THE AXISYMMETRIC RING GALAXIES: AM 0053-353, AM 0147-350, AM 1133-245, AM 1413-243, AM 2302-322, ARP 318, AND HEAD-ON PENETRATIONS

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ABSTRACT

Axisymmetric ring systems can be identified from the new catalog of collisional ring galaxies by Madore et al. in 2009. These are O-type-like collisional ring galaxies. Head-on collisions by dwarf galaxies moving along the symmetric axis were performed through N-body simulations to address their origins. It was found that the simulations with smaller initial relative velocities between two galaxies, or in the cases with heavier dwarf galaxies, could produce rings with higher density contrasts. There is more than one generation of rings in one collision and the lifetime of any generation of rings is about one dynamical time. It was concluded that head-on penetrations could explain these O-type-like ring galaxies identified from the new catalog by Madore et al. in 2009, and the simulated rings resembling the observational O-type-like collisional rings are those at the early stage of one of the ring generations.

Key words: galaxies: formation – galaxies: interactions – galaxies: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

The morphology of galaxies has always been an attractive subject and has been investigated intensively through observational and theoretical approaches due to both the beautiful shapes and richness of the complicated components in galaxies. In addition to normal spiral, elliptical, and irregular galaxies, those dominated by ring-like structures, i.e., ring galaxies, are one of the most intriguing categories of peculiar galaxies.

Ring galaxies, a peculiar class of galaxies, contain various ring-like structures with or without clumps, nuclei, companions, or spores. For example, the famous Cartwheel galaxy, first discovered by Zwicky (1941), shows an outer ring, an inner ring, a nucleus, and spores (Theys & Spieg 1976; Fosbury & Hawarden 1977; Higdon 1995). According to the morphology of ring galaxies, Few & Madore (1986) studied 69 ring galaxies in the southern hemisphere and developed a classification scheme. The ring galaxies are classified into two main classes: O-type and P-type galaxies. The O-type galaxies have a central nucleus and a smooth regular ring, while P-type systems often contain an offset nucleus and a knotty ring.

As more and more observational data on ring galaxies have been obtained (Arp & Madore 1987; Bushouse & Stanford 1992; Marston & Appleton 1995; Elmegreen & Elmegreen 2006; Madore et al. 2009), three dominant theories have been proposed to explain the formation and evolution of ring galaxies: the collision scenario, the resonance scenario, and the accretion scenario. In the collision scenario suggested by Lynds & Toomre (1976), ring galaxies are formed after a head-on collision between an intruder galaxy and a disk galaxy. The formation of the Cartwheel galaxy is thought to be a prototype of this scenario. Furthermore, from the observational statistics by Few & Madore (1986), P-type galaxies have an excess of companions and can be considered as being formed by the collision scenario. In the resonance scenario, ring-like patterns are formed by gas accumulation at Lindblad resonances, which respond to external perturbations, such as a bar or an oval. O-type galaxies, with a central nucleus and no obvious companions, are thought to experience the resonance formation process (for instance, IC 4214 (Buta et al. 1999)). The third scenario, accretion, was proposed to explain the origin of the polar ring galaxies. The polar ring galaxies contain a host galaxy and outer rings with gas and stars that orbit nearly perpendicular to the plane of the host galaxy. This type of galaxy is believed to be formed when the material from another galaxy or intergalactic medium is accreted onto the host galaxy. A possible prototype of this scenario is the formation of NGC 4650A (Bournaud & Combes 2003).

On the other hand, Elmegreen & Elmegreen (2006) investigated 24 high-redshift galaxies with rings or partial rings and 15 bent chain galaxies in the Galaxy Evolution from Morphology and Spectral Energy Distributions (Rix et al. 2004) and Great Observatories Origins Deep Survey (Giavalisco et al. 2004) fields. They found that several rings are symmetric with centered nuclei and no obvious companions. For example, one of the interesting ring galaxies is COMBO-17 No. 44999, which has a bright knotty structure like a P-type galaxy but does not have companions. The brightness at the center of the galaxy COMBO-17 No. 44999 is comparable with that of the ring, so the densities at these two regions are similar. Due to the lack of companions, it might be assumed that they were formed through resonances. However, it is unclear whether there is any mechanism of resonance that could form these interesting rings because: (1) there is no obvious non-axisymmetric structure, i.e., bar or spiral, in these galaxies; (2) the galaxy COMBO-17 No. 44999 actually has a P-type property, i.e., knotty structures; and (3) the densities at the ring regions are very high.

Therefore, the above controversial results in Elmegreen & Elmegreen (2006) encourage the study of P-type-like O-type ring galaxies or O-type-like P-type ring galaxies. In fact, the dynamical relations between companions and main galaxies for P-type ring galaxies might not always be obvious. Those ring-structure-driving companions could have merged with the main galaxies and disappeared, and thus formed a P-type-like ring without companions. In contrast, the galaxies with axisymmetric rings might not have formed through the interactions with those...
obvious surrounding companions. They could have been formed through a head-on merger, in which the dwarf galaxy was destroyed and overlapped with the center of the main galaxy, forming an O-type ring.

