FORMATION OF A POLAR RING GALAXY IN A GALAXY MERGER

KENJI BEKKI
Astronomical Institute, Tohoku University, Sendai, 980-8578, Japan; bekki@astro.astr.tohoku.ac.jp
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ABSTRACT

We numerically investigate stellar and gas dynamics in star-forming and dissipative galaxy mergers between two disk galaxies with specific orbital configurations. We find that violent relaxation combined with gaseous dissipation in galaxy merging transforms two disk galaxies into one S0 galaxy with polar rings; both the central S0-like host and the polar ring component in a polar ring galaxy are originally disk galaxies. We also find that morphology of the developed polar rings reflects both the initial orbit configuration of galaxy merging and the initial mass ratio of the two merger progenitor disk galaxies. Based upon these results, we discuss the origin of the fundamental observational properties of polar ring galaxies, such as the prevalence of S0 galaxies among polar ring galaxies, the rarity of polar ring galaxies among S0 galaxies, the dichotomy between narrow polar rings and annular ones, the shapes of polar ring warps, and an appreciably larger amount of interstellar gas in the polar ring component.

Subject headings: galaxies: interactions — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

Polar ring galaxies are generally considered to be dynamically peculiar systems in which the outer rings composed of gas and stars are aligned roughly in a perpendicular orientation with respect to the major axis of the central host galaxies (Schweizer, Whitmore, & Rubin 1983; Whitmore et al. 1990; Sackett 1991). A growing number of observational studies have been recently accumulated which can provide valuable information about the origin of these peculiar polar ring galaxies. Nearly all of the central hosts are morphologically normal S0 galaxies, some of which are confirmed to be rapidly rotating by kinematical studies (Schechter & Gunn 1978; Schechter, Ulrich, & Bok 1984b; Whitmore et al. 1990; Whitmore 1991). Approximately only 0.5% of all S0 galaxies have observable polar rings, which suggests that a particular mechanism is required for the formation of polar rings in S0 galaxies. The ring component also shows rapid rotation comparable to that of the main host galaxies, implying that two dynamically different systems coexist in these polar ring galaxies. An appreciable amount of H I gas, which is sometimes comparable to the total mass of the host, is closely associated with the stellar ring component (e.g., Shane 1980; Schechter et al. 1984a; Richter, Sackett, & Sparke 1994; Arnaboldi et al. 1997; Galletta, Sage, & Sparke 1997). The morphology of the polar rings is basically divided into two broad classes (Whitmore 1991): (1) a narrow ring which is not extended in size (e.g., ESO 415-G26) and (2) an annulus which is a disk-like component with the central part cut out (e.g., NGC 4650a). Peculiar morphology is observed in some polar ring galaxies (e.g., the Helix galaxy, NGC 2685, and the double-ringed system, ESO 474-G26), which further implies considerably complicated physical processes in polar ring formation and simultaneously provides a clue to the understanding of the origin of polar ring galaxies (Sackett 1991). Roughly two-thirds of these polar rings show obvious galactic warps whose shapes look like an "integral sign" and/or a "banana" (Whitmore 1991). Statistical studies on the distribution of the angle between the ring component and the central host reveal that these two components strongly prefer to be orthogonal with each other. These peculiarities, both in the kinematics and the morphology observed in polar ring galaxies, have attracted a number of theoretical interests which are divided basically into two categories: (1) the origin of the polar rings and (2) the nature of dark matter halo surrounding polar ring galaxies. Although there are a large number of important studies addressing the three-dimensional shapes of dark matter halo in the galaxies (e.g., Whitmore, Mcelroy, & Schweizer 1987; Sackett & Sparke 1990; Reshetnikov & Combes 1994; Sackett et al. 1994; Combes & Arnaboldi 1996), we here restrict ourselves to the mechanisms that would naturally explain the formation of polar ring galaxies with spherical haloes.

It is generally believed that the formation of the polar rings is the result of a "secondary event" involving a pre-existing S0 galaxy (e.g., Steiman-Cameron & Durisen 1982; Sparke 1986; Quinn 1991; Rix & Katz 1991; Reshetnikov & Sotnikova 1997). Specifically, the host S0 galaxy is supposed to have acquired the material constituting the ring component by capturing the gas during tidal interaction with neighboring galaxies. The subsequent gravitational interaction combined with the gaseous dissipation then spreads the captured gas and forms the polar rings around the host galaxy. One of the promising models along this orthodox scenario is the "preferred plane model" in which the differential precession of the rings and the gaseous dissipation cooperate to play a vital role in leading the acquired gas to settle into the stable polar orbit and finally to form the polar rings (Tohline & Osterbrock 1982; Durisen et al. 1983; Schweizer et al 1983). A number of numerical simulations have already confirmed in what physical conditions the polar rings are more likely to form and continue to exist for a relatively longer timescale (Habe & Ikeuchi 1988; Christodoulou et al. 1992; Katz & Rix 1992). Indeed, these previously proposed models have provided a potential success in reproducing the polar rings in S0 galaxies; however, these models seem to be incapable of giving sufficiently conclusive and persuasive answers to the following seven questions on the origin of the polar ring galaxies (Sackett 1991; Whitmore 1991; Arnaboldi et al. 1997; Galletta et al. 1997):
1. Why are nearly all the central host galaxies morphologically classified as S0?
2. Why are polar ring galaxies so rare among S0 galaxies?
3. Why do some polar ring galaxies have a narrow ring while some have annuli?
4. Why are the mass and angular momentum of the ring component comparable or sometimes larger than those of the host?
5. Why are the rings so "polar"?
6. Why do some polar rings have considerably peculiar morphology such as helical and double-ringed shapes?
7. Why is there an appreciably greater amount of interstellar gas in the polar ring component?

In particular, questions (1), (4), and (7) could not be explained simply by the previous theoretical models, implying either that more elaborate and sophisticated models along the above orthodox scenario should be considered or that the alternative model should be proposed for the explanation of the above questions.

The purpose of this paper is to explore the origin of polar ring galaxies and to propound a new mechanism that more naturally and reasonably explains the aforementioned observational trends of polar ring galaxies. In the present study, we consider that the dissipative galaxy merging between two disks is a promising mechanism that quite reasonably answers the above seven questions. Therefore, we investigate how the dissipative galaxy merging transforms two disks into one early-type S0 galaxy with a polar ring. Furthermore, we investigate how the orbit configuration of galaxy merging and initial mass ratio of the two progenitor disk galaxies can affect the morphology of polar rings developed after galaxy merging. In this paper, the galaxy merging with specific orbit configurations and sufficient amount of gaseous dissipation is demonstrated to play a vital role in forming both the central S0-like host and the surrounding polar ring component in polar ring galaxies. This paper is an extended version of Bekki (1997) in which the basic mechanism of polar ring S0 galaxy formation in galaxy mergers is briefly summarized. The layout of this paper is as follows. Section 2 describes numerical models for dissipative galaxy merging. Section 3 gives the results obtained in the present study. In § 4 we mainly discuss whether or not the model proposed in the present paper can become a new promising model which naturally and reasonably explains the observational properties of polar ring S0 galaxies.

