1992PASJ...44..325S

PASJ: Publ. Astron. Soc. Japan **44**, 325–329 (1992)

Note

Formation of Galactic Bulges by Starbursts and the Origin of Hubble Morphological Types

Yoshiaki SOFUE
Institute of Astronomy, The University of Tokyo, Mitaka, Tokyo 181
and
Asao HABE
Department of Physics, Hokkaido University, Sapporo, Hokkaido 060

(Received 1991 November 11; accepted 1992 February 29)

Abstract

We point out a possibility that a significant fraction of galactic bulge stars are formed from gas clouds ejected by starbursts in the central regions of galaxies. Stronger bursts result in larger and more extended bulges, and therefore lead to early type galaxies, and vice versa. The Hubble morphological types can be understood in terms of primeval starburst history of individual galaxies. Since the burst strength depends on the strength of tidal interaction, Hubble types inevitably depend on the galaxian number density, which explains the density-morphology relation.

Key words: Galaxies: evolution — Galactic bulge — Hubble type — Galaxies: morphology — Starburst

1. Introduction

Starbursts are thought to be the consequence of gas accretion toward central regions of galaxies, and are enhanced by tidal encounters with surrounding galaxies (Noguchi 1987, 1988). Starburst galaxies are associated with gas outflows which contain a significant amount of molecular clouds. Examples of such molecular and dust outflows can be seen in M82, NGC 253, NGC 1808, etc. (Lynds and Sandage 1963; Véron-Cetty and Véron 1985; Nakai et al. 1987; Sofue 1987). An extremely high rate of star formation and large-scale gas ejection in the central region may significantly affect galaxy evolution. In particular, starbursts in primeval galaxies, which must have been much richer in gas than today, may play an essential role in the formation of central bulges and, accordingly in determining the Hubble types of individual galaxies.

There have been two standpoints regarding the formation of central bulges of galaxies: (1) one is the primeval origin hypothesis in which the bulges are formed during the initial spherical contraction of proto galactic clouds and on-going star formation (Eggen et al. 1962); (2) the other is that bulges can be formed by the concentration of disk stars toward the central region by a non-linear response in a bar potential, and subsequent "heating" of stellar orbits near the center (e.g., Pfenniger and Norman 1990).

In this paper we present a new possible scenario in which a significant fraction of bulge stars are formed by starburst activity. We also suggest that the Hubble types could be explained in terms of a history of starbursts in the primeval stage of individual galaxies.

2. Formation of Galactic Bulges by Starbursts

The most typical case of starburst is seen in galaxy M82, which has been extensively studied in various wavelength ranges (Rieke et al. 1980; Nakai et al. 1987; Sofue 1988; Telesco 1988). This galaxy contains a large amount of molecular gas in the central kpc region. A cylindrical outflow of dense molecular clouds has been observed, which is ejected from the disk at a velocity of several hundred km s^{-1} (Nakai et al. 1987). It contains low-temperature, dense molecular gas clouds with a total H_2 mass as large as $10^7 M_\odot$. The gas density is so high that CO emission is optically thick. The velocity dispersion in the cylinder is as large as ~ 100 km s^{-1}. In such a turbulent state, strong cloud-cloud collisions take place and the shock compression of clouds is enhanced. Moreover, efficient star formation occurs in such shock-compressed clouds (Fujimoto and Kumai 1991). Thus, a molecular outflow associated with starburst in a gas rich galaxy can become an active site for star formation. If stars are born in such outflowing gas clouds, they will initially attain high-velocities perpendicular to the disk plane, and form an extended stellar system around the center, which could become a central "bulge" of the galaxy. Similar, but much larger-scale bursts, are thought to have taken place in primeval galaxies, which might play a role in producing central bulges of galaxies.

