Bulge Formation by Starbursts in Young Galaxies

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ABSTRACT

We have studied the bulge formation process by starbursts in young disk galaxies whose disks and halos are gas-rich. If such galaxies tidally encounter another galaxies, large starbursts are easily induced and create galactic superwinds. We study the interaction between the superwind and the halo gas by using a similarity solution and show that a massive, radiativelly-cooled, gaseous shell is formed and becomes gravitationally unstable. In this way, we expect that shells of stars are formed. In order to study further evolution of these shells and their interaction with the disk, we model both the shell and the disk by using an N-body code. Our numerical results show that a large bulge with de Vaucouleurs' density profile is formed from the shell. We also show that the disk is thickened due to the interaction with the shell. The large bulges and thick disks are very similar to these found in S0 galaxies.

1 INTRODUCTION

Starburst galaxies release huge energy by frequent supernovae. In some starburst galaxies, hot gas and molecular outflows are observed. These outflows are called superwinds (Heckman *et al.* 1990; Tomisakak and Ikeuchi 1988; Mac Low and McCray 1989). Since some starburst galaxies are interacting galaxies, it was proposed that the starbursts occurs due to gravitational interaction between galaxies (*e.g.* Noguchi 1988). Such interactions induce bar formation in a galaxy, and the subsequent gas inflow towards the galactic center, as a result of gas-bar interaction and due to the self-gravity in the gas (*e.g.* Wada and Habe 1990).

In an early universe, since galaxies are young and have much more gas than now, galactic encounters induce even more violent star formation, causing large energy releases. We investigate the effects of these starbursts on the host galaxies. In section 2, we investigate the evolution of a superwind produced by violent starbursts, by using the similarity solution, and demonstrate that the superwind can produce a large-scale cold gaseous shell in the halo and can become gravitationally unstable. We can expect the star formation in this gaseous shell. In section 3, we show the numerical simulation of a shell of stars produced by the gravitational instability in the gaseous shell. We demonstrate that the shell evolves into a large bulge-like structure and gravitational interaction between the shell and the disk changes the structure of the disk which fattens. These numerical results suggest the explanation for the distribution of S0 galaxies in clusters, if starbursts favor denser regions and if the shells of stars are formed from large gaseous shells driven by superwinds.

2 SUPERWINDS PRODUCED BY STARBURSTS

We show the propagation of a shock induced by energy release from many supernovae in a starburst galaxy. The similarity solution is given by Umemura and Ikeuchi (1987). In this solution, there is a critical energy over which the halo gas is blown out,

$$L_{\rm w,cr} = 8.9 \times 10^{42} \left(\frac{n_{\rm c}}{0.01\ {\rm cm}^{-3}}\right) \left(\frac{r_{\rm c}}{10\ {\rm kpc}}\right)^{1/2} \ {\rm erg\ s}^{-1},$$

where the halo gas is assumed to have $n_{\rm g}(r) = n_{\rm c}(r/r_{\rm c})^{-1/2}$. This energy corresponds to 1 supernova per year with $\epsilon = 0.1-$ the efficiency of supernovae-to-outflow energy conversion factor, and is larger than the energy released in nearby starburst galaxies. With this energy, the shock wave propagates the distance of $R_{\rm s} = 7.6(t/10^8\ {\rm yr})^{2/3}$ kpc, where t is age of the shock wave. We adopt this case as a typical one. Next, we consider the radiative cooling effects on the shock wave. The condition $t_{\rm cool} < t$ for the shocked gas is, $t > 0.7{\times}10^6(n_{\rm c}/0.01\ {\rm cm}^{-3})^{-0.58}(r_{\rm c}/10\ {\rm kpc})^{-0.29}$ yr. where $t_{\rm cool}$ is the radiative cooling time of shocked gas at the shock front. If this condition is satisfied, a radiatively-cooled shell is formed and the halo gas is swept-up. When this shell becomes massive enough, it will be gravitationally unstable. The energy condition of self-gravitational instability is given by Ostriker and Cowie (1980), $E_{\rm tot} < 0$, where $E_{\rm tot}$ is the total energy of a part of the shell in the comoving frame, and is defined by $E_{\rm tot} = E_{\rm k} + E_{\rm g} + E_{\rm T}$, where $E_{\rm k}$, $E_{\rm g}$ and $E_{\rm T}$ are kinetic, self-gravitational, and thermal energy in this part of the gas shell. Hence,

$$t_{\rm cr} = 1.6. \times 10^8 \left(\frac{n_{\rm c}}{0.01\ {\rm cm}^{-3}}\right)^{-3/4} \left(\frac{r_{\rm c}}{10\ {\rm kpc}}\right)^{-3/8} \ {\rm yr},$$

