Dwarf Galaxies: From the Deep Universe to the Present
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Evolution of dwarf galaxies in a semi-analytic galaxy formation model

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Abstract. Dwarf galaxies provide us many important clues to understanding of galaxy formation. By using the current version of our own semi-analytic model of galaxy formation, in which cosmic structure forms and evolves based on the cold dark matter model of cosmology, we analyze dwarf galaxies. We find that the model well reproduces many properties such as magnitudes, sizes, and velocity dispersions of, especially, dwarf elliptical galaxies. We also find that the dynamical response of the gravitational potential well of dwarf galaxies to the supernova-induced gas removal plays a very important role to obtain large sizes and small velocity dispersions as observed.

Keywords. galaxies: dwarf, galaxies: evolution, galaxies: formation, large-scale structure of universe

1. Introduction

Dwarf galaxies provide us important clues to understanding of galaxy formation, because they are very sensitive to the supernova heating, or, *supernova feedback*, owing to their shallow gravitational potential well, and therefore, we can easily see the underlying physics in galaxy formation.

According to the current standard cosmological model, the *cold dark matter (CDM)* model of the Universe, the cosmic structure forms hierarchically, that is, larger objects form via mergers of smaller objects. Because baryons gravitationally follow the CDM, we must consider galaxy formation within the framework of the CDM model.

We have developed our own semi-analytic galaxy formation model of galaxy formation for a long time (e.g., Nagashima *et al.* 2005, Makiya *et al.* 2016). We have shown that these models well reproduce many observational aspects of local and high redshift galaxies, including active galactic nuclei (AGNs) (e.g., Oogi *et al.* 2017).

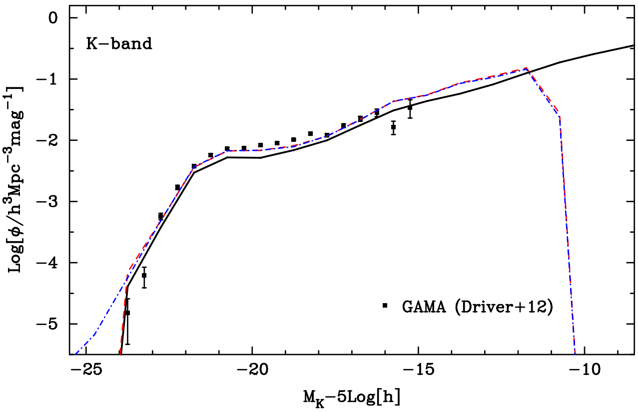

Figure 1. Luminosity functions in K-band. Thick solid line indicates the luminosity function given by the model with higher resolution and small box N-body result ($70h^{-1}$Mpc; νGC-H2), and dot-dashed line that with low resolution and large box ($280h^{-1}$Mpc; νGC-S). For comparison, we plot that with low resolution and small box result indicated by dashed line. All luminosity functions well agree. The symbols are observations given by GAMA survey (Driver *et al.* 2012).

Here, by using the current version of our model (Shirakata *et al.* 2018), we verify our model in terms of formation of, especially, dwarf elliptical galaxies. The details of the model is shown in the above paper.

2. Results

When we analyze dwarf galaxies, we should care about the resolution of N-body simulations used for constructing merger trees of dark matter halos. To see the effect of the resolution, we use simulations with two different resolutions. The ν^2GC-H2 simulation is done by using 70 h^{-1} Mpc box and 2048^3 particles, in which the minimum halo mass reaches $1.4 \times 10^8 h^{-1} M_{\odot}$. This mass corresponds to the circular velocity $V_{\rm circ} \simeq 17$ km s^{-1}, or virial temperature $T_{\rm vir} \simeq 10^4$ K at $z \simeq 5$, enough below the characteristic mass after the cosmic reionization. Because the most active star formation epoch is $z \sim 2$, we can say that this simulation resolves the Jeans mass. In the other simulation, ν^2GC-S, the box size is 280 h^{-1}Mpc and the minimum mass of dark halos is $\sim 9 \times 10^9 h^{-1} M_{\odot}$, which is similar to the characteristic mass at $z \simeq 0$. This is not enough to resolve the dwarf galaxy formation. In this case, there exists an artificial minimum mass of galaxies. This means that gas which should have been taken into lower mass galaxies goes into larger mass galaxies. Thus the resolution effect might affect even more massive galaxies.

In Figure 1, we show the K-band luminosity functions of the models. The solid line denotes the model on the ν^2GC-H2 simulation, and the dot-dashed line that on the ν^2GC-S simulation. Clearly the formation of dwarf galaxies is affected by the resolution at $M_K - 5\mathrm{Log}(h) \gtrsim -12$. This magnitude is the artificial lower limit. The number of more luminous galaxies increases as the resolution becomes worse as mentioned above. Nevertheless, the difference can be negligible, and both models well reproduce the observations which are indicated by the symbols (GAMA survey, Driver *et al.* 2012).

The difference at the bright-end is originated by the difference of the box size. The ν^2GC-S has a larger sample, so more massive galaxies emerge. To see this effect, we also show the model with the same box size as the ν^2GC-H2 simulation and the same resolution of the ν^2GC-S simulation. Clearly this model agrees the ν^2GC-S having worse resolution at faint-end, and agrees the ν^2GC-H2 having smaller box at bright-end.