1992PASJ...44..325S

By analogy and scaling from M82, we try to estimate the total mass ($M_{\rm B}$) of the central "bulge" of burst origin, as follows:

$$M_{\rm B} \sim \eta_{\rm SF} \frac{dM_{\rm ej}}{dt} \tau_{\rm B}, \tag{1}$$

where

$$\frac{dM_{\rm ej}}{dt} \sim \mu_{\rm ej} \left(\frac{dM_{\rm ej}}{dt} \right)_{\rm M82}. \tag{2}$$

Here, $M_{\rm ej}$ is the mass of gas ejected by a primeval burst. The parameter $\eta_{\rm SF}$ is the star-formation efficiency from the ejected gas clouds, and is defined by the ratio of the mass fraction of born stars and the total ejected gas; it may be taken as $\sim$ 0.01–0.1. The time scale ($\tau_{\rm B}$) is the burst duration. The parameter $\mu_{\rm ej}$ is the efficiency of gas ejection, normalized by that of M82. This quantity could be simply approximated as

$$\mu_{\rm ej} \sim \frac{M_{\rm G}}{M_{\rm M82}}, \tag{3}$$

although it seems more likely that this efficiency is larger in the bursting phase of a primeval galaxy. Here, $M_{\rm G}$ and $M_{\rm M82}$ are the total masses of the concerned galaxy and that of M82, respectively. The ejection rate of gas in M82 is estimated to be

$$\left(\frac{dM_{\rm ej}}{dt} \right)_{\rm M82} \sim \frac{M_{\rm ej}}{\tau_{\rm ej}}, \tag{4}$$

with $M_{\rm ej} \sim 10^7 M_\odot$ and $\tau_{\rm ej} \sim 10^6$ yr (Nakai et al. 1987). As is shown later, since a primeval starburst lasts for a billion years, $\tau_{\rm bs} \sim 10^9$ yr. Hence, for a galaxy of mass $M_{\rm G} \sim 10^{11} M_\odot$, we obtain a total mass of a "bulge" of burst origin as $M_{\rm B} \sim 10^9 - 10^{10} M_\odot$.

Namely, about 1 to 10% of the galaxy mass is occupied by the central bulge; this seems to be reasonable for a normal disk galaxy (Miyamato and Nagai 1975; Yoshizawa and Wakamatsu 1975). The bulge mass depends on the parameter $\mu_{\rm ej}$, which might be larger in some cases (as mentioned above); larger bulges may result in such cases. Considering the uncetainty involved in the parameters, it may be possible to produce a bulge with a mass fraction from 1% (late type disk galaxies) to 30% (early type), which is the range observed by Yoshizawa and Wakamatsu (1975).

We next discuss the energetics of bulge stars in order to determine whether their extent of one to a few kpc can be maintained by the kinetic energy given by the starburst ejection. The kinetic energy given to the ejected gas, and therefore to the bulge stars, can be estimated as

$$E_{\rm kin} \sim \eta_{\rm PBSF} M_{\rm n.g.d.} \xi_{\rm SN} E_{\rm SN}, \tag{5}$$

where $\eta_{\rm PBSF}$ is the star-formation efficiency in primeval galaxies, $M_{\rm n.g.d.}$ the mass of the nuclear gas disk where the primeval star burst takes place ($\xi_{\rm SN}$) is the number of supernova explosions per mass of formed stars; $E_{\rm SN}$ is the kinetic energy released by a single SN explosion. We may take $\eta_{\rm PBSF} \sim 0.1$, $M_{\rm n.g.d.} \sim M_{\rm n.g.d.M82} \times \frac{M_{\rm G}}{M_{\rm M82}}, \xi_{\rm SN} \sim 1 - 10/(100 M_\odot)$, and $E_{\rm SN} \sim 10^{51}$ ergs. For $M_{\rm n.g.d.M82} \sim 10^{8-9} M_\odot$, we obtain $E_{\rm kin} \sim 10^{57-58}$ ergs. Since a significant fraction of this kinetic energy is given to the ejection of gas outflow, from which the bulge stars form, the velocities of stars can be roughly estimated by

$$V_{\rm bulge} \sim \sqrt{\frac{2 \times E_{\rm kin}}{M_{\rm B}}} \sim 100\text{–}300 \ {\rm km\ s^{-1}}. \tag{6}$$

We may thus consider that the stars formed from the ejected gas can have an extent of one to a few kpc from the galactic center because of their high velocity dispersion. We may here recall that the ejection velocity of molecular gas in star burst galaxy M82 is about 300 to 500 km s^{-1}, and that the gas already extends for more than one kpc above the galactic plane (Nakai et al. 1987).