2. MODEL

2.1. Structural and Kinematical Properties of Initial Disks

We construct models of galaxy mergers between gas-rich late-type disk galaxies by using the Fall-Efstathiou model (Fall & Efstathiou 1980). In the present merge model, a galaxy intruding from the polar axis of the other galaxy in a merger is referred to as the "intruder," whereas the other is referred to as the "victim." In the present model, the dynamical and kinematical properties of the victim are set to be exactly the same as those of the standard model described below, whereas those of the intruder with a given mass $m_2$ and size $r_2$ are determined by rescaling those of the standard model. Both the density profile of the disk and the rotational curve profile are assumed to be self-similar between the two galaxies, and these two galaxies satisfy Freeman’s luminosity-size relation (Freeman 1970). For example, if we set the intruder mass to be 2.0, the size of the intruder is automatically set to be 1.41.

In the standard model (corresponding to the victim model), the total mass $M_d$ and the size $R_d$ of a progenitor disk are set to be 1.0 and 1.0, respectively. From now on, all the mass and length are measured in units of $M_d$ and $R_d$, respectively, unless specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $t_{\text{dyn}} = (R_d^2/GM_d)^{1/2}$, respectively, where $G$ is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_d = 1.0 \times 10^{10} M_\odot$ and $R_d = 10.0$ kpc as a fiducial value, then $v = 6.53 \times 10^3$ km s$^{-1}$ and $t_{\text{dyn}} = 1.49 \times 10^8$ yr, respectively. These fiducial values are appreciably smaller than those adopted in Bekki (1997) principally because we intend here to discuss the formation of polar rings in less luminous galaxies prevalent among polar ring galaxies. In the present model, the rotation curve becomes nearly flat at 0.35$R_d$ with the maximum rotational velocity 2.22 in our units, corresponding to total halo mass within $R_d$ equal to 3.58 in our units. The radial $R$ and vertical $Z$ density profile of a disk are assumed to be proportional to $\exp (R/R_d)$ with scale length $R_0 = 0.2$ and to sech$^2 (Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. The velocity dispersion of dark halo particles at a given point is set to be isotropic and given by the virial theorem. In addition to a rotational velocity set by the gravitational field of disk and halo components, the initial radial and azimuthal velocity dispersions are assigned to disk components according to the epicyclic theory with Toomre’s parameter $Q$ (Binney & Tremaine 1987) equal to 1.0. The vertical velocity dispersion at a given radius are set to be 0.5 times as large as the radial velocity dispersion at that point.

The collisional and dissipative nature of the interstellar medium (ISM) are modeled by the sticky-particle method (Schwarz 1981). It should be emphasized here that this discrete cloud model can at best represent the real ISM of galaxies in a schematic way. As is modeled by McKee & Ostriker (1977), the ISM can be considered to be composed mainly of "hot," "warm," and "cool" gas, each of which mutually interacts hydrodynamically in a rather complicated way. Actually, this considerably complicated nature of ISM in disk galaxies would not be so simply modeled by the "sticky-particle" method, in which gaseous dissipation is modeled by ad hoc cloud-cloud collision; any existing numerical method probably could not model the real ISM in an admitted proper way. In the present study, as a compromise, we only try to address some important aspects of hydrodynamical interaction between the ISM in disk galaxies and in dissipative mergers. More elaborated numerical modeling for the real ISM would be necessary for our further understanding of dynamical evolution in dissipative galaxy mergers. The size of the clouds relative to the disk size is set to be $7.5 \times 10^{-3}$ in our units in the present simulations. The corresponding size and mass of each cloud in the present study are 75 pc and $10^8 M_\odot$, respectively. The radial and tangential restitution coefficient for cloud-cloud collisions are set to be 1.0 and 0.0, respectively. In all the simulations, the initial gas mass fraction represented by $m_2$ is set to be 0.0 for the intruder and 0.2 for the victim unless specified. The reason for this initial condition is principally that we do not believe that interaction between two gas disks is essential for polar ring formation in the present model, and it also introduces a great deal of complexity. The adopted value of 0.2 is a typical one for gas-rich spiral
of the numbers are linearly proportional to disk component, 20,000 for the gas component. For the halo component, 10,000 for the stellar component. 

The main reason for our adopting these two types of orbit configuration is that we intend to elucidate more clearly the formation mechanism of polar ring galaxies. Formation of polar ring galaxies in a more complicated and less idealized situation of galaxy merging will be investigated in our future papers.

In what follows, we investigate how a polar ring galaxy is developed during galaxy merging between two disks and clarify the formation mechanism of the polar rings. Furthermore, we vary the initial mass ratio of two progenitor galaxies (m2) and thereby investigate how the initial mass ratio controls the final morphology of the developed polar ring galaxies in dissipative galaxy mergers. All the simulations have been carried out on the GRAPE board (Sugimoto et al. 1990) at the Astronomical Institute of Tohoku University. The gravitational softening parameter is fixed at

galaxies (e.g., Roberts & Haynes 1994). Total particle numbers used in the standard model (for the victim galaxy) are 10,000 for the halo component, 10,000 for the stellar disk component, 20,000 for the gas component. For the intruder, the total particle numbers depend on m2 in such a way that the numbers are linearly proportional to m2. For example, total particle numbers are 20,000 for the halo component and 20,000 for the stellar disk component in the model with m2 = 2.0.

2.2. Star Formation

We incorporate physical processes of star formation into the present model in a more idealized manner. We consider only the conversion of the gaseous component to the stellar component and do not include here other important effects of star formation, such as effects of thermal and dynamical heating by Type II supernova on the dynamics in this preliminary stage. In the present study, we will use the term “star formation” to refer to the process of gas consumption. A new stellar particle (collisionless particle, referred to as “new stars” or as “new stellar component”) is created at the position of the original gas particle according to the Schmidt law (Schmidt 1959) with exponent γ = 2.0 as the controlling parameter of the rate of star formation. The amount of gas consumed by star formation for each gas particle in each time step, Mγ, is given as \( M_\gamma \propto (\rho/\rho_0)^{\gamma-1} \), where \( \rho_0 \) are the gas density around each gas particle and the mean gas density at 0.48 radius of an initial disk, respectively. The coefficient of the Schmidt law is set to be exactly parallel to the x-y plane and specified by a parameter \( \theta_1 \), which describes the angle between the z-axis and the spin angular momentum vector of the victim disk. The initial spin of the intruder is set to be exactly parallel to the z-axis for all models. Two different types of orbit are adopted in the present study. One is that the two disks are set to move initially on an x-y plane with absolute magnitude of relative velocity \( V_{rel} \) ("polar axis collision"). This type of initial orbit configuration with nearly zero orbital angular momentum is frequently adopted in the studies of the formation of collisional galactic rings (e.g., Hernquist & Weinberg 1993; Appleton & Struck-Marcell 1996; Gerber, Lamb, & Balsara 1996). The other is that the two disks are set to merge with a parabolic encounter and with a given pericenter distance, \( r_p \) ("parabolic collision"). This type of initial orbit configuration with an appreciable amount of orbital angular momentum in a bound system is adopted in the studies of elliptical galaxy formation in galaxy mergers (e.g., Barnes 1992). The main reason for our adopting these two types of orbit configuration is that we intend to elucidate more clearly the formation mechanism of polar ring galaxies. Formation of polar ring galaxies in a more complicated and less idealized situation of galaxy merging will be investigated in our future papers.