$$M_{\rm s}(t_{\rm cr}) = 2.6 \times 10^{10} \left(\frac{n_{\rm c}}{0.01\ {\rm cm}^{-3}}\right)^{-1/4} \left(\frac{r_{\rm c}}{10\ {\rm kpc}}\right)^{-1/8} \ {\rm M}_\odot,$$

and

$$R_{\rm s}(t_{\rm cr}) = 10.7 \left(\frac{n_{\rm c}}{0.01\ {\rm cm}^{-3}}\right)^{-1/2} \left(\frac{r_{\rm c}}{10\ {\rm kpc}}\right)^{-1/4} \ {\rm kpc}.$$

Under these conditions the large shell becomes gravitationally unstable. Although the star formation efficiency is uncertain, the massive shell of stars is expected to be formed. Note, that a high efficiency of star formation has been suggested in the central star cluster (Lada *et al.* 1985). After stellar shell formation, it falls onto the disk, changing its shape and going through relaxation process. If the shell is massive enough, its gravity affects the galactic structure. Below, we investigate these dynamical effects.

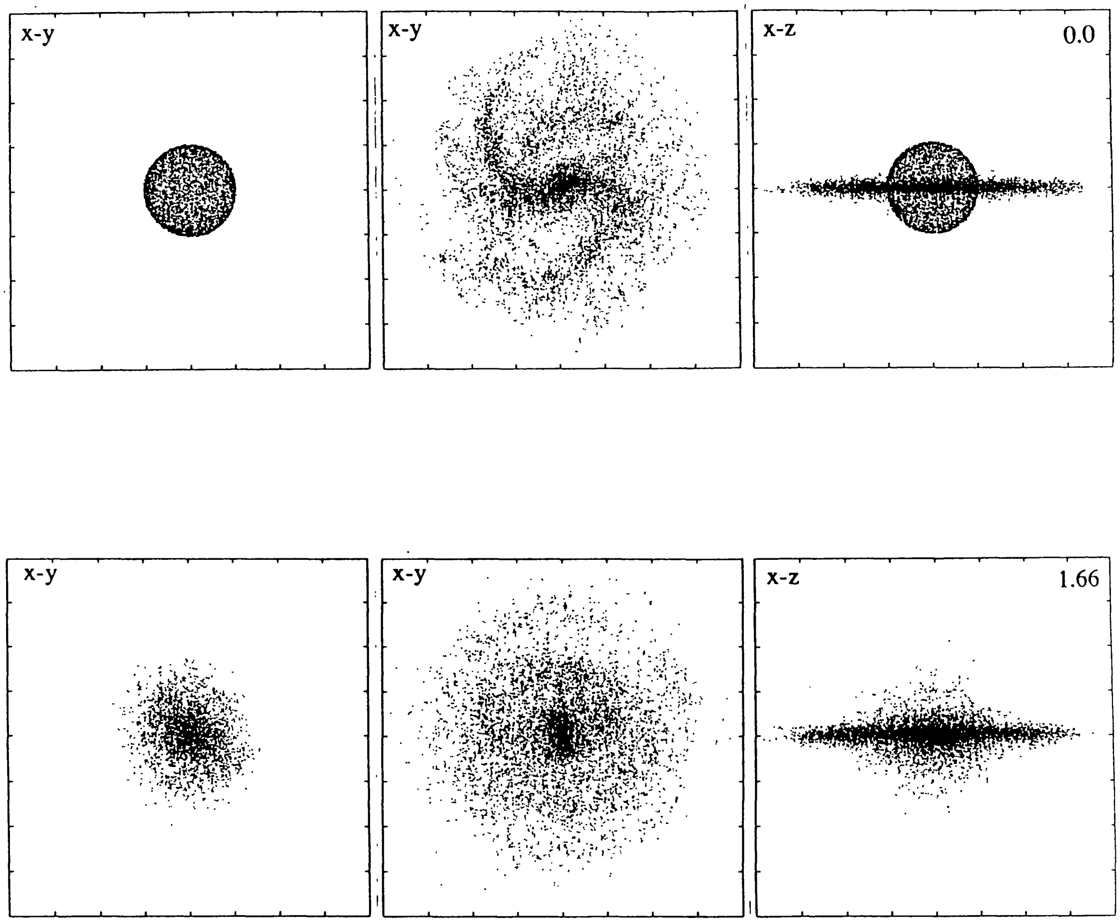

Fig. 1—Time evolution of a shell of stars and a disk. Left, center and right panels show the shell projected onto the disk, the shell component and both the shell and disk components, respectively.