In order to see how high-velocity stars behave in the central region of a galaxy, we carried out a simulation to follow the motions of stars (test particles) in the central area of a Miyamoto-Nagai potential, which represents the gravitational field for a realistic disk galaxy (Miyamoto and Nagai 1975; Nagai and Miyamoto 1976). We assume two components: one is an oblate disk of mass $10^{11} M_\odot$ with radial and z-directional scale lengths of 5 and 0.5 kpc, respectively. The second component is a central round component with a scale radius of 0.5 kpc and having a mass of 1% of the disk mass. In our simulation, the masses and potentials of the two components are fixed. Although they, particularly the central component, should actually evolve in mass, our simulation would give a good approximation as long as the bulge mass is sufficiently small compared to the total mass, i.e., it is smaller than 10% of the disk mass.

We assume that clouds are ejected at random from a rotating torus into a semi-conical cylinder. In addition to the rotational and vertical velocities along the cylinder, the clouds are given a velocity dispersion. Stars are born from these clouds, and orbit around the galactic center according to their initial velocities at their birth positions.

Figure 1a shows the distribution of thus-formed stars, where the ejection took place from a torus of radius 500 pc and width 100 pc, which mimicks a scale-up version (twice in size) of the starbursting torus in M82. The ejections occurred into a semi-conical cylinder with an opening angle 30°. The ejection velocity and velocity dispersion are 200 and 100 km s^{-1}, respectively. An extended stellar system with a broad cylindrical shape or a "boxy bulge" of a full vertical extent of about 0.8 kpc

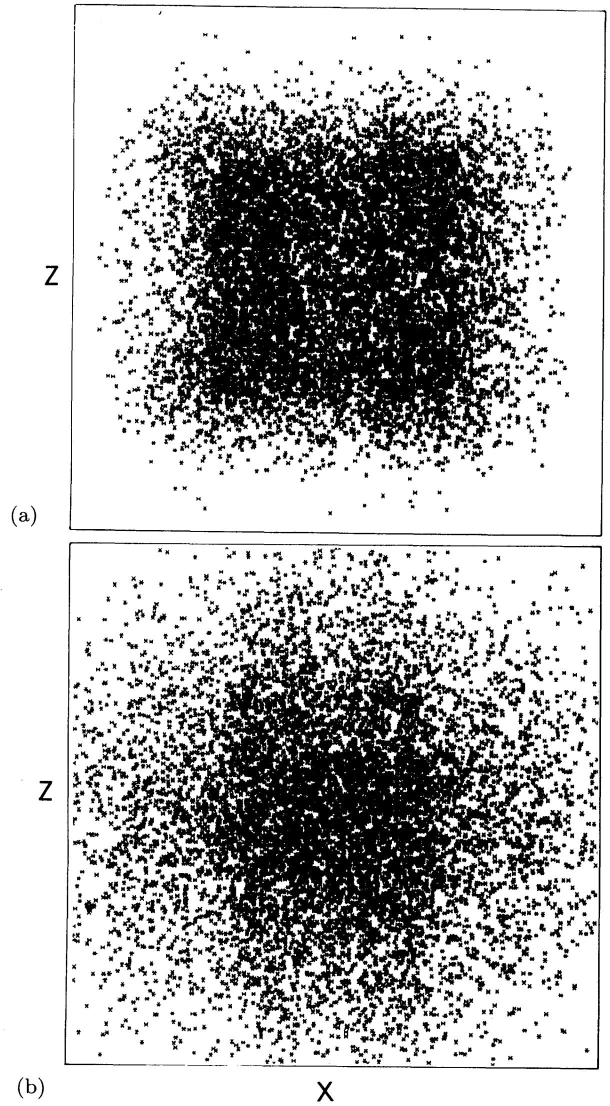

Fig. 1. (a) A boxy galactic bulge is formed by stars which were born in gas clouds ejected from a rotating torus into a semi-conical cylinder driven by a starburst. The X- and Z-axes are the galactic plane and rotation axis, respectively, and the box size is about 4 × 4 kpc. (b) The same as (a), but if the ejection is isotropic, a spherical bulge is formed.