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### Table 1

| Model (1) | Orbit Type | \( m_2 \) (3) | \( r_2 \) (4) | \( M_\gamma \) (5) | \( \theta_1 \) (6) | \( V_{rel} \) (7) | \( r_p \) (8) | Ring Morphology (9) |
|-----------|------------|---------------|-------------|-----------------|---------------|---------------|-----------|-------------------|
| 1         | PO         | 2.0           | 1.41        | 0.2             | 90.0          | 0.5           | ...       | Narrow ring       |
| 2         | PO         | 2.0           | 1.41        | 0.2             | 90.0          | 0.5           | ...       | Narrow rings      |
| 3         | PO         | 2.0           | 1.41        | 0.2             | 90.0          | 0.5           | ...       | No rings          |
| 4         | PA         | 2.0           | 1.41        | 0.2             | 90.0          | 0.5           | ...       | No rings          |
| 5         | PO         | 2.0           | 1.41        | 0.2             | 90.0          | 0.5           | ...       | No rings          |
| 6         | PO         | 2.0           | 1.41        | 0.2             | 90.0          | 1.5           | ...       | Disturbed narrow ring |
| 7         | PO         | 1.5           | 1.22        | 0.2             | 90.0          | 0.5           | ...       | Narrow ring       |
| 8         | PO         | 1.0           | 1.00        | 0.2             | 90.0          | 0.5           | ...       | Narrow ring       |
| 9         | PO         | 0.7           | 0.84        | 0.2             | 90.0          | 0.5           | ...       | Narrow ring       |
| 10        | PO         | 0.7           | 0.84        | 0.2             | 90.0          | 1.5           | ...       | Peculiar narrow ring |
| 11        | PO         | 0.7           | 0.84        | 0.2             | 90.0          | 2.5           | ...       | Peculiar double rings |
| 12        | PO         | 0.7           | 0.84        | 0.2             | 90.0          | 5.0           | ...       | Transient Cartwheel-like ring |
| 13        | PO         | 0.5           | 0.71        | 0.2             | 90.0          | 0.5           | ...       | Double rings      |
| 14        | PO         | 0.5           | 0.71        | 0.2             | 90.0          | 0.5           | ...       | Double rings      |
| 15        | PA         | 0.5           | 0.71        | 0.2             | 80.0          | 0.5           | ...       | Double rings      |
| 16        | PO         | 0.3           | 0.55        | 0.2             | 90.0          | 0.5           | ...       | Disk (transient annular rings) |
| 17        | PO         | 0.1           | 0.32        | 0.2             | 90.0          | 0.5           | ...       | Disk (no rings)   |
0.03 in all the simulations. Considering the particle number of the present study (less than 100,000) and the timescale of the numerical calculation (an order of ten dynamical time), the two-body relaxation due to the finite particle number (and due to the adoption of the softening length) has negligible dynamical effects on the relatively global dynamics investigated in the present merger model. The time integration of the equation of motion is performed by using the 2-order leap-frog method. PO and PA in the column (2) of Table 1 specify the type of orbit configuration of galaxy merging: PO and PA represent the polar axis collision and parabolic one, respectively. The values of model parameters \( m_2, r_2, M_g, \theta_1, V_{rel}, \) and \( r_p \) are summarized in Table 1 for 17 models (models 1–17). Characteristic of polar ring morphology developed after galaxy merging are described in the column (9) of Table 1 for each model. For example, the “double ring” means that the developed polar ring morphology looks like a double ring.

3. RESULT

In this section we first observe how a S0 galaxy with polar rings is formed in a dissipative merger with a particular orbit configuration (§ 3.1). Next we describe how the initial mass ratio of two progenitor disk galaxies, \( m_2 \), controls the final morphology of the developed polar rings (§ 3.2).

3.1. Dynamics of Polar Ring S0 Formation

First, we present the results of model 1 which shows a typical behavior of polar ring formation in the present study. S0 galaxies with narrow polar rings are found to be more likely to form in this model with the initial mass ratio of two progenitor disks, \( m_2 \), equal to 2.0, as is shown in Figure 1. The time evolution of merger orbit projected onto the \( x \)-axis for model 1 is given in Figure 2. Time evolution of gas mass for this model is given in Figure 3. In this model, the intruder galaxy is found to be inevitably transformed into the central S0-like component, whereas the victim is.

Fig. 1.—Initial mass distribution of two progenitor disks in a galaxy merger (left panel) and final mass distribution of the merger remnant at \( T = 14.0 \) in our units (right panel) projected onto the \( x-z \) plane for model 1. A galaxy that intrudes from the polar axis of the other one is referred to as the “intruder,” whereas the other galaxy is the “victim.” An arrow indicates the direction of initial relative velocity of these two galaxies. In order to show more clearly the polar ring component in the merger remnant, we plot only the gaseous component of the victim and the stellar component of the intruder in the right panel. The halo component is not plotted in these two panels.

Fig. 2.—Time evolution of the merger orbit projected onto the \( x \)-axis for model 1. Time is in units of \( t_{dyn} \). Note that owing to dynamical friction of galaxy merging, oscillation of the merger orbit along the \( x \)-axis is damped rapidly within \( \sim 10t_{dyn} \).

Fig. 3.—Time evolution of gas mass in our units for models with \( m_2 = 2.0 \) (model 1) and 0.3 (model 16). Time is in units of \( t_{dyn} \). Note that the interstellar gas of merging galaxies is more rapidly consumed by star formation in the model with larger \( m_2 \) because of the stronger dynamical interaction of galaxy merging.
Fig. 4.—Morphological evolution of the intruder (top) and the victim (stellar component, second from the top; gaseous component, third from the top; new stellar component, bottom) projected onto the x-z plane in model 1. Time $T$, indicated in the upper left-hand corner of the top frame, is in units of $t_{\text{dyn}}$. 

Fig. 5.—Same as Fig. 4, but for $T = 8.0, 10.0$, and 12.0

Fig. 6.—Morphological evolution of the intruder (top) and the victim (stellar component, second from the top; gaseous component, third from the top; new stellar component, bottom) projected onto the y-z plane in model 1. Time $T$, indicated in the upper left-hand corner of the top frame, is in units of $t_{\text{dyn}}$.

Fig. 7.—Same as Fig. 6, but for $T = 8.0, 10.0$, and 12.0
found to be dramatically transformed into a narrow polar ring, as is described below.

