ORIGIN OF DWARF IRREGULAR GALAXIES WITH OUTER EARLY-TYPE STRUCTURES

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ABSTRACT

Recent observations have reported that some gas-rich dwarf irregular (dIrr) galaxies appear to have spherical distributions in the outer underlying old and intermediate-age stellar populations (e.g., NGC 6822). These observations imply that some dIrr’s have two distinct (or “two-component”) structures, i.e., inner disky and outer spherical ones, although the number fraction of dIrr’s with such structures remains observationally unclear. We discuss how such two distinct structures are formed during dIrr formation on the basis of observations and simulations. Our numerical simulations show that the remnants of mergers between two gas-rich dIrr’s with initially extended gas disks can have both extended spheroids composed of older stellar populations and disks composed mostly of gas and young stars. The simulated remnants with two distinct structures can be still identified as dIrr’s owing to the presence of star-forming regions. The structural properties of outer spherical structures in dIrr’s formed from dIrr-dIrr merging depend on initial conditions of merging, which suggests that outer structures in dIrr’s can be diverse. We also discuss other possible physical mechanisms for the formation of outer spherical structures composed of older stars in dIrr’s.

Subject headings: galaxies: dwarf — galaxies: evolution — galaxies: irregular — galaxies: ISM — galaxies: stellar content

Online material: color figures

1. INTRODUCTION

Luminous galaxies like the Milky Way can be formed from merging and accretion of numerous low-mass galactic building blocks like dwarf galaxies in hierarchical galaxy formation scenarios based on the cold dark matter cosmology (e.g., White & Rees 1978). Physical properties of dwarf galaxies thus have been discussed extensively in many different contexts of galaxy formation and evolution, such as the physical mechanism for the galaxy-scale star formation process in dIrr’s (e.g., Hunter 1997) and evolutionary links between different types of dwarfs (e.g., Grebel et al. 2003). Stellar populations, structures and kinematics of H i gas, and spatial distributions of young stars in gas-rich dIrr’s particularly have attracted much attention from theoretical works on the formation of stars and star clusters (e.g., Gallagher & Hunter 1984; Hunter 1997) and inner structures of their dark matter halos (e.g., Burkert 1995).

Although previous observations revealed fundamental physical properties of star-forming regions, young stellar populations, and H i gas in dIrr’s (e.g., Hunter 1997), structural and kinematical properties of underlying older stellar populations remain fairly unclear. Observational studies of dIrr’s based on broadband imaging (UBVIJK) revealed that the structures of the main disk components in dIrr’s can be described as exponential profiles (Hunter & Elmegreen 2006). Furthermore observational studies on the mid-infrared properties of dIrr’s suggested that their overall structure is the same in different passbands for most dIrr’s (Hunter et al. 2006). Since these observations are based on integrated stellar lights, they did not allow the authors to investigate separately structures of stellar populations with different ages in detail.

Recent observational studies on spatial distributions of individual older (e.g., RGB stars) and intermediate-age (e.g., AGB ones) stars in nearby dIrr’s have shown that some dIrr’s (e.g., NGC 6822 and the Small Magellanic Cloud [SMC]) have apparently spherical distributions in the outer underlying older stellar populations (e.g., Battinelli et al. 2006; Cioni et al. 2006; Demers et al. 2006). These observations combined with the above-mentioned imaging ones (e.g., Hunter et al. 2006) imply that some dIrr’s possibly have inner main disky structures with younger stellar populations surrounded by extended spherical structures composed of older stellar populations: some dIrr’s have two distinct (or “two-component”) structures. It is, however, unclear how such two-component structures were formed in some dIrr’s (e.g., NGC 6822).

The purpose of this Letter is twofold. The first purpose is to introduce a classification scheme that divides the structures of outer underlying older stellar populations in dIrr’s into the following two: “early type” (spherical) and “late type” (disky). The possible candidates of dIrr’s with early- and late-type outer structures are summarized in Table 1, and the schematic diagram for the proposed structure classification scheme is shown in Figure 1. Outer early-type structures in NGC 6822, IC 10, and IC 1613 are confirmed by Battinelli et al. (2006), Demers et al. (2003), and Battinelli et al. (2007), respectively.