is formed. If the torus radius becomes smaller and the ratio of velocity dispersion to ejection velocity becomes larger, the bulge shape becomes more spherical. We show in figure 1b the case for isotropic ejection from the central region with a velocity dispersion of 200 km s^{-1} . Figures 2a and b show a superposition of simulated bulges on an artificial disk of stars moving in the same potential with a smaller velocity dispersion in the z-direction (perpendicular to the disk plane) in order to obtain some impression of how galaxies with such bulges might look.

In the present simulation the shapes of the formed bulges are stable, since the gravitational potential is given. However, if selfgravity is taken into account, the relaxation process within the system would change the shape. This process must be analyzed by a self-gravitating N-body simulation under the existence of a rotating galactic disk as well as under the existence of a bar structure; this remains a future problem.

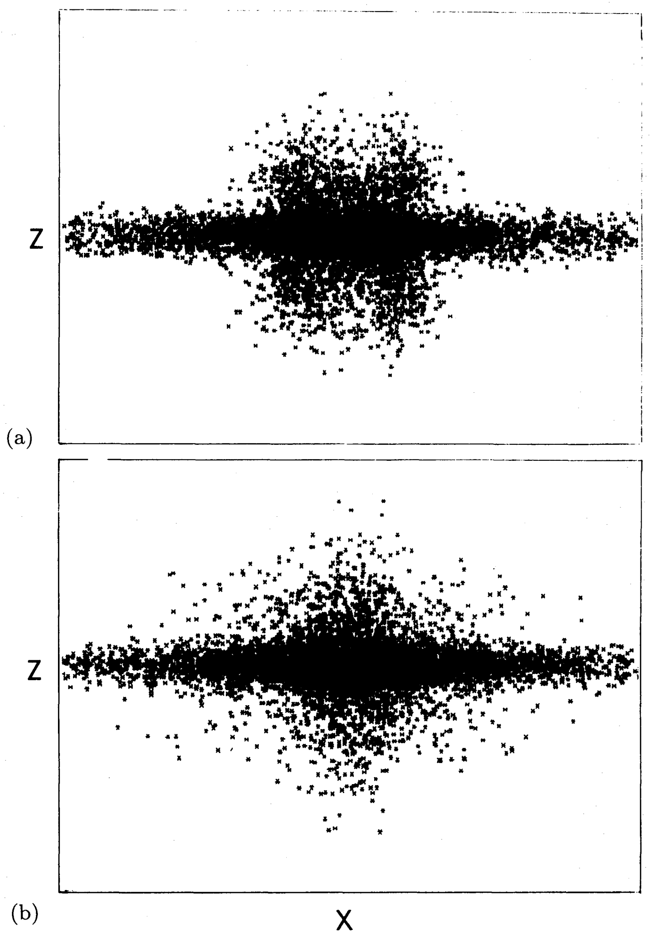

Fig. 2. Superposition of (a) a boxy bulge and (b) a spherical bulge on an artificial disk. The horizontal size of the box is about 12 kpc.

3. Primeval Bursts and Galaxy Morphology

We may now draw a scenario for a morphological evolution of galaxies based on the assumption that galactic bulges are formed by primeval starburts: Galaxies are formed by the gravitational contraction of protogalactic gas clouds during the early universe as rotating disks of gas; the protogalaxies are already clustering in a protocluster. The principal mass distributions of individual galaxies are determined by the viscous inflow and the ongoing star formation model (Yoshii and Sommer-Larsen 1989). Here, we do not assume a rapid contraction of the bulge component alone prior to disk formation (Larson 1974).