Recently, Madore et al. (2009) provided a new catalog of collisional ring galaxies. Although these galaxies are classified as the P-type, we tried to find axisymmetric ring systems with central nuclei in this catalog. In this study, we considered them as O-type-like collisional ring galaxies and investigated their formation history. Due to these systems being axisymmetric systems with non-offset central nuclei, head-on penetrations by dwarf galaxies moving along the symmetric axis are considered to be standard models. The stellar components of dwarf galaxies will overlap with the central nucleus when the systems are viewed along the symmetric axes. Those identified companions around the ring galaxy, as listed in the catalog, might not be the main drivers to produce these axisymmetric rings. Many interesting questions could be addressed for the above O-type-like collisional ring galaxies. Could the standard models for head-on collisions explain these observed systems? How bright or strong are these observed rings? When would rings start to form during the collisions? How long could ring structures survive? These were the main goals for the investigation in this paper.

In fact, as a first attack, Struck (2010) used an analytic theory to study a number of systems in Madore et al. (2009). None of the galaxies studied in that paper were examined in this paper. To provide more realistic models, N-body simulations were used to study the symmetric rings. The main differences between the proposed model and the one in Struck (2010) are that (1) the impulse approximation is used in Struck (2010) but not in this study; (2) in this study, close encounters between the main galaxy and the dwarf galaxy could happen several times during one collisional event in the simulations, but the analytic model cannot have this; (3) the dwarf galaxy and the main galaxy actually gravitationally influence each other, but only the proposed model’s simulations can show this self-consistently; and (4) the dwarf galaxy finally merges and becomes part of the main disk galaxy, but the model in Struck (2010) does not consider the contribution from the dwarf’s stellar part.

This study also developed a procedure to quantify the characteristics of the rings, which is helpful for the study of the formation and evolution of the rings. Through comparison between the observational and simulation results, the age of the rings can be estimated.

The observational data of this study’s O-type-like collisional ring galaxies are shown in Section 2, and the details of the models are shown in Section 3. In Section 4, the results of the collision simulations and the formation and evolution of the rings are presented. The observation–simulation comparisons are presented in Section 5, the simulation of the effect of the disk’s length scale is in Section 6, and conclusions are given in Section 7.

2. OBSERVATIONS

Madore et al. (2009) presented a new catalog of 127 collisional ring galaxies with plausible colliders identified around their central galaxy in the images. To study these systems, and in particular to investigate the relation between ring formation and the processes of galaxy-intruder collisions, all of the systems in the catalog were examined. As a first step, this study focused on symmetric cases; therefore, systems with axisymmetric rings were chosen. To make it easier to study ring structures, only systems where the identified colliders were not closely connected with the main galaxies were chosen, leaving 13 systems to study. Finally, only those with known redshifts were used as sample systems in this paper. These final six systems are shown in Figure 1. The images, redshifts, and the spatial resolution were all obtained from the NASA/IPAC Extragalactic Database (http://nedwww.ipac.caltech.edu/). The redshift are written in the upper left corner of each panel, and the thick horizontal lines in the lower left corner represent 10 arcsec. The image data were taken in wave band He II (λ = 468 nm) using a UK Schmidt Telescope (UKST), which is a 1.2 m Schmidt telescope located at the Siding Spring Observatory in Australia. The UKST was operated by the Royal Observatory, Edinburgh, from 1973 to 1988, and it became part of the Anglo-Australian Observatory thereafter. It has carried out many survey projects, for instance, the ESO/SERC Southern Sky Survey, the H-alpha Survey of the Milky Way and the Magellanic Clouds, and the 6dF (6 degree Field).

For each image in Figure 1, because only the relative flux contrast was important for this study, the flux value, $F$, in all pixels was linearly rescaled to be within the interval [0, 1], by multiplying a factor $(F - F\text{min})/(F\text{max} - F\text{min})$, where $F\text{min}$ and $F\text{max}$ were the minimum and maximum flux values in a particular image.

To determine the length scale of these ring galaxies, the spatial resolution of each pixel, kpc pixel$^{-1}$, was calculated by the small-angle formula, where the angular size of each pixel was 1.7 arcsec. The distance to the galaxy, which was needed in the small-angle formula, was determined by the relativistic equation for the Doppler shift and the Hubble law with Hubble constant $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ (Spiegel et al. 2007). Thus, the distance to the galaxy, $d$, was derived as follows:

$$d = \frac{(z + 1)^2 - 1}{(z + 1)^2 + 1} \left(\frac{c}{H_0}\right),$$

where $z$ is the redshift of the galaxy and $c$ is the speed of light.