Tikhonov (2006) found that young stars in a dIrr form a thin disk with the size corresponding to its visual size whereas older ones form an extended thick disk for a number of dIrr’s (e.g., DDO 216, ESO 381-018, IC 1574, and IC 3104); these dIrr’s with outer late-type structures may well be regarded as normal dIrr’s. Furthermore Demers et al. (2003) found that IC 1613 does not have an outer spherical halo composed of old stars (e.g., red giants) but shows a disky structure composed of carbon stars: IC 1613 is an example of a dIrr with late-type structure.

The second purpose of this Letter is to demonstrate that gas-rich dwarf-dwarf merging can transform dIrr’s with outer late-type structure into those with early-type ones. We mainly describe the physical properties of the remnants of dwarf-dwarf mergers with different model parameters in order to discuss the origin of dIrr’s with outer early-type structures. It should be stressed here that dIrr’s with early-type structures discussed in the present Letter are different from “transition-type dwarfs” (e.g., Phoenix and DDO 210), which are an intermediate class of objects between dIrr’s and dE’s/dSph’s and have H i gas
mass of at most a few $10^6 M_\odot$ (e.g., Grebel et al. 2003): formation and evolution of the transition-type dwarfs are discussed in detail by Skillman et al. (2003). We do not intend to discuss dIrr’s in the Local Group, although observations of them provided some clues to the formation and evolution of dIrr’s in general (e.g., Mateo 1998).

Recent observational studies on stellar kinematics in dIrr’s have shown that there can be kinematical differences between stars and H i gas: Hunter et al. (2002) found that stellar components in NGC 4449 have a much smaller amount of rotation in comparison with gaseous ones. Since we consider that dIrr’s with these gas-star kinematical differences are possible candidates for those with outer early-type structures, we list the candidates in Table 1: such star-gas kinematical differences in NGC 6822 and the SMC are observationally confirmed by Demers et al. (2006) and Harris & Zaritsky (2006), respectively.

2. THE MODEL

We investigate chemodynamical evolution of gas-rich mergers between dIrr’s with stellar and gaseous disks embedded in massive dark matter halos by using our original N-body/SPH (TREESPH) codes with models of chemical evolution and globular cluster formation (Bekki et al. 2003). Since the details of numerical techniques and methods (e.g., ways to model chemical enrichment processes) are already given in above paper and our forthcoming papers (Bekki & Chiba 2008), we briefly describe them here. We adopt the Burkert profile (Burkert 1995) for the radial density profile of the dark matter halo of a dIrr. The total masses of the dark matter, the stellar component, and the gaseous component for the dIrr are set to be $8.0 \times 10^8 M_\odot$, $4.0 \times 10^8 M_\odot$, and $8.0 \times 10^8 M_\odot$, respectively.

The dIrr is described as a disk, and the radial ($R$) and vertical ($Z$) density profiles of the initially thin disks are assumed to be proportional to exp ($-R/R_0$) with scale length $R_0 = 1$ kpc and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.2 R_0$, respectively. The H i diameters of gas-rich galaxies are generally observed to be significantly larger than their optical disks (Broeils & van Woerden 1994). Therefore, the ratio ($s_g$) of the stellar disk size ($r_s$) to the gaseous one ($r_g$) is assumed to be a free parameter. We however mainly show the results of the model with $s_g = 4.0$. Star formation in gas is modeled by converting the collisional gas particles into collisionless new stellar particles according to the Schmidt law (Schmidt 1959) with exponent $\gamma$ equal to 1.5 (e.g., Kennicutt 1998). The stars formed from gas are called “new stars” whereas stars initially within a disk are called “old stars” throughout this Letter. The simulations have mass and size resolutions of $10^3 M_\odot$ and 50 pc, respectively, for stars in all models.

The mass ratio of the two merging dIrr’s ($m_2$), the pericenter distance ($r_p$), and the eccentricity ($e_p$) are assumed to be free parameters. The orbits of the two dIrr’s are set to be the same as the $xy$ plane, and the distance between the center of mass of the two dIrr’s is 20 kpc. The spin of each galaxy in a merger is specified by two angles $\theta$ and $\phi$, where suffix $i$ is used to identify each galaxy; $\theta$ is the angle between the $z$-axis and the vector of the angular momentum of a disk; $\phi$ is the azimuthal angle measured from the $x$-axis to the projection of the angular momentum vector of a disk onto the $xy$ plane. Although we run many models with different orbits, we mainly show models with $r_p = 1$ kpc, $e_p = 1.0, \theta_1 = 30^\circ, \theta_2 = 120^\circ, \phi_1 = 90^\circ$, and $\phi_2 = 30^\circ$.