If galaxies are formed in high galaxy-density regions (HGDR), they experience frequent tidal encounters. The encouters trigger accretion of gas toward the central region by a bar-shock mechanism (Sϕrensen et al. 1976; Noguchi 1987, 1988); further concentration of gas in the central region may be induced by gravitational instability of this accumulated gas (Wada and Habe 1991). Hence, an intense burst of star formation is expected to occur in such primeval galaxies in HGDR, which we call a primeval burst (PB). On the other hand, in low galaxy-density regions (LGDR), tidal encounters are less frequent and gas accretion is correspondingly weaker. Therefore, the galaxies experience weaker PB.

Primeval bursts may be similar to the burst in M82, but must be much stronger, since M82 is a small-mass galaxy of only about $\sim 10^{10} M_{\odot}$, while normal-mass proto-galaxies should be tens-times more massive and should contain a much greater amount of gas. Accordingly, they should be associated with intense gas ejection. Star formation in such outflowing gas clouds may result in the formation of central bulges (as discussed above). The stronger is PB, the larger is the ejection velocity of clouds and, therefore, the larger becomes the bulge size. Hence, galaxies that experienced stronger PB tend to have larger bulges than do those that experience a gentler evolution. If a galaxy is born in a very low galaxy-density region, where the tidal interaction is negligible, a simple viscous-inflow and on-going star formation scenario may apply, and an exponential disk with a small bulge should appear (Yoshii and Sommer-Larsen 1989).

We comment on the epoch for the determination of galaxy morphology. A tidal encounter produces a bar structure which lasts for several galactic rotations, or for $\sim 10^9$ yr (Noguchi 1988). Accordingly, gas accretion and PB are enhanced for this period, or $\tau_{\rm B} \sim 10^9$ yr. Thus, the bulges are formed within the first billion years of galaxy formation in the early universe. Bulge stars resulting from PB are, therefore, old population stars. Accordingly, galaxy morphologies, at least the bulge sizes, are determined within the first billion years. It is suggested that some elliptical galaxies are formed by merging. Since merging also occurs within several galactic rotations (Barnes 1989) a group of galaxies, which had an initial condition for final merging into a single elliptical, cannot survive longer. This means that E galaxies of merging origin must be formed within the first billion years of formation of merging bodies in the early universe. These arguments are consistent with the facts that galactic bulges and E galaxies are made up of old-population stars.

4. Hubble Sequence and Density-Morphology Relation

Based on this scenario, we might be able to understand the Hubble morphological sequence as follows:

Sc,d Galaxies: Late-type galaxies are those that were born in LGDR. Because of rare tidal encouters, the primeval gas accretion was mild, so that the galaxies experienced relatively quiet PB. Accordingly, gas ejection was weak and slow, and only small bulges could form. Because the gas accretion was weaker, more gas remains in the disks compared with later type galaxies. Mass concentration as a central bulge is smaller, and the disk occupies a relatively larger mass fraction. Hence, since the disk is more selfgravitating and unstable against longer-wavelength instability, spiral arms with larger pitch angles are formed.

Sb Galaxies: Sb galaxies were born in relatively LGDR. Medium-size bulges were formed. Gases near the central regions were accreted and caused bursts, while gases in the outer disks remained unaccreted. This resulted in a broad ring-like distribution of gas, often of several-kpc radius, like in our Galaxy and in M31. This type of galaxy has characteristics between Sa and Sc.

Sa Galaxies: Sa's are galaxies that were born in relatively HGDR. Because of tidal encounters during the early phase, gas accretion and subsequent starbursts were strong, and large bulges were formed. The central bulge occupies a significant mass fraction, and the disk mass is relatively smaller compared to Sc and Sd galaxies. The disk is therefore more stable against long-wavelength instability, and only small-scale fractuation developes into tightly wound fragmentary spiral arms.

SB Galaxies: According to the present scenario, galaxies experienced a bar phase in their primeval stage in order for their gas accretion and bulge formation to take place. Bars are formed by interactions among galaxies, and are long-standing structures lasting at least for $\sim 10^9$ yr (Noguchi 1987). The barred spirals observed today could be remnants of such primeval bars which have been maintained for a longer time by some unknown mechanism. Alternatively, some "recent" interaction, preferably within $\sim 10^9$ yr, may have triggered it.