To obtain the exact ring profiles of the above six galaxies, this study concentrated on the main regions with rings. Figure 2 shows the flux–surface-density (i.e., flux per unit area) plots around the area with ring regions. The center of each ring galaxy was at the origin (0, 0) and the visible extent of the rings were within the boundaries of the plots. The flux–surface-density values were rescaled to be from 0 to 1, using the same method as in Figure 1.

Using the numerical values of the plots shown in Figure 2, the surface density profile was produced as a function of distance $R$. To do that, each pixel was assigned a space coordinate. The pixel where the center of each ring galaxy is located was set as the coordinate origin (0, 0). Other pixels’ coordinates were set accordingly, for example, the coordinate of the pixel just to the left of the central pixel would be ($-1, 0$). Given that coordinate system, the distance $r$ from the origin to a particular pixel could be defined easily. The pixels belonging to the ith annulus would be those with $i < r \leq i + 1$, where $i = 0, 1, 2, \ldots$ and $r$ is the pixel’s distance to the origin. Then, the flux–surface-density of all the pixels belong to the ith annulus would be summed as the total flux–surface-density $F_i$. The flux–surface-density, $\Sigma(R)$, of each annulus was defined as $F_i/N_i$, where $N_i$ is the total number of pixels belonging to this annulus. This study calculated $\Sigma(R)$ for all annuli and rescaled it to be within the [0, 1] interval. The data points shown in Figure 3 give the resulting density profiles.

To obtain an analytic curve to fit the above surface-density profile, this study first integrated the three-dimensional-mass-
density profile of the stellar disk in Hernquist (1993) to yield the surface-density profile as

$$\Sigma_H(R) = \frac{M_d}{2\pi h^2} \exp\left(\frac{-R}{h}\right).$$

(2)

It was then modified to be

$$\Sigma_f(R) = \alpha \frac{M_d}{2\pi h^2} \exp\left(\frac{-\beta R}{h}\right),$$

(3)

where two additional fitting parameters, $\alpha$ and $\beta$, were introduced. The best-fitting parameter set $(\alpha, \beta)$ was determined by minimizing $\chi^2$ (Wall & Jenkins 2003) as

$$\chi^2 = \sum_{i=1}^{k} \frac{(Q_i - E_i)^2}{E_i},$$

(4)

where $Q_i$ is the surface density at a radius $R_i$ and $E_i$ is the $\Sigma_f(R_i)$ with the fitting parameter set $(\alpha, \beta)$.

In the left panels of Figure 3, i.e., Figures 3(a), (c), and (e), the empty circles and the filled circles are the surface density profiles of the ring galaxies. The dotted and the dashed lines are the best-fitting profiles for the empty circles and the filled circles, respectively. The best-fitting parameter set $(\alpha, \beta)$ for the ring galaxies in Figures 3(a), (c), and (e) were $(12.44, 0.67)$, $(12.55, 0.70)$, $(12.17, 0.65)$, $(10.74, 0.61)$, $(15.44, 0.92)$, and $(10.65, 1.06)$ in sequence.
The density contrast was defined as $\Delta \Sigma(R)/\Sigma_f(R)$, where $\Delta \Sigma(R)$ is the difference between the surface density and the best-fitting profile at a radius $R$, i.e., $\Delta \Sigma(R) \equiv \Sigma(R) - \Sigma_f(R)$. Figures 3(b), (d), and (f) show the density contrast as a function of radius $R$ for the ring galaxies. These three panels show that the location of the inner ring structure for these six ring galaxies was from 4 kpc to 20 kpc, and the density contrast of the inner ring was from 0.09 to 0.9.

3. MODEL

In the simulations, the target and the intruder were assumed to be a disk galaxy and a dwarf galaxy, respectively, to investigate the response of collisions between a target disk galaxy, consisting of the stellar disk and the dark matter halo, and a less massive dwarf galaxy, containing the dark matter halo and the stellar component. To study the effect of the intruder’s mass, two dwarf galaxy models were set up, i.e., DG_A and DG_B.

3.1. Units

In the simulations, the unit of length was 1 kpc, the unit of mass was $10^{10} M_\odot$, the unit of time was $9.8 \times 10^8$ years, and the gravitational constant $G$ was 43007.1.

3.2. Initial Setting

Both the stellar disk and the dark matter halo of the target galaxy followed the profiles employed in Hernquist (1993).
Figure 3. Surface-density profiles and the density contrasts of the ring galaxies. For panels (a), (c), and (e), the empty circles and the filled circles represent the surface-density profiles of the ring galaxies. The dotted and the dashed lines show the fits to the empty circles and the filled circles, respectively. For panels (b), (d), and (f), the empty circles and the filled circles show the density contrasts of the ring galaxies.
The density profile of the stellar disk was

$$\rho_d(R, z) = \frac{M_d}{4\pi h^2 z_0} \exp(-R/h) \sech^2 \left( \frac{z}{z_0} \right),$$

where $M_d$ is the disk mass, $h$ is the radial scale length, and $z_0$ is the vertical scale length. Furthermore, the halo density profile was

$$\rho_h(r) = \frac{M_h}{2\pi^{3/2} r_c^2} \exp(-r^2/r_c^2)$$

where $M_h$ is the halo mass, $r_c$ is the tidal radius, and $r_t$ is the core radius. The normalization constant $\alpha$ is defined as

$$\alpha = [1 - \sqrt{\pi} q \exp(q^2) \{1 - \text{erf}(q)\}]^{-1},$$

where $q = r_c/r_t$ and erf$(q)$ is the error function as a function of $q$.