We mainly describe the results of the four representative models with $m_2 = 0.1, 0.3, 0.5$, and 1.0, because the merger remnants of these models show (i) early-type morphologies in their underlying older stellar populations and (ii) diversity in the morphologies. We do not intend to discuss star formation histories, chemical evolution, and formation of globular clusters in dIrr’s with outer early-type structures and their dependences on model parameters: these will be discussed in our forthcoming papers. The stellar mass-to-light ratio in the $B$-band ($M_*/L_B$) is assumed to be 1.78 for old stars and 0.25 for new ones, so we can convert the simulated stellar mass densities into the $B$-band surface brightness ($\mu_B$). The adopted $M_*/L_B$ for old (new) stars are from the tables of stellar population synthesis models with $\text{[Fe/H]} = -1.28$ and ages of 5 (0.5) Gyr by Vazdekis et al. (1996).

3. RESULTS

Figure 2 shows that spatial distributions of old and new stars are significantly different in the sense that spatial distributions of new stars are much more compact and flattened than those...
of old ones in the four representative models with different \( m_s \). Spatial distributions of underlying old stars depend on \( m_s \) such that they are more spherical in the models with larger \( m_s \). Extended gas disks surrounding new stars can be clearly seen in all of the four models, and very low-level star formation with the rate of 0.03–0.1 \( M_\odot \) yr\(^{-1} \) is still ongoing within the gas disks in a sporadic manner for the models. The formation of extended gas disks in merger remnants is due essentially to the presence of extended gas disks in merger precursor dIrr’s. Thus, these remnants with outer (flattened) spheroids composed of old stars, disky structures of young stars, and extended gas disks can be morphologically classified as dIrr’s with outer early-type structures.

About 30% of initial gas masses corresponding to \( \sim (2–5) \times 10^8 M_\odot \) can still be within the remnants, which mean that the remnants can be regarded as gas-rich dwarfs. Figure 3 shows that the gas mass fractions \( (f_g) \) are significantly higher in the outer parts of the merger remnant for the model with \( m_s = 0.3 \) \( (f_g \sim 0.6 \text{ for } R \sim 5 \text{ kpc}) \). This radial dependence of gas mass fraction can be seen in models with different \( m_s \), which implies that dIrr’s with early-type structures formed from the merging of dIrr’s have most of their H\,i gas in their outer parts. Figure 3 also shows that although there is a strong concentration of new stars in the central region \( (R \sim 1 \text{ kpc}) \) of the merger remnant \( (f_g > 0.5) \), the dark matter halo already dominates in mass there \( (i.e., f_g < 0.3) \).

Figure 4 shows \( B \)-band surface brightness distributions \( \mu_B \) estimated separately for old and new stars in the merger remnant with \( m_s = 0.3 \). New stars have significantly higher \( \mu_B \) than old ones within the central 5 kpc of the remnant, so the optical morphology of the remnant can be determined largely by the distribution of new stars: in spite of its regular (flattened) spherical morphology in the underlying old stars, this remnant can still be classified as a dIrr rather than a dSph (or dE) in the canonical morphological classification scheme, because the outer spherical distribution of old stars \( (R > 1 \text{ kpc}) \) with very low \( \mu_B \) (>27 mag arcsec\(^{-2} \)) is hard to detect. It is confirmed that low surface brightness outer envelopes composed mostly of old stars are common in the remnants of dwarf-dwarf mergers with different \( m_s \) in the present study. Thus, the present study demonstrates that two dIrr’s with late-type structures can be transformed into one dIrr with an outer early-type structure through gas-rich merging.