3.1.1. Mechanism of Polar Ring Formation

Figures 4, 5, 6, and 7 describe the morphological evolution of each component in each of the two galaxies. As is shown in these figures, as the intruder pierces the victim and shoots through it, the initially thin stellar disk of the intruder becomes thicker and thicker, owing to strong dynamical heating during the violent gravitational interaction between these two galaxies (the time $T$ equal to 2.0 in our units). While the intruder is then pulled gravitationally back to pierce again the victim ($T = 4.0$), the stellar disk of the intruder suffers from violent relaxation to form a more disky S0-like spheroid ($T = 8.0$). The density profile of the intruder at $T = 14.0$ shows clear deviation from the initial exponential profile, looking more like the so-called $R^{1/4}$ law. Furthermore, its kinematics within the central host show an appreciable amount of global rotation (see Fig. 8). These results clearly demonstrate that the formation of S0-like hosts in polar ring galaxies is closely associated with the violent dynamical interaction of the two merging galaxies and, furthermore, that the formation of the S0-like host (which is the intruder in the present model) is inevitable in the formation of polar ring galaxies, owing to the stronger gravitational interaction of galaxy merging.

As is shown in Figures 4–7, the victim disk, on the other hand, is finally transformed into a narrow polar ring surrounding the central spheroid, mainly composed of the stellar disk of the intruder. As the intruder pushes the central part of the victim out and simultaneously excites the outwardly propagating density wave in the victim, the stellar component of the victim is dynamically relaxed to form the diffuse spheroidal component in the merger remnant because of the violent relaxation of galaxy merging. The gaseous component of the victim forms the compressed gas layer with a higher density owing to the enhanced cloud-cloud collisions and the resultant gaseous dissipation. Subsequent star formation and further gaseous dissipation at the compressed gas layer dynamically transforms the victim disk into a narrow polar ring composed of gas and new stars. Morphology of the gaseous polar ring projected onto the $x$-$z$ plane looks more like an "integral-sign" galactic warp at $T = 10.0$ and a "banana" galactic warp at $T = 12.0$, implying that warps frequently observed in polar ring galaxies are closely associated with the gas and stellar dynamics of the merging victim galaxy. The victim at $T = 14.0$ shows mass distribution clearly deviating from an exponential profile and does not have any remarkable global rotation along the major axis of the central host (see Fig. 8). As is shown in Figure 9, the mass distribution of new stars formed after $T = 8.0$ seems to be more disky, whereas that of new stars formed before $T = 8.0$ seems to be more extended and spherical. This result reflects the fact that an appreciable amount of new stars are produced in the shocked and ringlike gas layer during galaxy merging. This new stellar component formed in the relatively later phase of galaxy merging can be observed as the stellar polar ring in polar ring galaxies. These results quite naturally explain why some polar ring galaxies have an appreciable amount of interstellar gas in the polar rings. This is simply because the polar ring component is originally a gas-rich galactic disk. What we should stress, furthermore, is that in this Figure 9, a discernible amount of interstellar gas and new stars is fueled to the central part of the merger remnant. This result is consistent with the observational evidence that some polar ring galaxies actually show the pronounced activity (e.g., post starbursts and LINER activity) in their central part (e.g., Schechter et al. Reshetnikov & Schechter 1984; Reshetnikov & Combes 1994). This result also implies that such polar ring galaxies showing the central activity are examples of polar ring S0s formed by merger events.

As is described above, the successive radially propagating wave excited by the intruder is found to play an important role in the earlier stage of polar ring formation. Moreover, the gaseous dissipation and subsequent star formation in the compressed gaseous region in the wave are found to
damp the radial oscillation of the wave and then to change the wave into the stational polar ring material in the later stage of polar ring formation. Such damping of the radial oscillation due to gaseous dissipation in galaxy merging is described by Figure 10, in which the same analysis as that of Athanassoula, Puerari, & Bosma (1997) is adopted. This two-fold polar ring formation is a unique physical process of dissipative galaxy mergers with specific orbital configurations, thus providing an alternative explanation for the polar ring formation. The developed polar ring component is found to show discernible precession, even after a merger remnant reaches the nearly dynamical equilibrium state, reflecting the fact that the formation of the polar ring is a result of the past violent gravitational interaction between two disk galaxies. This precession is one of the characteristics of polar rings developed in the present merger model for polar ring formation, as is described in detail later.

Thus a central S0-like host galaxy with a narrow polar ring is formed by a dissipative galaxy merging with specific orbital configurations within only ~12\(t_{\text{dyn}}\) corresponding to ~1.8 \times 10^9 yr. These results demonstrate that the strong dynamical effect on the central part of the victim disk is indispensable for the formation of polar rings in this picture, which is quite different from the previously proposed models, such as the preferred plane models. Moreover the timescale of polar ring formation in the present merger model, which is typically ~10\(t_{\text{dyn}}\) of the system, is relatively short compared to that in the preferred plane one. The present merger model for polar ring formation accordingly seems to be a new and promising candidate theory, which can give reasonable and plausible explanations for a number of fundamental observational properties of polar ring galaxies. However, it is safe for us to say that it is not certain whether or not the present merger model is a unique mechanism for polar ring formation; there are a number of observational indications that, in a certain interacting galaxy, the polar ring seems about to form, according to the preferred plane scenario (e.g., Reshtnikov, Hagen-Thorn, & Yakovlera 1996). Observability of polar ring S0s formed by dissipative galaxy merging is discussed in detail in § 4.

3.1.2. Physical Conditions Required for Polar Ring S0 Formation

We describe under what physical conditions S0 galaxies with polar rings are more likely to form in dissipative galaxy merging. We observe the results of four comparative experiments of models (models 2–5) which are designed to elucidate more clearly the essential parameters for the formation of polar rings. Figure 11 gives a collection of the final morphology of the three models (models 3–5). We find
that neither the model with a less inclined victim disk (θ = 30.0, model 3) nor the model with an appreciably larger amount of initial orbital angular momentum (model 4) shows any remarkable polar ring component. This result suggests that both the more inclined victim disk and the relatively smaller amount of orbital angular momentum are required for the formation of polar rings in the present merger model (see Fig. 11). This result of model 3 explains why the polar rings are so polar (e.g., Whitmore 1991). This is because if the two progenitor disks are not so highly orthogonal with each other, the merger remnant just becomes a morphologically normal S0 galaxy. The result of model 4, the orbit configuration of which has been investigated more extensively by several authors in the context of E/S0 galaxy formation, naturally explains why the polar ring E/S0 galaxies are so rare among E/S0 galaxies. This is because a specific kind of orbit configuration of galaxy merging is required for the formation of polar ring E/S0 galaxies. We also find that the model with no gas particle (i.e., without gaseous dissipation), model 5, does not show any ringlike component surrounding the central spheroid developed after galaxy merging (see Fig. 11). This result suggests the following important role of gaseous dissipation in the polar ring formation: gaseous dissipation can remove random kinetic energy of the gaseous component in the victim disk, which is caused by violent gravitational interaction between two disks, and accordingly it enables some of the gas component to settle again in a well-ordered disky configuration. This result of model 5 naturally explains why polar ring galaxies are less massive or luminous on average; this is principally because less luminous late-type spirals generally have an appreciably larger amount of interstellar gas (e.g., Roberts & Haynes 1994), which is indispensable for polar ring formation.