3 *N*-BODY SIMULATION OF A SHELL OF STARS AND A LIVE DISK

In order to investigate the evolution of stellar shell formed by superwinds in the starburst galaxies as well as the effect of shell's gravity on the disk, we simulate both the shell of stars and the stellar disk. Our main assumptions are as follows:
Initially, the disk is thin and the central bulge is absent. We set a stellar disk to be stable according to Ostriker and Peebles criterion (Ostriker and Peebles 1973), by assuming a massive dark halo as a static potential and subsequently confirm that it is stable by using *N*-body simulations. Initial shell of stars is spherical and its mass

is $0.2 - 0.5M_d$. We use $N_s = 2,000 - 5,000$ for the shell component and $N_d = 10,000$ for the disk component.

We use a workstation with the GRAPE-3 board, which is a special purpose hardware for calculating gravitational interactions between particles by the direct method. Its peak speed is 15 Gflops. We use the Runge-Kutta method for time integration. The softening length is 100 pc.

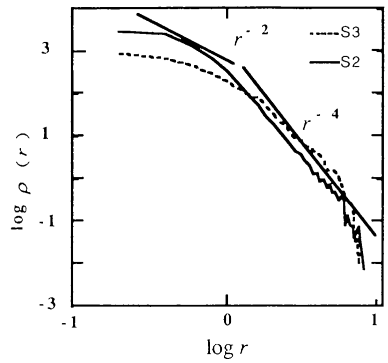

Fig. 2—The density distribution of final state for the fat stellar component.

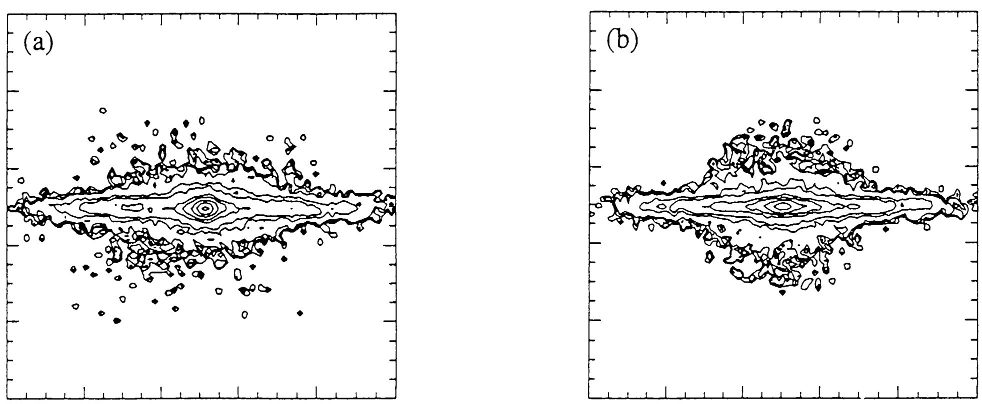

Fig. 3—The final isodensity contours for our models. Left panel shows only disk component; right panel shows disk and shell components.

We show one of our results in Figure 1. Initially, there is a weak spiral wave in the disk. Figure 1 shows the density wave in disk component induced by the gravity of the shell after it passes through the disk. Finally, a large fat stellar system and a thick stellar disk are formed. Figure 2 shows the density distribution of the fat stellar system. The fat stellar system rotates, as a result of gravitational interaction with the disk component. As in numerical simulation of a violent relaxation of a stellar system, core and halo structure are found. The density distribution of fat stellar system is similar to the 1/4 law of de Vaucouleurs (1948). We show the isodensity contours of our numerical results in Figure 3.

4 SUMMARY AND DISCUSSION

We study the effect of the starburst on the galactic structure in young galaxies. Since the galaxy encounters are frequent during cluster of galaxies formation, the starbursts are expected to be frequent as well. These starbursts are very energetic, since the young galaxies retain much gas in the disk and the halo.

We show that the energy released by many supernovae can create a superwind, and a large gaseous shell is formed due to the interaction between the superwind and the gas in the halo. We examine gravitational stability of the gaseous shell in a radiative cooling stage. We show that the gaseous shell can be gravitationally unstable and a shell of stars is formed. We simulate the evolution of both the large shell of stars and the stellar disk. We show that the evolution leads to a large bulge and a thick disk. Final structures of model galaxies resemble the S0 galaxies. If starbursts are induced by galaxy encounters, the process must be more efficient in a galaxy-crowded region. This process can explain the density-dependent morphology (Dressler 1980).

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