The intruder dwarf galaxy was composed of the dark matter halo and a stellar part with Plummer spheres (Binney & Tremaine 1987; Read et al. 2006), as follows:

$$\rho_{\text{plum}}(r) = \frac{3M_p}{4\pi a^2} \frac{1}{(1 + r^2/a^2)^{5/2}},$$

where $M_p$ and $a$ are the mass and scale length of each component.

The initial positions of the particles could be easily determined according to the density profiles given above. The initial velocities were assigned to particles by the methods described in Wu & Jiang (2009).

The simulations were carried out with the parallel tree code GADGET (Springel et al. 2001), and the softening lengths were set as 0.05 kpc, 0.03 kpc, and 0.035 kpc for the target disk galaxy, the dwarf galaxy DGA, and the dwarf galaxy DGB, respectively.

### 3.3. Model Galaxies

Three model galaxies were needed in the simulations, including the disk galaxy and the dwarf galaxies DGA and DGB. The mass and the scale of the disk galaxy were chosen to be those of a standard spiral galaxy, such as the Milky Way, using the details from Hernquist (1993). Using the chosen units for the disk galaxy, the disk mass, $M_d$, was 5.6, the disk radial scale length, $h$, was 3.5, the disk vertical scale length, $z_0$, was 0.7, the halo mass, $M_h$, was 32.48, the halo core radius, $r_c$, was 3.5, and the halo tidal radius, $r_t$, was 35.0. The disk galaxy had a total of 340,000 particles, i.e., 290,000 dark matter particles and 50,000 stellar particles in the disk. The above parameters’ values are summarized in Table 1.

| Model Parameters of the Disk Galaxy |
|-------------------------------------|
| **Dark halo**                        |
| Mass $M_h (10^{10} M_\odot)$        | 32.48 |
| Core radius $r_c$ (kpc)              | 3.5  |
| Tidal radius $r_t$ (kpc)             | 35.0 |
| Number of particles                  | 290,000 |
| **Stellar disk**                     |
| Mass $M_d (10^{10} M_\odot)$        | 5.6  |
| Radial scale length $h$ (kpc)        | 3.5  |
| Vertical scale length $z_0$ (kpc)    | 0.7  |
| Number of particles                  | 50,000 |

Once the above parameters were set, the dynamical time, $T_{\text{dyn}}$, could be defined by the velocity, $v_{1/2}$, of a test particle at a disk's half-mass radius, $R_{1/2} = 5.95$, that is $T_{\text{dyn}} \equiv 2\pi R_{1/2}/v_{1/2} = 0.174$, where $v_{1/2} = 214.77$.

This study combined the dark matter halo and the stellar disk to set up the disk galaxy after constructing the components independently. The components of the disk galaxy influenced each other and then approached a new equilibrium. According to the virial theorem, when the disk galaxy is in equilibrium, the value of $2K/|U|$ should be around 1, where $K$ and $U$ are the total kinetic energy and the total potential energy, respectively. Thus, the same method used in Wu & Jiang (2009) could be used to examine the equilibrium of the disk galaxy. The disk galaxy approached a new equilibrium at $t = 15T_{\text{dyn}}$, and the energy conservation was fulfilled because the total energy variation was 0.082%. Hence, the disk galaxy at $t = 15T_{\text{dyn}}$ was used to represent the target disk galaxy at the beginning of the collision simulations.

To study the effect of the mass ratio between the main galaxy and intruder dwarf galaxy, two dwarf galaxies with different masses, DGA and DGB, were set up. For DGA, the total mass was 9.52, which was a quarter of the mass of the disk galaxy and had a mass-to-light ratio of 5. The scale lengths of the dark matter halo and the stellar component were 3.0 and 1.5, respectively. The total number of particles was 85,000, containing 68,000 dark matter particles and 17,000 stellar particles. For DGB, the total mass was 4.76, which was half of the mass of DGA. The mass-to-light ratio, the scale lengths of the dark matter halo, and the stellar component were the same as in DGA. To make sure that the mass of each particle in the simulations was the same, the total number of particles of DGB was 42,500, including 34,000 dark matter particles and 8500 stellar particles. Because the dark matter halo and the stellar component of the dwarf galaxy were both spherically symmetric and could be set up simultaneously, the whole dwarf galaxy with two components was initially in equilibrium. The parameters of DGA and DGB are summarized in Table 2.