These comparative experiments clearly demonstrate that both a minimum amount of gaseous dissipation and a specific kind of orbit configuration are required for the formation of polar rings, which naturally explains why the polar ring galaxies are so rare among S0 galaxies. In this model with m2 = 2.0, the polar ring morphology depends weakly on the relative velocity of two merger precursor disks. As the relative velocity becomes larger (e.g., in the model with Vrel = 1.5, model 6), the polar ring component looks more like a disturbed dynamical system.

3.2. Dependence on Initial Mass Ratio of Two Progenitor Disks

In this subsection we mainly describe how the initial mass ratio of two progenitor galaxies affects the final morphology of the central S0-like spheroid and the surrounding ring component developed after galaxy merging. Figures 12 and 13 summarize the final mass distribution for models with m2 = 1.5, 1.0, 0.7, 0.5, 0.3, and 0.1 (corresponding to models 7–9, 13, 16, and 17, respectively) in which orbit configuration of galaxy merging is exactly the same as that of model 1, but the initial mass ratio of progenitor disks (mj) is different from that of model 1. These figures clearly indicate the m2 dependence of the final morphology of polar ring galaxies formed by dissipative galaxy merging, as is described later. In the following, for each model with different m2, the dependence of structure and kinematics of the developed polar ring galaxies on the relative velocity of two merger precursor galaxies are given only if the results of this dependence are considered to be remarkably important.

3.2.1. m2 = 1.5

Like model 1, the model with m2 = 1.5 (model 7) shows...
both the central disky S0 host and the surrounding thin and narrow polar ring component (see Fig. 12). The essential physical processes of polar ring formation are nearly the same as those in model 1. The central S0 in this model looks more puffed out compared to that of model 1, probably because the intruder suffers from the stronger dynamical interaction with the victim disk. The axis of intrinsic angular momentum of the developed S0 galaxy is more appreciably inclined compared to the initial intrinsic spin axis of the intruder. These results suggest that both the morphology of the central S0 host and the inclination angle between polar rings and the central host in a polar ring S0 galaxy can reflect the initial mass ratio $m_2$ of two merger precursor disks, which, furthermore, suggests that the strength of dynamical interaction in galaxy merging is an important factor for structure and kinematics of merger remnants. In the present study, S0 galaxies with a narrow polar ring (e.g., ESO 415-G26) are found to be reproduced more successfully in the models with $m_2$ larger than 1.5.

### 3.2.2. $m_2 = 1.0$

For the model with $m_2 = 1.0$ (corresponding to the so-called major merger, model 8), both the intruder and the victim disks suffer from the stronger violent dynamical relaxation of galaxy merging, principally because the total mass of the intruder is exactly the same as that of the victim. Consequently, the central spheroidal galaxy developed after galaxy merging looks more like an elliptical galaxy. The polar ring component, on the other hand, looks more strongly disturbed than those of models 1 and 7, probably because of the stronger dynamical relaxation of galaxy merging. For this model (and the models with $0.5 \leq m_2 \leq 1.0$), the dynamical interaction between the developed central spheroid and the polar ring component is very significant such that the polar ring shows discernible precession around the central host after galaxy merging. Considering the relatively smaller probability of major merging, polar ring galaxies developed in major galaxy mergers like this model 8 could be considerably rare, which can give a natural explanation for the extremely rare existence of elliptical galaxies with polar rings (e.g., AM 2020-5050).

### 3.2.3. $m_2 = 0.7$

Essential physical processes of polar ring S0 formation in the model with $m_2 = 0.7$ (model 9) are basically the same as those of model 1, as is described in Bekki (1997). In this model, the transient morphology of the ongoing merger at the time when the intruder pierces the victim disk is strikingly similar to the morphology of the two disks in NGC 660 (e.g., van Driel et al. 1995). This result suggests that galaxies like NGC 660 are characteristic and probably rare examples of polar ring galaxies formed by dissipative galaxy merging. Even for this model, both the density profile of the intruder and that of the victim ultimately show clear deviation from their initial exponential profile, looking more like $R^{-1.4}$ law, and, furthermore, the kinematical property of the central host shows an appreciable amount of global rotation. What is remarkable in this model is that the ring morphology in the merger remnant depends more strongly on the relative velocity of the two galaxies. It is found that the larger the initial relative velocity is, the more peculiar the morphology of the developed polar ring is (models 10 and 11). For models with the relative velocity larger than 1.5 but less than the escape velocity of the system, some merger models show double rings or other peculiar structure, especially in the gaseous component of the merger remnant. Furthermore, as has already been described in Bekki (1997), polar rings do not form but rather transient "cartwheel"-like rings form in the victim disk if the relative velocity of the two merger precursor exceeds the escape velocity of the system (model 12). In this model (model 12), the intruder galaxy, having completely escaped from the gravitational trap of the victim, is transformed into an S0-like galaxy after the galaxy interaction. These results imply that only the initial relative velocity of merger precursors is the difference in the formation process between the two apparently different types of galactic rings (i.e., polar rings and collisional "cartwheel"-like rings).

### 3.2.4. $m_2 = 0.5$

It is found that if the $m_2$ is approximately equal to 0.5, the stellar disk of the victim galaxy is not so completely destroyed by the intruder galaxy during galaxy merging, primarily because the intruder does not dynamically disturb the victim disk strongly enough to cause violent dynamical relaxation. This incomplete destruction of the victim disk results in peculiar morphological evolution of polar rings surrounding the central early-type galaxy in a galaxy merger. For the model with $m_2 = 0.5$ (model 13), the gaseous (and new stellar) component in the merger remnant show precession even after the completion of galaxy merging, principally because the gaseous component and the stellar component in the merger remnant mutually interact with each other even after galaxy merging. Conse-
sequently, the long-term dynamical evolution of the gaseous component in this model is remarkably different from that of other models with $m_2 = 2.0$ and 1.5 (models 1 and 7). As is shown in Figure 14, the gaseous polar ring developed after galaxy merging finally looks like a double-ringed system due to mutual dynamical interaction with the stellar component of the merger remnant (at $T = 26.0$). We also find that this peculiar double-ringed morphology can be observed in the models with different initial collisional parameters of galaxy mergers (models 14 and 15). These results suggest that the formation of S0 galaxies with morphologically peculiar polar rings, such as helical rings (e.g., NGC 2685) and double rings (e.g., ESO 474-G26), is closely associated with the later dynamical interaction between the stellar merger remnant and the developed polar rings. Furthermore, these results imply that the mass ratio of merger precursor galaxies required for the formation of double-ringed early-type galaxies should be approximately 0.5. Future numerical studies with high-resolution and more sophisticated gas dynamics and star formation would enable us to reproduce more successfully the S0 galaxies with peculiar polar rings that are strikingly similar to NGC 2685 and ESO 474-G26, both in kinematics and mass distribution.

