DWARF GALAXY FORMATION INDUCED BY GALAXY INTERACTIONS

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ABSTRACT

Growing evidence is being accumulated that some gas-rich dwarf galaxies are formed from material liberated by galaxy collisions and/or mergers. Also, gas-poor dwarf elliptical galaxies are often found in the central regions of clusters of galaxies. These observations suggest strongly that the formation of most dwarf galaxies is linked to galaxy interactions. Therefore, now seems like the right time to investigate the formation efficiency of such tidal dwarf galaxies. Adopting the galaxy interaction scenario proposed by Silk & Norman, we find that if only a few dwarf galaxies are formed in each galaxy collision, we are able to explain the observed morphology-density relations for both dwarf and giant galaxies in the field, groups of galaxies, and clusters of galaxies. It seems worthwhile noting that tidal dwarf formation may be coupled with the transformation from gas-rich disk galaxies to early-type galaxies such as S0 and elliptical galaxies.

Subject headings: galaxies: formation — galaxies: interactions — galaxies: structure

1. INTRODUCTION

Although dwarf galaxies are the most numerous systems in the nearby universe (Ferguson & Binggeli 1994; Binggeli, Sandage, & Tammann 1988; Mateo 1998), it seems unclear how they are related in origin to typical giant galaxies. Dwarf galaxies could be formed through the same physical formation process as giant galaxies, i.e., the gravitational collapse of protogalactic gas clouds (Dekel & Silk 1986; White & Frenk 1991; Frenk et al. 1996; Kauffmann, Nusser, & Steinmetz 1997). However, it is known that dwarf elliptical galaxies (dEs) appear to belong to a different class from giant ellipticals (Es) in the fundamental plane (Kormendy 1985), suggesting that the formation and/or evolution processes of dwarfs may not be the same as those of giants.

It has been argued from an observational viewpoint that dwarf galaxies may be formed by galaxy collisions because there appears to be morphological evidence for dwarf galaxies in tidal tails of interacting galaxies (Zwicky 1956; Schweizer 1978); i.e., gas-rich dwarf irregular galaxies can be made out of stellar and gaseous material pulled out by tidal forces from the disks of colliding parent galaxies into the intergalactic space. This possibility has been recently reinforced by a number of pieces of observational evidence (Schweizer 1982; Bergvall & Johansson 1985; Mirabel, Lutz, & Maza 1991; Mirabel, Dottori, & Lutz 1992; Duc & Mirabel 1994, 1998; Yoshida, Taniguchi, & Murayama 1994; Braine et al. 2000; Weilbacher et al. 2000; Hunter, Hunsberger, & Roye 2000). Such formation of tidal dwarf galaxies has also been demonstrated by numerical simulations of merging/interacting galaxies (Barnes & Hernquist 1992; Elmegreen, Kaufman, & Thomasson 1993). Therefore, tidal formation seems to be one of the important formation mechanisms of dwarf galaxies; note that these tidal dwarf galaxies (TDGs) are basically dwarf irregular galaxies when they are born.

The most populous type of dwarf galaxy is the dE (Ferguson & Binggeli 1994). It is known that dEs generally trace the spatial distribution of giant galaxies in clusters of galaxies and that they tend to be close companions to giant galaxies (Binggeli, Tarenghi, & Sandage 1990). It should also be noted that the relative frequency of both dEs and giant early-type galaxies is a monotonically increasing function of the richness of groups and clusters (Ferguson & Binggeli 1994) and that this trend is found to be continued in less rich environments such as the field (Vader & Sandage 1991). These observational results suggest that the formation of dEs is strongly related to that of early-type galaxies (E and S0 galaxies). If the formation of early-type galaxies is related to galaxy interactions and/or merger events, as suggested by Silk & Norman (1981, hereafter SN81), a significant part of dEs may be fossils of TDGs which were formed through past tidal interactions. Therefore, it seems important to investigate the possibility that most early-type dwarf galaxies are also made by galaxy interactions.