4. DISCUSSION AND CONCLUSIONS

This Letter has shown that if gas-rich dIrr’s have extended gas disks, merging between the two can hardly transform them into one gas-free dSph owing to the presence of the gas disk and star-forming regions in the remnant. The Faint Irregular Galaxies GMRT Survey (FIGGS) has recently revealed that the median ratio of \( r_d/r_s \) is about 2.4 for dIrr’s with a median \( M_\odot \sim -13 \text{ mag} \) (Begum et al. 2008). This observation combined with the present results implies that morphological transformation from two gas-rich dIrr’s into gas-free dSph’s via merging is highly unlikely, at least, in the present universe. We thus suggest that the remnants of merging between dIrr’s can be identified as dIrr’s with outer early-type structures and gas such as NGC 6822 (Demers et al. 2006). Possibly, stripping of H\,i gas due to tidal interaction with luminous galaxies and ram pressure of hot gas in group and cluster environments could
drive further evolution from dIrr’s with early-type structures into gas-free dSph’s.

Given that the merging of low-mass galactic building blocks can be a fundamental mode of galaxy formation in the hierarchical clustering scenarios (e.g., White & Rees 1978), the present dIrr’s with outer early-type structures could be the relic of such hierarchical galaxy formation. However, it is observationally unclear what fraction of dIrr’s are actually those with early-type structures owing to the lack of extensive statistical studies on spatial distributions of older stellar populations in the outer parts of dIrr’s. Van den Bergh (1988) suggested that typical dIrr’s are triaxial systems with axis ratios of 1.0 : 0.9 : 0.4 based on the observed distributions of inclination angles of nearby dIrr’s. Observational studies on the distribution of ellipticities in light distributions of 30 low surface brightness dIrr’s suggested that the intrinsic shape of the dIrr’s is triaxial and slightly less spherical than dE’s (Sung et al. 1998). Although these observations imply that the inner main components of dIrr’s have more flattened distributions, it remains unclear whether outer older ones also have such distributions.

As shown in Figure 4, the outer underlying structure composed of older stars in a dIrr formed by merging is hard to detect owing to its very low surface brightness (e.g., $\mu_B > 30$ mag arcsec$^{-2}$ for $R > 3$ kpc), even if the mass fraction of the older stars is significant. This suggests that observations based on spatial distributions of individual bright stars (e.g., RGB/AGB/carbon stars) rather than on broadband imaging would be better to reveal the presence of outer extended structures composed mostly of older stars in dIrr’s. Although the presence of intermediate-age stars within the outer halos for a number of dIrr’s has been reported (e.g., Albert et al. 2000), the details of their spatial distributions are not so clear for some of the dIrr’s. As suggested in the present simulations, the possible presence of two distinct structures (i.e., inner disks and outer spheroids) would have valuable information on the formation of dIrr’s. Thus, it is doubtlessly worthwhile for future observations to detect outer spherical or disk structures composed of older stars in dIrr’s.

Although nearby dIrr’s are observed to show signs of rotational kinematics in their gaseous components (e.g., Mateo 1998 for a review), it is observationally unclear whether their stellar components also have rotational kinematics (e.g., Hunter et al. 2002, 2005). The present study predicts that $V/\sigma$ can be significantly different between gas and stars in the merger remnants in the sense that their stellar $V/\sigma$ values are smaller than gaseous ones. Therefore, gas-rich dIrr’s with kinematically hot stellar components are promising candidates for the remnants of mergers between dIrr’s with extended gas disks. Thus, future systematical studies of stellar kinematics of dIrr’s will help us to understand what fraction of dIrr’s are those with early-type structures and thus possibly formed from dwarf-dwarf merging.

Both the presence of intermediate-age stars in very outer regions of dIrr’s (e.g., Albert et al. 2000; Letarte et al. 2002) and the apparently spherical distributions of these stars (e.g., Battinelli et al. 2006) can be explained by the present merger scenario of dIrr formation, if merging can happen 2–10 Gyr ago. However, dIrr-dIrr merging can be only one of several possible physical mechanisms for the formation of outer structures composed of intermediate-age stars. For example, minor merging of very tiny dwarfs with intermediate-age stars onto a dIrr can be also responsible for the presence of AGB and carbon stars in the outer region of the dIrr, although such minor merging can hardly produce an outer spherical structure. If supersonic gaseous outflow driven by central star formation activity in a dIrr can interact with the outer halo gas and consequently trigger star formation in the high-density shocked gaseous regions, such new stars might well be identified as intermediate-age halo stars several Gyr later; dynamical relaxation after the formation of halo stars can be responsible for the formation of a spherical structure around the dIrr in this scenario. We thus suggest that the physical properties of older and intermediate-age stars in the very outer regions of dIrr’s can provide valuable information on the formation and evolution of dIrr’s.

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