3.2.5. $m_2 = 0.3$

We find that if the $m_2$ is approximately less than 0.3, the victim galaxy is not substantially disrupted by the intruder and only suffers from dynamical thickening of the disk, whereas the intruder is completely destroyed by the strong disturbance. Figures 15, 16, 17, and 18 describe how a central host galaxy with polar rings that look more like annular rings is formed during dissipative galaxy merging in the model with $m_2 = 0.3$ (model 16). As is shown in these figures, the intruder galaxy with smaller mass is completely destroyed during violent relaxation of galaxy merging to form a less centrally concentrated spheroid in the merger remnant. As a result of this, the intruder does not dynamically damage the victim strongly enough to trigger the violent relaxation of the victim stellar disk. Accordingly, the stellar disk in the victim is not destroyed completely to keep the disk configuration, even after galaxy merging. In the gaseous disk of the victim, outwardly propagating gaseous waves, which are excited by the intruder galaxy during
galaxy merging, are transformed into the annular gaseous rings at $T = 6.0$ and finally to a nonaxisymmetric structure at $T = 12.0$. In total, more than 50% of initial gas mass is converted to new stars within $14.0t_{\text{dyn}}$, and most of the new stars are located in the victim disk even after galaxy merging in this model. The warp of gaseous disk shows variously different morphology at different times, which suggests that morphological types of warps observed in polar rings can reflect the time dependent gas dynamics in the polar rings (or victim disk). As is shown in Figure 19, the radial mass distribution of the intruder shows clear devi-

![Figure 17](image1.png)

**Fig. 17.**—Morphological evolution of the intruder (top) and the victim (stellar component, second from the top; gaseous one, third from the top; new stellar one, bottom) projected onto the $y$-$z$ plane in model 16. Time $T$, indicated in the upper left-hand corner of the top frame, is in units of $t_{\text{dyn}}$.

![Figure 18](image2.png)

**Fig. 18.**—Same as Fig. 17, but for $T = 8.0$, 10.0, and 12.0.

![Figure 19](image3.png)

**Fig. 19.**—Top panel shows the radial mass distribution of the intruder (solid line with open triangles) and the victim component (dotted line with open squares) projected onto the $x$-$y$ plane at $T = 14.0$ in model 16. In this top panel, the initial exponential mass distribution of the victim projected onto the $y$-$z$ plane (solid line) and that of the intruder projected onto the $x$-$y$ plane (dotted line) are also indicated. Note that the mass distribution of the victim shows clear deviation from the initial exponential mass distribution. The bottom panel shows the projected velocity profile along the $x$-axis for the intruder (solid line) and the victim component (dotted one) at $T = 14.0$ in model 16. Note that the intruder does not show remarkable global rotation, especially in the inner part of the merger remnant after galaxy merging.
ations from initial exponential profiles owing to the stronger dynamical relaxation in galaxy merging. The developed disk with a morphologically peculiar gaseous component might actually be observed as annular polar rings in the nearly edge-on view of the galaxy.

Thus a smaller spheroidal galaxy with a larger and morphologically peculiar gaseous disk and a stellar disk are found to be formed, which looks like the edge-on view of a S0 galaxy with transient annular polar rings such as NGC 4650a. In particular, the face-on view of the victim disk in Figure 17 at $T = 4.0$ could be similar to that of annular polar ring galaxies. Furthermore, the annular ring feature in Figure 17 at $T = 4.0$ reminds us of Hoag's objects (Schweizer et al. 1987), which suggests a close physical connection between annular polar ring galaxies and Hoag's objects. Appleton & Struck-Marcell (1996) describe the details of the possible mechanism for the formation of Hoag's objects in terms of epicyclic interference patterns resulting from multiple encounters. It is not clear, at least in the present study, whether Hoag's objects are actually face-on views of annular polar ring S0s or are forming collisional rings such as a "cartwheel" ring. Furthermore, there are no extensive studies investigating whether or not such epicyclic interference patterns, as are described in Appleton & Struck-Marcell (1996), can provide a mechanism for the formation of annular polar rings. It should be accordingly addressed in our future papers whether the mechanism for the formation of Hoag's objects is essentially the same as that for the polar ring S0 formation. Nonetheless, the results derived in the model with $m_2 = 0.3$ provide a clue to the understanding of the origin of the appreciably larger amount of mass and angular momentum in polar rings observed in NGC 4650a. The larger "polar ring" component in NGC 4650a was once a more massive gas-rich disk galaxy which had finally transformed into "polar rings" because of the past galaxy merging with a less massive galaxy. The results of this model 1 and those of model 16 imply that both narrow polar rings and annular ones, which are considered to be the two basic morphological types of polar ring galaxies, are originally disk galaxies before they manifest themselves as polar rings and that the dichotomy between the narrow rings and annular ones can be understood in terms of the difference in the initial mass ratio of two merger progenitor disks in galaxy merging.

What we should stress here is that we have only succeeded in reproducing a central galaxy whose edge-on view is apparently similar to the S0 galaxy with annular polar rings. Actually, the central galaxy that was developed in the model with $m_2 = 0.3$ does not show such large global rotation as is observed in annular polar ring galaxies (e.g., NGC 4650a), as is also shown in Figure 19. Furthermore, it is clear from the mass distribution of the merger remnant (Fig. 19) that the central part of the merger remnant is not completely cut out. That is, we appear to have failed to reproduce an annular polar ring galaxy with the central part of the ring component completely cut out and with the central host showing a relatively larger amount of global rotation. This apparent failure implies either that the galactic model adopted in the present study, including the star-formation law, gas physics, and the assumption of Freeman's law (i.e., self-similar disks), are not so appropriate or that S0 galaxies with annular polar rings cannot be formed by galaxy merging. Considering the relatively smaller parameter space investigated in the present study and the present rather idealized gas dynamics and star formation of dissipative galaxy mergers, it is safe for us to say that it is not clear, at least in this preliminary stage of the present study, whether our future elaborated numerical models can simulate the formation of an S0 galaxy with annular polar rings. The problems concerning the formation of annular polar rings and the promising ways to remove these are discussed in detail in the section of discussion (§ 4).

3.2.6. $m_2 = 0.1$

It is found that if the initial mass ratio is less than 0.1, neither the central spindly S0-like host nor the disk component with peculiar morphology are formed. The main reason for this is that the intruder galaxy is completely destroyed during merging to form a considerably diffuse spheroid, which would not be identified with a spindly S0 galaxy, and thus cannot give the stronger dynamical impact to the victim disk. This result suggests that, in addition to the particular orbit configuration of galaxy merging and gaseous dissipation, a certain range of mass ratio of merger precursor galaxies (basically $m_2 \geq 0.3$) is required for the formation of polar ring galaxies.