2. TIDAL FORMATION OF DWARF GALAXIES

2.1. Model

Let us suppose that galaxy interactions and/or merger events act as the dominant formation mechanism of dwarf galaxies in any environment. In order to model this scenario, we adopt the galaxy interaction scheme proposed by SN81 because their scheme can be responsible for the observed morphology-density relation found by Dressler (1980). In this scenario, it is presumed that galaxy interactions occur during the course of the hierarchical structure formation in the universe. In order to account for the tidal formation of dwarf galaxies, we assume that some dwarf galaxies are made in each interaction. This modified interaction scheme is shown in Table 1. Here, following SN81, we take account of only the interactions between disk galaxies (spiral [Sp] and S0 galaxies).

Based on the above assumption, we obtain a set of kinetic equations for morphological-type evolution as a consequence of galaxy interactions in the following form:

$$\frac{1}{\gamma} \frac{dn_{S0}}{dt} = -2n_{Sp}^2 - n_{S0} n_{Sp},$$

(1)

$$\frac{1}{\gamma} \frac{dn_{Sp}}{dt} = n_{Sp} + (1 - 2a)n_{Sp} n_{S0} - 2hn_{S0}^2,$$

(2)
implicit solutions to equations (1), (2), (3), and (4) as follows:

\[ \frac{1}{\gamma} \frac{dn_{E}}{dt} = bn_{S0}^{2} + an_{S0} n_{Sp}, \quad (3) \]

\[ \frac{1}{\gamma} \frac{dn_{de}}{dt} = k_{1} n_{Sp}^{2} + [k_{2} a + k_{3} (1 - a)] n_{S0} n_{Sp} + [k_{4} b + k_{5} (1 - b)] n_{S0}^{2}, \quad (4) \]

where \( n_{Sp}, n_{S0}, n_{E}, \) and \( n_{de} \) are the number densities of spirals, S0s, ellipticals, and dwarfs, respectively, \( \gamma \) is the mean collision rate, and \( k_{i} \) (\( i = 1 - 5 \)) is the number of dwarfs formed by one collision in each case. Note that the first three equations are the same as those in SN81.

In order to solve these equations, following SN81, we introduce the variable \( x = \frac{n_{S0}}{n_{Sp}} \) which decreases monotonically with increasing galaxy density. Then we obtain the analytical solutions to equations (1), (2), (3), and (4) as follows:

\[ n_{Sp} = \frac{x^{2}}{x^{2} + (3 - 2a)x + 1 - 2b} \left\{ \tan^{-1} \left( \frac{2x + 3 - 2a}{\Delta} \right) - \frac{\pi}{2} \right\}, \quad (5) \]

\[ n_{S0} = n_{Sp} x^{-1}, \quad (6) \]

\[ n_{E} = \int_{x}^{\infty} \frac{(b + ax) n_{Sp} dx}{x^{2}[x^{2} + (3 - 2a)x + 1 - 2b]}, \quad (7) \]

\[ n_{de} = \int_{x}^{\infty} \frac{k_{1} x^{2} + k_{2} a + k_{3} (1 - a)x + k_{4} b + k_{5} (1 - b)] n_{Sp} dx}{x^{2}[x^{2} + (3 - 2a)x + 1 - 2b]}, \quad (8) \]

where

\[ \Delta^{2} = 4(1 - 2b) - (3 - 2a)^{2}. \quad (9) \]

Since \( x \) decreases monotonically with the increasing number density of giant galaxies, we obtain the following constraints on \( a \) and \( b \):

\[ 0 \leq b \leq \frac{1}{2} - \frac{3(2a - a)^{2}}{4}, \quad \text{and} \quad \frac{1}{2} \leq a \leq 1. \quad (10) \]

We assume that all galaxies are initially spiral galaxies and their initial number density is \( n_{o} \). For simplicity, we suppose that the number of dwarfs formed by each collision case is identical in all cases, i.e., \( k_{1} = k_{2} = k_{3} = k_{4} = k_{5} = k \). Since our analysis is made from a statistical point of view, we allow noninteger values of \( k \) in later analysis. Then, we have only three parameters, \( a, b, \) and \( k \), in our model. Our goal is to find a plausible solution responsible for the observed number densities of various types of galaxies as a function of galaxy number density.

