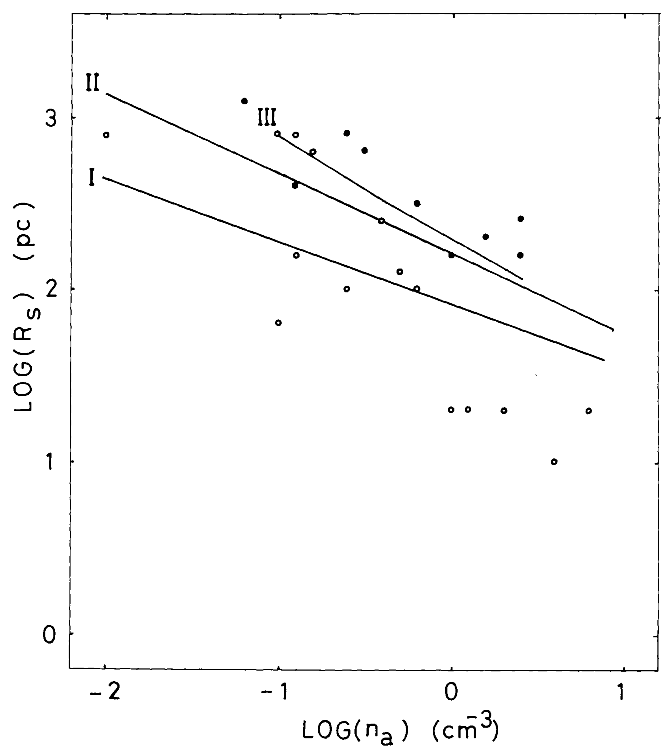

Fig. 3. Relations between the radii of H I shells and ambient gas densities. Dots and circles represent, respectively, the expanding shells and the stationary ones. The curves (I), (II) and (III) show, respectively, the final radius of an ordinary SNR (Equation (1)), the radius of the final phase of a superbubble (Equation (22)) and that of the fragmentary shell (Equations (22) and (24)).

radius becomes

$$R_B = 31.7 n_a^{-0.29} n_{\rm OB}^{0.22} n_g^{0.49}\ \mathrm{pc}\,, \tag{25}$$

if $\tau_B = 3\times10^6$ yr. If we take $n_{\rm OB} = 30$ and $n_g = 4$, this radius exceeds 130 pc, and the size of the Orion-Eridanus complex and/or Gum nebula are well explained even in $n_a \cong 1\ \mathrm{cm}^{-3}$. (Case 2) A superbubble is formed only by the sequential supernova explosions without contributions from stellar winds. If we take the number of supernovae as $n_{\rm SN} = t_{\rm age}/\Delta\tau$, $t_{\rm age}$ being the age of an OB association, the radius of shock front is given from Equation (17) as

$$R_s = 32.2 n_a^{-0.26} n_{\rm SN}^{0.43}\ \mathrm{pc}\,, \tag{26}$$

if $\Delta\tau = 2\times10^5$ yr. Since the number of supernovae in an OB association is considered to be the total number of O, B stars, we may take $n_{\rm SN} = n_{\rm OB} n_g$. If $n_{\rm SN} \simeq 60$, the Orion-Eridanus complex and the Gum nebula are explained also in this case. (Case 3) As the intermediate case of the above two, we can imagine the mixed contributions of stellar winds and supernova explosions. In this case, the expansion law of a superbubble is determined by the dominant energy source. That is, if $L_K > E_0/\Delta\tau$, the stellar wind dominates and the superbubble expands as $R \propto t^{1/2}$. If $L_K < E_0/\Delta\tau$, the superbubble looks like an SNR with the sequential supernova explosions.

Anyhow, the superbubble will be formed by activities of massive stars in an OB association, and its expansion law is described as $R \propto t^m$, $m = 0.25 \sim 0.50$ depending upon the ambient gas density and the supernova rate.

4.3. Star formation rate in OB associations

If we assume the superbubbles are formed in sequential supernova explosions, the star formation rate in OB associations in our Galaxy is deduced as follows. Taking the initial mass function as $f(m)\,\mathrm{d}m = Am^{-\alpha}\,\mathrm{d}m$ between the lower mass limit m_1 and the upper one m_2, the total number of supernovae in an OB association of the age $t_{\rm age}$ is given as

$$n_{\rm SN} = t_{\rm age}/\Delta\tau \simeq \int_{m_*}^{m_2} Am^{-\alpha}\,\mathrm{d}m\,. \tag{27}$$

where m_* is the smallest mass of a star which explodes as a supernova within the time $t_{\rm age}$. The star formation rate in this OB association is given as

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\rm OB} = \frac{1}{t_{\rm age}} \int_{m_1}^{m_2} mAm^{-\alpha}\,\mathrm{d}m\,. \tag{28}$$

Summing up the star formation rates of all OB associations in our Galaxy as $(\mathrm{d}M/\mathrm{d}t)_{\rm OB,G} = N_{\rm OB}(\mathrm{d}M/\mathrm{d}t)_{\rm OB}$, we obtain from Equations (27) and (28) that

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\rm OB,G} = N_{\rm OB}\frac{\alpha-1}{\alpha-2}\left(\frac{m_*}{m_1}\right)^{\alpha-2}\frac{m_*}{\Delta\tau}\,, \tag{29}$$

in which we assume $m_2 \gg m_1$ and m_*. We take $m_1 = 0.1\,M_\odot$, $\alpha = 2.25$ and $m_* = 8\,M_\odot$. This shows the rate of star formation occurred at OB associations, where the sequential supernova explosions occur with the mean time interval $\Delta\tau$.

Since three superbubbles are discovered within the distance 2 kpc from the Sun, the total number of superbubbles in our Galaxy will by $N_{\rm OB} \sim 3 \times 10^2$. Then the star formation rate in such active OB associations will be $(\mathrm{d}M/\mathrm{d}t)_{\rm OB,G} \cong 0.18\,M_\odot\,\mathrm{yr}^{-1}$ for $\Delta\tau = 2 \times 10^5$ yr.

On the other hand, if we use the expressions $\Delta\tau = S_{\rm OB}^{-1} \cong N_{\rm OB}(S_{\rm G} f_{\rm II} f_{\rm OB})^{-1}$ in Section 2, Equation (29) is rewritten as

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\rm OB,G} \simeq f_{\rm OB} f_{\rm II} \frac{\alpha - 1}{\alpha - 2} \left(\frac{m_*}{m_1}\right)^{\alpha - 2} \frac{m_*}{\tau_{\rm SN}} \qquad (30)$$

$$\sim 1.6\,M_\odot\,\mathrm{yr}^{-1}.$$

In comparison with the star formation rate $1 \sim 4\,M_\odot\,\mathrm{yr}^{-1}$ evaluated by Tinsley (1976), we may conclude that a considerable portion of the stars in our Galaxy are formed in OB associations.

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