### 4. COLLISION SIMULATIONS

The motivation of the present study was to examine whether a collision scenario could account for the origin of the axisymmetric ring galaxies, such as those described in Section 2. One target disk galaxy and one dwarf galaxy were employed in each collision simulation. For each simulation, the stellar disk of the target galaxy lay on the $x$–$y$ plane, and the initial relative velocity of the galaxies was along the $z$-axis. The initial separation of the disk galaxy and the dwarf galaxy was 200 kpc, which was far enough to make sure that the two galaxies were initially well separated.

To understand the effects of the mass ratio and the initial relative velocity between the target disk galaxy and the intruder dwarf galaxy, this study presented four collision simulations, which were the combinations of two different initial relative velocity and mass ratios. Table 3 lists the details of the four simulations, titled S1, S2, S3, and S4.
Table 3

| Simulation | Intruder | Initial Relative Velocity |
|------------|----------|---------------------------|
| S1         | DG_A     | 143.1 km s$^{-1}$         |
| S2         | DG_A     | 286.2 km s$^{-1}$         |
| S3         | DG_B     | 135.7 km s$^{-1}$         |
| S4         | DG_B     | 271.4 km s$^{-1}$         |

The initial relative velocities in S1 and S3 were derived from parabolic orbits. Thus, the initial relative velocity, $v_i$, was given according to the equation $E_{orb} = 0$, in which $E_{orb}$ is defined as

$$E_{orb} = \frac{1}{2} \frac{M_1 M_2}{M_1 + M_2} v_i^2 - \frac{G M_1 M_2}{r_i},$$

where $r_i$ is the initial separation of two galaxies, and $M_1$ and $M_2$ are the masses of the disk galaxy and the dwarf galaxy, respectively. The initial relative velocity in S2 (S4) was simply two times the one in S1 (S3); therefore, S2 (S4) had a hyperbolic orbit.

4.1. Evolution

This section presents both the orbital and morphological evolution of the galaxies during the collisions. To obtain more detail about the evolution of the galaxies in the simulations, the time interval between each snapshot was set as $T_s = 0.1 T_{dyn}$.

Figures 4(a)–(d) show the centers of the mass of the disk and dwarf galaxies as a function of time during the collisions in S1–S4. The solid and dotted curves represent the centers of the mass of the whole disk galaxy and dwarf galaxy (both the stellar part and dark matter are included); the short dashed and long dashed curves are for the centers of the mass of the stellar disk and the dwarf’s stellar component. For S1, i.e., in Figure 4(a), the disk galaxy and the dwarf (DG_A) had a close encounter at $t = 55 T_s$ and became well separated at $t = 65 T_s$. After $10 T_s$, i.e., at $t = 75 T_s$, two galaxies became close again due to the gravitational attraction. However, in S2, due to the higher initial relative velocity, the first close encounter took place earlier, the galaxies had a much larger separation, and returned back at a later time (Figure 4(b)). Because the DG_B’s mass was only a half of DG_A’s, in S3 (Figure 4(c)), the gravitational force between the galaxies was smaller, and everything happened slightly later than in S1. Finally, for S4 (Figure 4(d)), due to a weaker gravitational force and larger initial relative velocity, the two galaxies became more separated and did not return back as much as in previous cases.

To visualize the structure evolution, S1 was used as an example to illustrate the time evolution of the stellar disk, together with the dwarf’s stellar component. Figure 5 is the surface number density of the stellar particles (the target and dwarf galaxies were both included) on the $x$–$y$ plane, and Figure 6 is for the $x$–$z$ plane. The two galaxies were separated by 200 kpc initially, and they approached each other from...
Figure 5. Time evolution of the projected density of the stellar components, including the stellar disk and the dwarf’s stellar part, on the x–y plane in S1. (A color version of this figure is available in the online journal.)
Figure 6. Time evolution of the projected density of the stellar components, including the stellar disk and the dwarf’s stellar part, on the x-z plane in S1. (A color version of this figure is available in the online journal.)
t = 0 to t = 54T_s during the first stage. They made contact at t = 55T_s. Later on, the gravitational impact from the dwarf galaxy warped the stellar disk upward and downward from t = 56T_s to t = 75T_s (Figure 6). During this stage, the ring structure formed and expanded outward (Figure 5). Moreover, the dwarf galaxy started to expand after the encounter, and many of the dwarf galaxy’s particles escaped. Consequently, the stellar disk took on a layered appearance at t = 80T_s as viewed on the x−y plane, and its thickness increased with time. Most of the dwarf galaxy’s particles were concentrated around the stellar disk, but some of them extended to a distance of about 100 kpc.