It is uncertain whether or not interactions of gas-poor S0s produce dwarfs similar to those formed in spiral mergers. It seems likely that stars liberated tidally from S0s may remain as a sparse stellar system like low surface brightness (LSB) dwarfs. However, since there is no such numerical simulation, we have no firm answer to this question. Therefore, in our analysis, we treat all kinds of dwarf galaxies as one population of dwarf galaxies. This treatment is enough when we compare our results with observations because no detailed classification is made in the observational data given in § 2.2. However, this treatment will be refined in future theoretical and observational studies.

### 2.2. Observational Data

We use the following two data sets: (1) The sample of Jerjen, Tamman, & Binggeli (1992, hereafter the JTB sample). They investigated galaxy populations brighter than \( M = -15 \) in the Virgo Cluster, the Coma Cluster, and some groups of galaxies using data compiled from the literature. Five morphological types (E, S0, Sp, Irr, and dE) are taken into account in their analysis. In later analysis, irregular galaxies are included in the spiral sample. (2) The sample of Ferguson & Sandage (1991, hereafter the FS sample). They investigated galaxy populations in seven nearby groups of galaxies. Taking account of the completeness of their survey, we use the data of galaxies with \( M_{B} < -15.5 \). Although the galaxies are classified morphologically into nine types, we classify dE, dE,N (nucleated dE), and dS0 as E and Sd-Scd and Sd-Im as Sp in our analysis. In Table 2, we give a summary of the two samples. Since the limiting magnitudes are different between the two samples, we treat them as independent samples.

### 2.3. Comparison of Model Results with the Observations

Here we solve the kinetic equations (1), (2), (3), and (4) numerically. In these equations, there are the free parameters \( a, b, \) and \( k \). Taking the constraints in equation (10), we vary \( a \) from 0.5 to 1 with a step of 0.01 and \( b \) from 0 to 1. We give a summary of the two samples. Since the limiting magnitudes are different between the two samples, we treat them as independent samples.

### Table 1

| Scheme | Collision | Parameter | Result       |
|--------|-----------|-----------|--------------|
| 1      | Sp + Sp   |           | S0 + k₁ dEs  |
| 2      | Sp + S0   | a         | E + k₂ dEs   |
| 3      | S0 + S0   | b         | E + k₃ dEs   |

**Note:** In this scheme, a merger between two spiral galaxies evolves not into an elliptical galaxy but into an S0 one. The reason for this is as follows: It is widely accepted that elliptical-like products are formed by dissipationless collapse. Mergers between gas-rich spiral galaxies can achieve a similar physical condition in their final phase. However, if the star formation timescale is longer significantly than the dynamical timescale, the remaining gas will settle to a disk and the end product will not become an elliptical-like galaxy. This is confirmed by numerical methods.

### Table 2

| Morphological Populations | E   | S0  | Sp  | dE  |
|---------------------------|-----|-----|-----|-----|
| **JTB Sample**            |     |     |     |     |
| Groups                    | 3   | 6   | 88  | 3   |
| Virgo                     | 6   | 9   | 40  | 45  |
| Coma                      | 10  | 12.5| 2.5 | 75  |

| Morphological Populations | E   | S0  | Sp  | dE  |
|---------------------------|-----|-----|-----|-----|
| **FS Sample**             |     |     |     |     |
| Leo                       | 20.8| 15.0| 47.5| 8.3 |
| Dorado                    | 14.1| 23.3| 50.3| 9.2 |
| NI400                     | 18.6| 27.5| 15.0| 39.0|
| N5044                     | 21.6| 15.5| 27.2| 31.5|
| Fornax                    | 15.4| 15.5| 33.5| 31.9|
| Antlia                    | 11.7| 14.6| 30.4| 41.0|
| Virgo                     | 7.4 | 10.8| 37.9| 38.7|
suggest that the dwarf formation efficiencies ($k$) may be more affected by their environments rather than by the local value of $x$ because $x$ does not always correspond to the richness of groups and clusters. For example, the Virgo cluster is the system with both the largest number of galaxies and the lowest $x$, while the N1400 group is a relatively poor group with the largest $x$.