3.2.7. Brief Summary of $m_2$ Dependence

As is described above, a spiral galaxy intruding from the polar axis of the victim galaxy excites the outwardly propagating density wave in the gaseous component of the victim. The subsequent gaseous dissipation and star formation dramatically transform the victim into polar rings. The intruder galaxy, on the other hand, is inevitably transformed into a rapidly rotating and spindly S0 galaxy, owing to the violent gravitational interaction of galaxy merging. One of the advantages in the present merger model of polar ring S0 formation is that, depending on $m_2$ (and $V_{rel}$), variously different morphology of polar rings in polar ring galaxies can be reproduced. As the $m_2$ becomes smaller, the polar ring(s) can change from a narrow ring to peculiar double rings, and to transient annular rings. This result reflects the fact that the structure and kinematics of merger remnants depend strongly on the strength of the dynamical interaction of galaxy merging (or the degree of violent relaxation), which is basically determined by the mass ratio of merger precursor disks. The present explanation for the origin of variously different polar ring morphology in polar ring S0 galaxies is difficult to be observationally confirmed; however, the present scenario for the formation of polar ring galaxies seems to provide a clue to the thorough understanding of the formation and evolution of polar ring galaxies.

4. DISCUSSION

4.1. Possible Candidates of Forming Polar Ring Galaxies

The best way to assess the validity of the present merger model of polar ring S0 formation is to observe the polar ring galaxies that are just forming in galaxy mergers. Considering the relatively short timescale of polar ring formation in the present model (within several dynamical times of the merger system, corresponding to less than $10^9$ yr, depending on the initial mass of the system), the observable number of such forming polar ring galaxies is likely to be small. There are a few examples, however, especially in the Atlas of Peculiar Galaxies (Arp 1966) and the catalog of polar ring galaxies (Whitmore et al. 1990), that provide us
with valuable information on the formation process of polar ring galaxies. NGC 660 is one of the most promising candidates, in which the central host is surprisingly classified by a late-type galaxy (Sb or Sc), and the ring component has an appreciably larger amount of H I gas. This polar ring galaxy is possibly an ongoing galaxy merger between two late-type spirals with exponential disks, and the central spiral host galaxy would be transformed into an early-type galaxy with a smaller relative velocity are actually prevalent in spirals with exponential disks, and the central spiral host galaxy would be transformed into an early-type galaxy within ~10^9 yr because of continuing violent relaxation in the galaxy merging process. Furthermore, this galaxy actually does not show noticeable tidal tails, a fact of which is consistent with the present result that the ongoing mergers required for the formation of polar ring galaxies do not develop tidal tails. Another example is the ESO 199-IG12 (Schweizer et al. 1983; Whitmore et al. 1990), in which the center of the polar ring component seems to not coincide with the center of the central host S0 galaxy, and a number of tidal debris can be observed in the edge of the S0. This galaxy strongly suggests that the polar ring component is still developing in an ongoing galaxy merger. NGC 5544 (and 5545) and NGC 6240 could be also promising candidates of forming polar ring galaxies in galaxy mergers.

All of these possible polar ring galaxies in formation contain valuable information about the formation and evolution histories of the galaxies. Accordingly, more extensive observational studies that address in more detail the kinematical and structural properties of these systems are very desirable. The following three are important diagnostics for polar ring S0 galaxies in formation. The first is the relative radial velocity of the two interacting galaxies (if any, and if possible), which is a key factor determining whether the interacting galaxy becomes a cartwheel-like ring galaxy (if the relative velocity is larger than the escape speed of the system) or a polar ring galaxy (if not), as is indicated by Bekki (1997). The second is to confirm whether or not there are diffusely dispersed stellar components (e.g., long-lived stars) in ongoing mergers. The present merger model predicts that in the formation of polar rings, a greater amount of the victim stellar components is dynamically pushed out by the intruder in a galaxy merger. The third is to check whether the central host in a possibly forming polar ring galaxy is an oblate spheroid or a prolate spheroid. In the present merger model, the central host is still an oblate disk galaxy when the polar ring is developing in a ongoing merger. It is doubtlessly worthwhile to investigate observationally a number of physical properties of possible forming polar ring galaxies along the above three diagnostics.

Furthermore, what we should stress is that if polar ring S0 galaxies are formed in such a way as the present merger model predicts, the suitable site for observing polar ring S0s in formation is in a higher redshift universe. This is primarily because the smaller relative velocity required for polar ring formation in galaxy mergers is more likely to occur in a higher redshift universe (where multiple galaxy encounters can happen more frequently, and these encounters can contribute to the formation of galaxy mergers with such lower relative velocity) rather than in the lower redshift universe (where a dynamical system including possible galaxy mergers is fully virialized and thus has a larger velocity dispersion in the member galaxies). If galaxy mergers with a smaller relative velocity are actually prevalent in higher redshift (thus, if most of the polar ring S0s are formed at higher redshift), polar ring components observed in the present epoch are “older.” Although more extensive observational studies, including not only dynamical and kinematical properties of polar rings but also chemical and photometric evolution of polar ring galaxies, are indispensable for clarifying the formation epoch, a growing number of recent observational results seem to support the “older” polar rings. Eskridge & Pogge (1997) reveal that abundance of H II regions in polar ring galaxy NGC 2685 amounts to 0.8–1.1 solar abundance, which means that chemical evolution in the polar ring proceeds for a longer timescale (corresponding to the chemical evolution timescale of typical galactic disks). Brocchia, Bettoni, & Galletta find (1997) that there is no remarkable environmental difference between polar ring S0s and normal galaxies, which suggests that if polar rings are formed in interacting/merging galaxies, the preferred epoch of interaction/merging is not present but past. Reshetnikov (1997) reveals that the detection rate of possible polar ring galaxies in the sample of Hubble Deep Field (HDF) is extremely higher (0.7% among the HDF galaxies) than that of the local universe (0.05%), which implies that polar ring galaxies are more likely to form in higher redshift. These observational studies do not necessarily imply that the preferred epoch of polar ring galaxy formation is a higher redshift universe; however, these studies seem to suggest that polar rings in formation can be more easily observed in a higher redshift universe.