### 4.2. Ring

The results shown in Figures 5 and 6 indicate which snapshots contained ring structures; therefore, we focused on these snapshots. Figure 7(a) shows the surface density of the stellar particles on the x−y plane, as well as the fitted surface-density profile at t = 56T_s, t = 57T_s, and t = 58T_s, in S1. To obtain an analytic curve to fit the surface-density profiles, the modified surface-density profile in Equation (3) was used. The best-fitting parameter set (α, β) was also determined by minimizing χ^2, as in Equation (4). In the χ^2 fitting procedure, the surface density beyond the radius R_ending, where the surface density Q_ending is zero, is neglected. In Figure 7(a), the open circles, filled circles, and crosses represent the surface density at t = 56T_s, t = 57T_s, and t = 58T_s, respectively. The solid, dotted, and short dashed lines are the best-fitting profiles with the parameter set (α, β) = (2.5, 1.3), (2.3, 1.2), and (2.5, 1.2) for open circles, filled circles, and crosses, respectively. As shown in Figure 7(a), it was clear that after the encounter, a ring-like feature was evident at t = 56T_s, which then propagated outward as an expanding ring after t = 56T_s.

To determine the position of the ring, the density contrast as a function of R was needed. The ΔΣ(R) and the density contrast, ΔΣ(R)/Σ(R) (as defined in Section 2), as a function of radius R at t = 56T_s, t = 57T_s, and t = 58T_s are shown in Figures 7(b) and (c), respectively. The different symbols (i.e., the open circles, filled circles, and crosses) represent the ΔΣ(R) and the density contrast at different times (as described in Figure 7(a)).

From the density contrast shown in Figure 7(c), the “ring region” around a ring-like feature could be determined to be the region in which all of the density contrasts were larger than zero. Then, the average of density contrasts in this region, (∆Σ/Σ)_av, could be calculated and the corresponding radius a and b, where the density contrasts were equal to (∆Σ/Σ)_av, could be determined. The boundaries of the ring were then...
Figure 8. Density contrast as a function of radius. (a) $t = 71 T_i$ in S1; (b) $t = 51 T_i$ in S2; (c) $t = 71 T_i$ in S3; (d) $t = 47 T_i$ in S4; (e) $t = 89 T_i$ in S3; (f) $t = 91 T_i$ in S3.
Figure 9. Characteristics of the rings in S1. (a) The average of the density contrast in the ring region as a function of time. (b) The location of the ring as a function of time. (c) The width of the ring as a function of time. (d) The average number of particles in the angular bins. The error bars show the variation in the different angular bins.

defined to be at radius \(a\) and \(b\). The ring location, \(L\), was defined by \(L = (a + b)/2\) and the width of the ring was \(W = |b - a|\).

Figure 7(d) shows the number of particles as a function of the angle in the ring region on the \(x\)–\(y\) plane. The bin size of the angles was 1 deg. The average number of particles in each bin was about 40, and the standard deviation was about 10. Because there were no particular directions where the number of particles was much larger or much less than the average value, this panel confirmed that there were no big clumps, and the shoulder-like features appearing in the surface-density profiles in Figure 7(a) were really the ring structures.

To summarize, Figure 7 gives an example of the procedure to determine the properties of ring structures. After fitting the surface-density profile of all stellar particles, the density contrast as a function of \(R\) is calculated and used to determine the boundaries, width, and the location of the ring. Finally, the numbers of particles in different directions on the \(x\)–\(y\) plane are checked to ensure whether big clumps exist or not. This standard procedure was used to investigate the ring structures in all of the simulation results.

The density contrasts as a function of \(R\) at \(t = 71T_s\) in S1, \(t = 51T_s\) in S2, \(t = 71T_s\) in S3, and also \(t = 47T_s\) in S4 are shown in Figures 8(a)–(d). These were the snapshots when the first-generation rings moved to the farthest distances in the simulations. The density contrasts could be larger at this stage. In addition, two peculiar density contrast plots at \(t = 89T_s\) and \(t = 91T_s\) in S3 are shown in Figures 8(e) and (f). Figure 8(e) shows that two rings were formed around \(R = 11\) kpc and 17 kpc, individually. Because the inner ring, which was located at \(R = 11\) kpc, moved faster than the outer ring, these two rings merged together (Figure 8(f)).

Through the standard procedure to investigate ring structures, the characteristics of rings at different times in S1–S4 were shown, as illustrated in Figures 9–12, respectively. The average density contrast, location, and width of the ring as a function of time are shown in panels (a)–(c). The average number of particles in angular bins (with a bin size of 1 deg) of the ring as a function of time is shown in panel (d), in which the error bars are the standard deviations among the different angular bins.

Considering S1 in Figure 9 as the first example, panel (b) shows that the first ring was formed at \(t = 55T_s\), and this ring moved outward with a nearly constant velocity until about \(t = 70T_s\). In fact, there were three generations of rings. The second was formed at \(t = 77T_s\) and the third was formed at \(t = 104T_s\). As shown in panel (a), the average density contrast increased while the ring moved outward. Moreover, in a comparison of panels (a) and (c), the width of the ring was wider when the density contrast was higher. Lastly, panel (d) confirmed that the ring structures at different times were smooth and without large clumps.