3. DISCUSSION

We have found that our model can be responsible for the observed numbers of dEs in the various environments from poor groups of galaxies to the usual rich clusters of galaxies. The formation rate of TDGs is estimated to be $\sim 1-2$ in each galaxy interaction. It is interesting to compare this value with the actual observed numbers of TDGs. In Table 3, we give a summary of the observed number of TDGs, $N_{\text{TDG}}$, in the seven interacting/merging galaxies. Although about 10 TDGs are detected in NGC 5291 (Duc & Mirabel 1998) and the Superantennae (Mirabel et al. 1991), a few TDGs are typically observed in the remaining five galaxies. Although the three TDGs in ESO 148-IG02 (Bergvall & Johansson 1985) are relatively bright, $M_B \sim -17$ to $-18$, most of the remaining TDGs are fainter than $M_B \sim -15$ (e.g., Yoshida et al. 1994). Since we use the data of galaxies brighter than $M_B \sim -15$ in the present study, our result ($k \sim 1-2$) appears consistent with the observations.

Barnes & Hernquist (1992) have shown that a dozen TDGs can be formed in the tidal tails of a merger between two gas-rich disk galaxies. The most massive objects among them reach several $10^9 M_\odot$ and are expected to be brighter than $M_B \sim -15$. However, it is noted that the majority of the TDGs in their simulations are fainter than $M_B < -15$. Therefore, our results also appear consistent with the numerical simulations.

The galaxy interaction scheme of SN81 adopted in this study is basically addressed to the early collapse phase of clusters of galaxies at high redshift. Therefore, even if numerous TDGs could be formed in each interaction between protodisk galaxies, a significant part of them would either merge to form more massive objects or return to some giant galaxies during the course of the dynamical evolution of clusters of galaxies. Therefore, our result (i.e., $k \sim 1-2$) should be regarded as the number of TDGs which have survived for $\sim 10^{10}$ yr. Even if a large number of TDGs were originally formed in early galaxy interactions,

TABLE 3

| Number | Galaxy   | $N_{\text{TDG}}$ | Reference |
|--------|----------|-----------------|-----------|
| 1...... | NGC 7252 | 2               | 1         |
| 2...... | ESO 148-IG02 | 3           | 2         |
| 3...... | Antennae* | 1               | 3         |
| 4...... | Superantennae* | 9   | 4         |
| 5...... | Arp 105  | 2               | 5         |
| 6...... | NGC 2782 | 1               | 6         |
| 7...... | NGC 5291 | 11              | 7         |

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*a NGC 4038 + NGC 4039.
*b IRAS 19254 – 7245.

REFERENCES.—(1) Schweizer (1982); (2) Bergvall & Johansson (1985); (3) Mirabel et al. (1992); (4) Mirabel et al. (1991); (5) Duc & Mirabel (1994); (6) Yoshida et al. (1994); (7) Duc & Mirabel (1998).
some of them could merge to form more massive objects or return either to the parent or to some neighboring galaxies.

Finally, it is interesting to note that the tidal formation of dwarf galaxies can be responsible for the dichotomy of dEs, i.e., nucleated or nonnucleated dEs. As demonstrated by the numerical simulations, the most massive objects tend to contain a lot of gas with respect to the stellar content. Even if the gas is dominated by H I gas, molecular gas formation could proceed from the H I-dominated gas, as demonstrated by recent CO observations of TDGs. Therefore, it seems very likely that intense star formation could occur in the center of such tidal dwarfs. The important point is that the resultant star cluster is expected to be dynamically decoupled from the remaining stellar system. Then, it is expected that gas-rich tidal dwarfs could evolve to nucleated dEs. On the other hand, less massive TDGs tend to have little gas, and thus they evolve to nonnucleated dEs, as suggested by Barnes & Hernquist (1992). In conclusion, the tidal formation scenario presented here has a number of merits to explain the observational properties of dwarf galaxies.

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