Did elliptical galaxies form via major mergers?

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1 Introduction

Two competing scenarios of the formation of elliptical galaxies have so far been proposed: [A] Elliptical galaxies should form monolithically by gravitational collapse of a gas cloud with considerable energy dissipation (e.g., [1, 2]), or alternatively [B] ellipticals should form via mergers of gaseous disk galaxies or of many dwarf galaxies (e.g., [3, 4, 5, 6]).

Stars in a galaxy are fossils; the star formation and chemical enrichment history of the galaxy are imprinted on their kinematics and chemical abundances. The internal structure of galaxies, spectrophotometric, chemical, and dynamical properties of various locations within a galaxy, is closely related to the processes of galaxy formation and evolution, and is being observationally obtained ([7]).

The aim of our study is to put constraints on the formation history of elliptical galaxies by comparing the observed internal structures of stellar population. To construct a self-consistent three-dimensional chemodynamical model, we have introduced various physical processes associated with the formation of stellar systems such as radiative cooling, star formation, feedback of Type II and Ia supernovae (SNe II and SNe Ia), and stellar winds (SWs), and chemical enrichment. The details are described in [8] and [9].

2 Results

We simulate 74 slowly-rotating spherical fields with CDM initial fluctuations (spin parameter $\lambda \sim 0.02$), and obtain 128 galaxies with stellar masses in the range $10^{9-12} M_\odot$ (74 ellipticals, 45 dwarfs, and 9 cD galaxies). In our scenario, galaxies form through the successive merging of subgalaxies. The merging histories are various with differences seeded in the initial conditions. In some cases, galaxies form through the assembly of gas rich small galaxies, and the process looks like a *monolithic collapse*. In other cases, the final galaxies form through a *major merger* of preexisting galaxies. Major mergers are defined as those with mass ratio $f \gtrsim 0.2$ occurring at $z \lesssim 3$.

2.1 Metallicity Gradients

The details are described in Kobayashi (2004). We examine the physical conditions during 151 merging events that occur in our simulation. Whether the merging event changes the metallicity gradient is mainly influenced by two factors; the mass ratio of the merging galaxies f and the induced star formation. The basic processes of the formation and evolution of the gradients are summarized below:

- Formation of initial gradients — The initial gradient is determined from the initial starburst at $z \gtrsim 3$. The gradient is steeper in the case of quiescent gas accretion, and is shallower in the case of violent assembly of subgalaxies. As a result, the initial gradients span from $\Delta[\mathrm{Fe/H}]/\Delta \log r = -1.5$ to -1.0.

- Destruction by mergers — The major merger changes the orbits of stars. The metal-rich stars at the center are able to move to the outer region of the galaxy. The gradient change is determined mainly from the mass ratio of merging galaxies f. With larger f, the gradients become shallower. If the mass ratio of merging galaxies is larger than $f \sim 0.2$, the gradient change is larger than ~ 0.5 dex.

- Regeneration due to the induced star formation — If the ratio of gas mass is as large as $M_{\mathrm{g},2}/M_{\mathrm{g},1} \gtrsim 0.5$, strong star formation is induced at the center of the primary galaxy, and the gradient change is smaller than ~ 0.5 dex.

- Passive evolution — If the gas fraction of the secondary galaxy is larger than $f_{\mathrm{g},2} \sim 0.5$, moderate star formation is induced in the outer region of the primary galaxy, and the gradient change becomes as large as ~ 0.5 dex, even if $f \sim 0$. In some case without a merging event, if a similar star formation is induced by the late gas accretion, the metallicity gradient gradually becomes shallower.

We succeed in reproducing the observations of metallicity gradients (e.g., [11]) and finding the origin of the variety of internal structures. From the distribution functions of the gradients for different merging histories, we discuss the origin of elliptical galaxies.

- The average metallicity gradient is $\Delta \log Z / \log r \simeq -0.3$ and the dispersion is ± 0.2, which are both consistent with observations of Mg_2 gradients.

- No correlation is produced between gradients and masses. The metallicity gradients do not depend on the galaxy mass, and the variety of the gradients stems from the difference in the merging histories; galaxies that form monolithically have steeper gradients, while galaxies that undergo major mergers have shallower gradients.

- The metallicity gradient distributions for [A] non-major merger ([1]-[3]) and [B] major merger galaxies ([4] and [5]) are quite different. The typical gradients for non-major merger and major merger galaxies are $\Delta \log Z / \Delta \log r \sim -0.3$ and -0.2, respectively. Simulated galaxies with gradients steeper than -0.35 are all non-major merger galaxies.

A major merger makes the gradient shallower. Merging histories can thus, in principle, be inferred from the observed metallicity gradients of present-day galaxies. Available observations for nearby galaxies suggest that there exist non-major merger galaxies and major merger galaxies half and half. The observed variation in the metallicity gradients cannot be explained by either *monolithic collapse* or by *major merger* alone. Instead, it is reproduced well in the present model in which both formation processes arise under the CDM scheme.

2.2 Scaling Relations

The details are described in Kobayashi (2005). Internal structure such as metallicity gradients is greatly affected by merging histories, while the global properties are determined from overall masses according to the scaling relations.

- Assuming that the star formation timescale is ten times longer than the local dynamical timescale (i.e., $c = 0.1$), we succeed in reproducing the observed global scaling relations, e.g., the Faber-Jackson relation, the Kormendy relation, the colour-magnitude relation, the mass-metallicity relation and the fundamental plane (e.g., [12, 13]).

- The different relations for ellipticals and dwarfs could be reproduced, although simulated dwarfs have larger effective radii than observed because of the lack of resolution. The luminosity-weighted ages of dwarfs span a wide range, $3-8$ Gyr, depending on their star formation histories, while ellipticals are as old as $7-10$ Gyr independent of their mass.

- Adopting the Salpeter IMF ($x = 1.35$), we could reproduce the mass-metallicity relation, although the slope is shallower and the scatter is larger than observed. This is because the feedback is not so effective that most metals are locked into stars in the simulation. The colour-magnitude relation also shows a larger scatter because the star formation does not terminated completely in the simulations.

- An intrinsic scatter exists along the fundamental plane, and the origin of the scatter in the simulation lies in differences in merging history. Galaxies that undergo major mergers tend to have larger effective radii and fainter surface brightnesses, which result in larger κ_1 (expressing masses), smaller κ_2 (surface brightnesses), and larger κ_3 (mass-to-light ratios).

3 Conclusions

We simulate the chemodynamical evolution of elliptical galaxies from CDM initial conditions with a GRAPE-SPH code that includes various physical processes associated with the formation of stellar systems; radiative cooling, star formation, feedback from SNe II, SNe Ia, and SWs, and chemical enrichment. The global properties are determined from overall masses according to the scaling relations, and the observed global scaling relations, i.e., the Faber-Jackson relation, the Kormendy relation, the colour-magnitude relation, the mass-metallicity relation and the fundamental plane, can be reproduced with our CDM-based scenario. However, because metallicity gradients are destroyed by major mergers and cannot be regenerated by the induced starburst, and the existence of metallicity gradients cannot be explained by the major merger scenario alone. Instead, it is reproduced well in our model in which both formation processes of *monolithic collapse* and *major merger* arise under the CDM scheme.

References

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