For S2, Figure 10(b) shows that three generations of rings were formed at \(t = 35T_s\), \(t = 59T_s\), and \(t = 105T_s\). The largest average density contrast was around five, and the largest ring width was about 10 kpc (Figures 10(a) and (c)).
Figure 10. Characteristics of the rings in S2. (a) The average of the density contrast in the ring region as a function of time. (b) The location of the ring as a function of time. (c) The width of the ring as a function of time. (d) The average number of particles in the angular bins. The error bars show the variation in the different angular bins.

In S3, at particular times, i.e., from \(t = 86T_s\) to \(t = 89T_s\), as well as \(t = 123T_s\), two rings existed simultaneously. The open circles and crosses in Figure 11 represent the corresponding values of the additional ring. The density contrast of the rings at \(t = 89T_s\) was previously illustrated in Figure 8(e). After \(t = 89T_s\), the two rings combined together and formed a ring-like structure at \(t = 90T_s\). Finally, there is no cross symbol in panel (c) because the widths of the two rings at \(t = 123T_s\) were the same, i.e., 2.8 kpc.

Figure 12 shows the characteristics of the ring-like structures in S4. In addition to the characteristics of the rings described above, it seems that a ring-like structure existed at \(R = 6\) kpc from \(t = 86T_s\) to \(t = 163T_s\). This ring was fixed around \(R = 6\) kpc without moving outward. For this fixed ring-like feature, the average density contrast was around 0.1 and the width was about 1 kpc. However, as shown in panel (d), the huge deviations from \(t = 86T_s\) to \(t = 163T_s\) indicated that this ring-like feature was not a ring; instead, it was composed of clumps.

To understand the effect of the initial relative velocity between the galaxies, this study compared the results between S1 and S2. Because the initial relative velocity in S2 was larger, the first-generation ring in S2 formed earlier. The higher average density contrast in S1 might have been due to the longer interaction timescale between the galaxies, which was from the smaller initial relative velocity. However, the location of the farthest ring and the width of the widest ring were not closely related with the initial relative velocity. Similar conclusions were obtained through the comparison between the results of S3 and S4.

On the other hand, after comparing S1 with S3 (or S2 with S4), we found that because the intruder dwarf galaxy was heavier, the density contrast of the ring was higher, and the location of the farthest ring was further out. Finally, because the moving velocities of the rings were close to constant, as shown in the plots of the ring locations as functions of time, the radial moving velocities of the rings could easily be calculated. The outward-moving velocities of the first-generation rings in S1–S4 were 116.19 km s\(^{-1}\), 108.10 km s\(^{-1}\), 91.13 km s\(^{-1}\), and 86.75 km s\(^{-1}\), in sequence.

5. O-TYPE-LIKE COLLISIONAL RING GALAXIES

Having performed the above simulations, this study examined all of the snapshots in S1–S4 and checked which of them could resemble an O-type-like collisional ring galaxy. All of the simulations were set up as pure axisymmetric simulations, and they did not produce any non-axisymmetric features, which could exist in the galactic nucleus of the observational images.

To compare the observational axisymmetric ring galaxies with the simulation results, it was necessary to numerically determine the exact location of the ring for each observational image. However, due to the poor observational resolution, there were not enough data points available. The location of the
Figure 11. Characteristics of the rings in S3. (a) The average of the density contrast in the ring region as a function of time. (b) The location of the ring as a function of time. (c) The width of the ring as a function of time. (d) The average number of particles in the angular bins. The error bars show the variation in the different angular bins. The open circles and crosses represent the additional ring at $t = 86T_s - 89T_s$ and $t = 105T_s$.

observational ring, $P$, was directly determined as the radius where the density contrast in the ring region was highest (Figure 3).

To obtain the best theoretical model from the simulations for each observational galaxy, the surface–mass–density profiles $\Sigma_M(R_M)$ of all of the snapshots in all of the simulations were compared with the observed flux–surface-density profile $\Sigma_F(R)$. To make $\Sigma_M(R_M)$ more consistent with $\Sigma_F(R)$, new length units of simulations and mass–flux-converting factors were considered.

The process was as follows. First, choose a value $l_u$ and $R_u = l_u \times R_M$ so that the simulation ring position is redefined by this new length unit. (The value of $l_u$ is allowed only if it makes the ring position of that simulation snapshot to be between 0.8 and 1.2 of the observed ring location.) Second, the new surface–mass–density as a function of $R_u$, i.e., $\Sigma_{NM}(R_u)$, under this new length unit is determined (the time unit becomes different accordingly). Third, choose a mass–flux-converting factor $M_F$ and $\Sigma_{MF}(R) = M_F \Sigma_F(R)$. Fourth, repeat the above with different values of $l_u$ and $M_F$ until the square of the difference between $\Sigma_{MF}(R)$ and $\Sigma_{NM}(R_u)$ (including all contributions from the available $R$) is the smallest. In other words, the process will stop when the smallest root mean square of deviations $rms = \sqrt{\sum_{i=1}^{N} (\text{dev}(R_i))^2}$ is obtained, where $\text{dev}(R_i) = \Sigma_{MF}(R_i) - \Sigma_{NM}(R_u)$, $R_i$ is the radii with the available observational data, and $N$ is the total number of observational data for this galaxy.