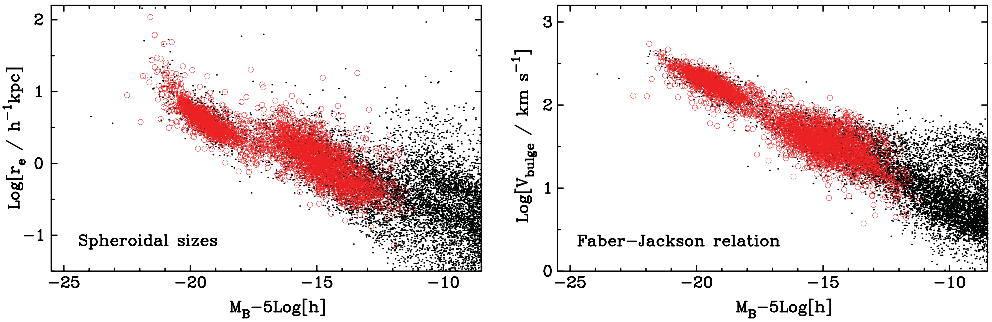

Figure 2. Left: size-magnitude relation of elliptical galaxies. Right: velocity dispersion-magnitude (Faber-Jackson) relation (Faber & Jackson 1976). Black dots indicate the ellipticals computed by using ν^2GC-H2, and open red circles those by using the low-resolution simulation, which are plotted for comparison.

The model on the ν^2GC-H2 simulation has a potential to analyze very dwarf galaxies, such as those found in the Local Group. Although in this analysis such dwarf galaxies is surely included, we focus on general trend of dwarf galaxies.

In Figures 2 and 3, we show some aspects of elliptical galaxies. To see the resolution effect, we plot two models on ν^2GC-H2 (black dots) and ν^2GC-S (red circles). In all panels, we can see that the difference between the black dots and the red circles is negligible at brighter than $M_K - 5$ Log $h \sim -14$. Thus we see only the high resolution results below.

The left panel of Figure 2 shows the size-magnitude relation of elliptical galaxies at present. The distribution cannot be approximated by a single power-law. At $M_K - 5$ Log$(h) \sim -16$, the sizes seem to be larger than simply expected. This is owing to the dynamical response to the supernova-induced gas removal, which makes the gravitational potential well shallower (Nagashima & Yoshii 2003, Nagashima & Yoshii 2004, Koyama *et al.* 2008).

The right panel of Figure 2 shows three dimensional velocity dispersion-magnitude relation, which is closely related with the so-called Faber-Jackson relation (Faber & Jackson 1976). In contrast to the previous panel, we see a single power-law feature for the distribution and widely spreaded distribution for dwarf ellipticals. This is also owing to the dynamical response. We have dwarf ellipticals with velocity dispersion much below 10 km s^{-1}, whereas the minimum circular velocity is above 10 km s^{-1} in the ν^2GC-H2 simulation. This is because galaxies expands and their velocity dispersions decrease due to the dynamical response. This panel implies the importance of the dynamical response.

The left panel of Figure 3 shows the surface brightness-magnitude relation. The model reproduces the well-known relation for giant ellipticals, that is, more luminous ellipticals have shallower surface brightness. For dwarfs, we have very widely spreaded distribution, including dwarf ellipticals and compact ellipticals. This also might include ultra-diffuse/compact ellipticals.

The right panel of Figure 3 shows the dependence of the mass-to-light ratio on the magnitude. The mass is given as the dynamical mass. This also reproduce the observational trend.

3. Summary

We have analyzed dwarf ellipticals by using our own semi-analytic model of galaxy formation, and found that the model well reproduces many aspects of observations. The agreement is brought mainly by the dynamical response of gravitational potential wells

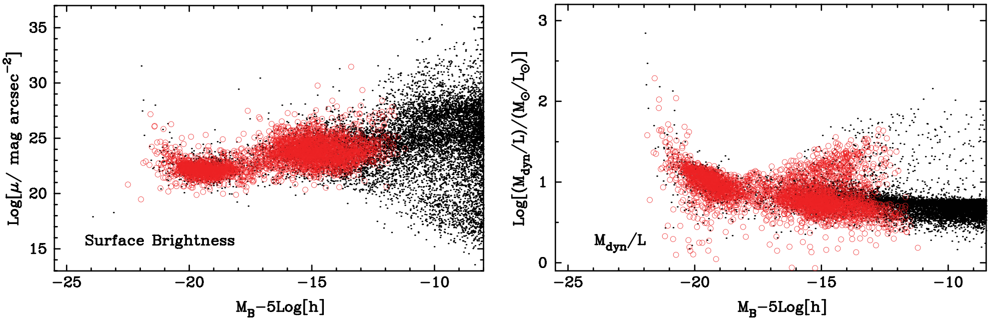

Figure 3. Left: surface brightness-magnitude relation of elliptical galaxies. Right: dynamical mass-to-light ratio-magnitude relation. The symbols are the same as Figure 2.

to the supernova-induced gas removal. We have also shown that the resolution of N-body simulations for constructing merger trees of dark halos does not affect the results. We would like to extend this analysis to recently discovered ultra compact/diffuse dwarf galaxies in future.

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