S0 Galaxies: S0 galaxies are those that were born in HGDR. They experienced frequent galaxy encouters and a rapid accretion of gas. Intense starbursts followed, which resulted in large-scale, high-velocity gas outflow, so that largely extended bulges were formed. The disk gas has been almost entirely accreted and exhausted in the PB phase; S0 disks thus contain little gas.

E Galaxies: E's are galaxies that were born in very high galaxy-density regions. In such regions, galaxies have experienced not only strong tidal encounters but also merging (e.g., Barnes 1989). Each galaxy experienced an S0 phase, whereby very active bursts occured. With rapid gas accretion and intense bursts, gas has been exhausted. Further, they may have experienced merging because of the high density of galaxies (e.g., McGlynn and Ostriker 1980; Barnes 1989).

According to the present scenario, the evolution of individual galaxies and their Hubble types are dependent of the size and mass of protoclusters: High-mass, compact proto-clusters evolve into HGDR and into rich clusters, which contain more early type galaxies because of stronger encounters and bursts. On the other hand, low-mass and diffuse proto-clusters evolve into LGDR, where late type galaxies dominate. This naturally explains the density-morphology relation in clusters of galaxies (Dressler 1979). Equivalently, we may state that star burst history and morphology evolution are governed by environmental factors such as the size, mass and galaxy density in a cluster or the region in which individual galaxies were born. In other words, the Hubble types are tracers not only of starburst history, but also of the birth environment of galaxies.

This work was finantially supported in part by the Japan Society of Promotion of Sciences, and by the Ministry of Education, Science and Culture under Grant No. 01420001, 01302009 (Y. Sofue) and 03249201 (A. Habe).

References

Barnes, J. E. 1989, *Nature*, **338**, 123.

Dressler, A. 1979, *Astrophys. J.*, **231**, 659.

Eggen, O. J., Lynden-Bell, D., and Sandage, A. 1962, *Astrophys. J.*, **136**, 748.

Fujimoto, M., and Kumai, Y. 1991, submitted to *Publ. Astron. Soc. Japan.*

Larson, R. B. 1974, *Monthly Notices Roy. Astron. Soc.*, **169**, 229.

Lynds, C. R., and Sandage, A. R. 1963, *Astrophys. J.*, **137**, 1005.

McGlynn, T. A., and Ostriker, J. P. 1980, *Astrophys. J.*, **241**, 915.

Miyamoto, M., and Nagai, R. 1975, *Publ. Astron. Soc. Japan*, **27**, 533.

Nagai, R., and Miyamoto, M. 1976, *Publ. Astron. Soc. Japan*, **28**, 1.

Nakai, N., Hayashi, M., Handa, T., Sofue, Y., Hasegawa, T., and Sasaki, M. 1987, *Publ. Astron. Soc. Japan*, **39**, 685.

Noguchi, M. 1987, *Monthly Notices Roy. Astron. Soc.*, **228**, 635.

Noguchi, M. 1988, *Astron. Astrophys.*, **203**, 259.

Pfenniger, D., and Norman, C. 1990, *Astrophys. J.*, **363**, 391.

Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Astrophys. J.*, **238**, 24.

Sofue, Y. 1987, *Publ. Astron. Soc. Japan*, **39**, 547.

Sofue, Y. 1988, in *Galactic and Extragalactic Star Formation*, ed. R. E. Pudritz and M. Fich (NATO ASI Series, Kluwer Academic Publishers, Dordrecht), p. 409.

Sørensen, S.-A., Matsuda, T., and Fujimoto, M. 1976, *Astrophys. Space Sci.*, **43**, 491.

Telesco, C. M. 1988, *Ann. Rev. Astron. Astrophys.*, **26**, 343.

Yoshii, Y., and Sommer-Larsen, J. 1989, *Monthly Notices Roy. Astron. Soc.*, **236**, 779.

Yoshizawa, M., and Wakamatsu, K. 1975, *Astron. Astrophys.*, **44**, 363.

Véron-Cetty, M.-P., and Véron, P. 1985, *Astron. Astrophys.*, **145**, 425.

Wada, K., and Habe, A., 1991, submitted to *Monthly Notices Roy. Astron. Soc.*.