The final results of this fitting are shown in Table 4. For each galaxy, the best snapshot resembling the observed image is listed in the second column. The corresponding $l_u$ and $M_F$ are in the third and fourth columns. The time unit becomes different accordingly after employing $l_u$ to change the length unit, and the real time of that snapshot is listed in the fifth column. Finally, the rms is in the sixth column.

The best-fitting density profiles are shown in Figure 13, where the solid curves with full circles are the observational data and the dotted curves with empty circles are the simulations. It was found that the simulations could produce general trends of these profiles for the first five galaxies in Figures 13(a)–(e). Particularly, the simulation and observational profiles were very close for the galaxy AM 1413-243 (Figure 13(d)). The six best snapshots listed in Table 4 are plotted in Figure 14.

The above results showed that the head-on penetrations in simulations S1–S4 could explain the first five O-type-like collisional ring galaxies found from Madore et al. (2009). For the sixth one, ARP 318, the major difference was that the central part was very big and extended to a much larger radius. The simulation profile dropped and could not fit the observed flat feature. In the next section, a simulation is introduced that doubles the length scale of the disk. The purpose was to see if the larger disk could produce a bigger central part with a flat
 density profile, as well as to study the effect of different initial conditions for the major galaxy.

6. THE EFFECT OF THE DISK’S LENGTH SCALE

In S1–S4, this study has mainly explored the effects of mass ratios and relative velocities between two merging galaxies. It would be interesting to check whether the ring evolution presented here depended on the initial conditions of the primary galaxy. For example, in relation to galactic disks, Chakrabarti & Blitz (2009) and Chakrabarti et al. (2011) found that disturbances in outer gas disks can be used to characterize galactic satellites, and these disturbances are not extremely sensitive to the assumed initial conditions of the primary galaxies.

To obtain a better model for the galaxy ARP 318, a primary galaxy with a larger length scale is used in the simulation presented here. The disk galaxy was set up using the same method as described in Section 3, except that the radial scale length $h$ was 7 kpc, which was two times the radial scale length of the main disk galaxy in S1–S4. After an initial relaxation of 15 dynamical time, this disk galaxy approached a new equilibrium and was used as the target galaxy in the merging simulation.

Because S3 provided the best fit to one of the O-type-like collisional galaxies described in the last section, all of the model setting and details in this simulation were the same as S3, except for the length scale of the primary galaxy. That is, the dwarf galaxy model DGB was employed as the intruder, the initial separation was 200 kpc, and the initial relative velocity was 135.7 km s$^{-1}$.

The results of the ring evolution are shown in Figure 15. It was found that the general evolution process was very similar to the one in S3 because there were also three ring generations. The locations and widths of the rings were also similar to those in S3. The main difference was that the density contrast was
smaller in this simulation. This could be because the disk had a larger length scale, so the amplitudes of any density disturbance became smaller.

All snapshots of this simulation were also compared with the six observational galaxies through the same procedure described in the last section. Finally, it was confirmed that none of the
7. CONCLUDING REMARKS

Motivated by the results in Elmegreen & Elmegreen (2006), this study found six axisymmetric rings with central nuclei from the new catalog of collisional ring galaxies in Madore et al. (2009) and presented their structures, profiles, and density contrasts. They were O-type-like collisional ring galaxies, and their possible formation scenario was addressed in this paper. Head-on collisions by dwarf galaxies moving along the symmetric axis were considered, and $N$-body simulations were used to investigate the evolutionary process. It was found that the simulations with smaller initial relative velocities between two galaxies or the cases with heavier dwarf galaxies could produce rings with higher density contrasts. Usually there was more than one generation of rings in any of the simulations. The lifetime of any generation of rings was about one dynamical time, and the rings continued moving outward with constant velocities until they disappeared at the outer part of the galactic disks.

Figure 14. Simulational snapshots resembling the observational O-type-like collisional ring galaxies. (A color version of this figure is available in the online journal.)

snapshots in this simulation provided a better fit to any of the six observational galaxies, including ARP 318.
Figure 15. Characteristics of the rings in the simulation described in Section 6. (a) The average of the density contrast in the ring region as a function of time. (b) The location of the ring as a function of time. (c) The width of the ring as a function of time. (d) The average number of particles in the angular bins. The error bars show the variation in the different angular bins.

Through the observation–simulation comparison shown in Figure 13, this study concluded that head-on penetrations could explain these low-density contrast ring galaxies. Moreover, it was found that the simulation rings that resemble the observational O-type-like collisional rings were those at the early stage of one of the ring generations.

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