4.2. Connection with Other Morphological Types of E/S0 Galaxies

Galaxy mergers are generally considered to transform two disk galaxies into one E/S0 galaxy with variously different morphology and kinematics (e.g., Barnes & Hernquist 1992). For example, Barnes (1992) demonstrates that elliptical galaxies with the radial density profile of the so-called R^1.4 law and smaller specific angular momentum are reproduced reasonably well in disk-disk mergers, owing to the efficient transfer of mass and angular momentum during the merging. Bekki & Shioya (1997a) suggest that both boxy and disky elliptical galaxies are formed by star-forming and dissipative galaxy mergers, depending on the star-formation history of merger precursors. Multiple merging, which could occur in the group of galaxies, are also demonstrated to produce normal elliptical galaxies (Barnes 1989; Weil & Hernquist 1996). Furthermore, barred early-type galaxies can be reproduced in galaxy mergers with prograde orbit configuration (Mihos, Walker, & Hernquist 1995; Bekki & Shioya 1997b) as well as in interacting galaxies (Noguchi 1987). In the present study, polar ring galaxies rather than the above “normal” E/S0 galaxies are produced, implying a close physical relationship between polar ring galaxies and “normal” E/S0 galaxies. Considering the physical conditions required for polar rings in the present study, it seems to be reasonable to claim that the physical conditions governing the difference in structure and kinematics between these two apparently different types of galaxies (polar ring S0s and normal E/S0 galaxies) are initial orbit configuration of galaxy merging and mass ratio of two interacting/merging galaxies. If two gas-rich disk galaxies with unequal mass merge with each other with relative inclination of the two galaxies highly perpendicular with each other and with the relative collisional velocity relatively smaller (less than escape velocity of the system), the merger remnant becomes a polar ring galaxy, otherwise they become a “normal”
E/S0 galaxy. Thus, the present study strongly suggests that “normal” E/S0 galaxies and polar ring galaxies are “relatives” in the sense that they are all merger remnants with different initial conditions of galaxy merging.

4.3. Future Study

4.3.1. Longevity and Stability of Polar Rings

Although it appears that the present merger model has succeeded in reproducing both the central S0-like host and the polar ring component in polar ring galaxies, there still remains a number of issues that we should address in order to confirm how plausible and viable the merger model actually is. Among these, we must first investigate how long polar rings, developed via dissipative merger events, can remain dynamically stable and look more like “polar rings” after the merger remnant reaches the virial equilibrium. Longevity and stability of polar rings have been demonstrated to depend on the characteristics of gaseous cooling and the degree of gaseous self-gravitation in the ring component as well as on the three-dimensional shapes of dark matter halo (e.g., Christodoulou et al. 1992; Katz & Rix 1992). In the present merger model, especially for the model with mass ratio of two disks approximately equal to 0.5 ($m_2 = 0.5$), the developed polar rings are observed to show precession even after the completion of galaxy merging, owing to the dynamical interaction between the central host galaxy and the ring component. In this model, most of the materials in the victim disk is dynamically dispersed due to the stronger tidal interaction between two disks; thus, self-gravity of the victim disk is not important. This result implies that in addition to the gaseous cooling and self-gravity, the dynamical interaction between the central host and polar rings is one of the key determinants for the stability and longevity of the polar rings. In the present stage of this preliminary work, however, it has not been demonstrated whether or not the developed polar rings can survive for more than several tens of dynamical times of the system (corresponding roughly to several $10^8$ yr) without being destroyed or absorbed into the central host because of the later dynamical interaction between these two components. Thus, in our future study, we must investigate how the later dynamical interaction between the central host and the polar ring component can determine the longevity and the long-term stability of the polar ring component in order to confirm the validity of the present merger model for polar ring(s) formation. In particular, we intend to examine the dependence of the stability of polar rings on the initial mass ratio of progenitor two disk galaxies in galaxy mergers. These studies would help us to predict how frequently we can observe the polar ring galaxies among S0 galaxies and, furthermore, give us more quantitative answers to the question as to why only 0.5% of the S0 galaxies actually show remarkable polar rings.

4.3.2. Formation of NGC 4650a

S0 galaxies with annular polar rings (e.g., NGC 4650a) are considered to show global rotation in the central S0 and have polar rings with the central part completely cut out (e.g., Schechter et al. 1984; Whitmore et al. 1990; Sackett et al. 1994). Although a S0 galaxy with narrow polar rings (e.g., ESO 415-G26) has been demonstrated to be reproduced relatively successfully by dissipative galaxy merging, we appear to have failed to reproduce exactly such annular polar ring galaxies. Actually, a self-gravitating disk with very peculiar edge-on morphology observed in models with $m_2 = 0.3$, the transient feature of which can be seen as annular polar rings, does not have such a central hole as that of the observed annular polar rings. One interpretation of this apparent failure is that the present merger model can only form S0 galaxies with narrow polar rings (not with annular rings) and thus that we should incorporate another important physical processes of galaxy merging for the explanation of annular polar ring galaxies. The other possibility is that the apparently “annular” rings are not actually annular rings, but parts of galactic disks. Recent observational studies on a typical annular polar ring galaxy, NGC 4650a, show that the morphology of the polar ring component is more like spiral arms rather than annular rings (e.g., Arnaboldi et al. 1997). This result suggests that the apparently “annular” ring component is actually a self-gravitating “galactic disk” with spiral arm morphology viewed from a specific angle. Furthermore, extensive observational study on the peculiar polar ring galaxy NGC 660 shows an exponential light profile in the gas-rich polar ring component, meaning that the polar ring component is actually a gas-rich spiral “galaxy” without a prominent central part (e.g., van Driel et al. 1995). These observational studies suggest that annular rings observed in polar ring galaxies are actually not the “rings” but normal galactic disks whose central density becomes very small for some unknown reasons. Further observational studies are desired to confirm whether the central part of annular rings in real polar ring galaxies are completely cut out or the apparently annular rings are, in fact, a galactic disk with peculiar morphology.

5. CONCLUSIONS

The present numerical study provides a new mechanism by which both the central S0-like host and the ring component in a polar ring galaxy are simultaneously formed. Although uncertainties of the numerical treatment of gas dynamics and star formation still remain, it appears that our model has succeeded in reproducing some polar ring galaxies and explaining naturally a number of important observational properties of them. In the proposed model, the formation of polar ring galaxies is essentially ascribed to the details of the dynamics of dissipative galaxy merging with specific orbital configurations. Specifically, the central host of a polar ring galaxy is the galaxy that has been inevitably transformed from a late-type spiral into an early-type S0 galaxy during the merging. The ring component, on the other hand, is the “galaxy” that has been dramatically transformed from a late-type spiral into a narrow ring or annuli owing to the violent gravitational interaction and gaseous dissipation during the merging. Although both specific orbital configurations and gaseous dissipation in galaxy merging are required for the formation of polar ring galaxies in the present model, these constraints also give natural explanations to observed trends, such as the prevalence of S0 among polar ring galaxies (e.g., Whitmore et al. 1990), the rarity of polar ring galaxies among S0 galaxies (e.g., Whitmore 1991), and an appreciably larger amount of interstellar gas in polar rings (e.g., Sackett 1991). Moreover, it is found that the morphology of polar rings, such as a narrow ring (e.g., ESO 415-G26), annular rings (e.g., NGC 4650a), helical rings (e.g., NGC 2658), and double rings (e.g.,
ESO 474-G26), can reflect both the orbital parameters of galaxy merging and the initial mass ratio of two merger precursor galaxies. Thus, the present study demonstrates that a merger remnant of a gas-rich galaxy merger is one of the promising candidates of polar ring S0 galaxies. We are grateful to the referee Curtis Struck-Marcell for his valuable comments which greatly contributed to improving the present paper. K. B. thanks the Japan Society for Promotion of Science (JSPS) Research Fellowships for Young Scientist.

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