Resolving the Rise and Fall of Star Formation in Galaxies
Proceedings IAU Symposium No. 373, 2023
T. Wong & W.-T. Kim, eds.
doi:10.1017/S1743921322004562

Collision-induced formation of dark-matter-deficient galaxies

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Abstract. The standard galaxy formation model predicts that galaxies form within a Cold Dark Matter (CDM) halo and that galaxies are dominated by dark matter. However, recent observations have discovered dark-matter-deficient galaxies with much less dark matter mass than theoretical predictions, and the process of their formation has been discussed. Here, we investigate the physical processes of galaxy formation by collisions between gas-rich dark matter subhalos within the context of the CDM paradigm. We investigate the formation process of dark-matter-deficient galaxies by running three-dimensional simulations of the collision process between dark matter subhalos (DMSHs) with the same mass of $10^9\,\mathrm{M}_\odot$ colliding the velocity of $100\,\mathrm{km\,s^{-1}}$. We then compared the effect of different supernova feedback models, the subgrid physics of the simulation, on the collision-induced formation of galaxies. The results show that the strong feedback model ejects gas out of the system more efficiently than the weak feedback model, leading to lower star formation rates and the formation of a more extended galaxy. Finally, dark-matter-deficient galaxies with stellar masses of $\sim 10^7\,\mathrm{M}_\odot$ and $\sim 10^8\,\mathrm{M}_\odot$ are formed in the weak and strong feedback models, respectively.

Keywords. galaxies: formation, galaxies: evolution

1. Introduction

In the standard galaxy formation model, cold dark matter (CDM) drives the hierarchical structure formation in the universe. Based on the CDM model, the correlation between stellar components and dark matter halos has been numerous studies from both theoretical and observational viewpoints. Almost all studies about the relationship between the stellar mass and the dark matter halo mass in galaxies have shown that the mass fraction of the dark matter in galaxies is expected to be more than 90% (e.g., Behroozi *et al.* 2013).

However, van Dokkum *et al.* (2018) recently reported that the satellite galaxy NGC1052-DF2, a member of the elliptical galaxy NGC1052 group, has very little dark matter component compared to the theoretical predictions. Its stellar mass is $2\times10^8\,\mathrm{M}_\odot$, whereas its dynamical mass is $<3.4\times10^8\,\mathrm{M}_\odot$ within a radius of 7.6 kpc. Additionally, NGC1052-DF4 in the NGC1052 group has also been discovered as a galaxy with similar properties (van Dokkum *et al.* 2019). These two galaxies are classified as ultra-diffuse galaxies (UDGs). UDGs are peculiar galaxies with extremely low surface brightness,

$\mu(g,0) > 24$ mag arcsec^{-2}, and large effective radii, $r_e > 1.5$ kpc (van Dokkum *et al.* 2015; Koda *et al.* 2015).

Furthermore, different observations have also reported the existence of other dark-matter-deficient galaxies. Mancera Piña *et al.* (2019) identified six H I-rich UDGs and Guo *et al.* (2020) found 19 dwarf galaxies which have high baryon fraction.

So far, only a few theoretical studies of the formation of such exotic galaxies have been discussed. Recently, it has been pointed out that high-velocity collisions between gas-rich dwarf galaxies are capable of forming dark-matter-deficient galaxies (Silk *et al.* 2019; Shin *et al.* 2020). Shin *et al.* (2020) showed that dark-matter-deficient galaxies formed when two dwarf galaxies collide with each other at a relative velocity of 300 km s^{-1} using self-gravitating hydrodynamics simulations.

Otaki & Mori (2022a) simulated head-on collisions between dark matter subhalos using a three-dimensional simulation code. They show that a dark-matter-dominated galaxy is formed when the collision velocity is 20 km s^{-1}, and a dark-matter-deficient galaxy is formed when the collision velocity is 100 km s^{-1} In this paper, we investigate the effects of subgrid physics for supernova feedback on subhalo collision and collision-induced formation of galaxies.

2. Simulations of dark matter subhalos collision

We ran simulations of head-on collisions between two dark matter subhalos as the formation process of dark-matter-deficient galaxies. The initial conditions and simulation setup are as in Otaki & Mori (2022a) thus the two colliding DMSHs each have a mass of 10^9 M$_\odot$ and the mass ratio between dark matter and gas is 5.36. The density profile of the dark matter is assumed to be the Navarro-Frenk-White (NFW) profile, and the gas is in hydrostatic equilibrium with the dark matter potential. The DMSH centres are initially at $(x, y, z) = (\pm 5, 0, 0)$ kpc, and the initial bulk-velocities of the DMSHs are $(v_x, v_y, v_z) = (\mp 100, 0, 0)$ km s^{-1}.

We use the N-body/Smoothed Particle Hydrodynamics (SPH) simulation code developed by Otaki & Mori (2022a), but modified to compare the effect of supernova feedback. Our feedback model assumes that SPH particles in the vicinity of newly born stellar particles receive the thermal energy released by the supernova explosions and evolve adiabatically without energy loss by the radiative cooling during the lifetime of a massive star with 8 M$_\odot$ (Mori *et al.* 1997, 1999). This model is referred to below as the strong feedback model. On the other hand, a weak feedback model does not turn off the radiative cooling calculation of the SPH particles when they receive energy from the supernova feedback. The cooling time is very short compared to the dynamical time of the star forming region (Otaki & Mori 2022b), therefore the energy injection by the supernova explosions does not affect the thermodynamic evolution of the gas significantly.

Figure 1 shows the time evolution of the dark matter subhalos collision with (a) the weak feedback model and (b) the strong feedback model. In each panel, the upper panels are dark matter distribution, the lower panels show baryon, in which the blue and red points represent gas and stars, respectively. At 50 Myr, the center of the subhalo collides and the gas density is enhanced at the colliding surface, which triggers star formation. The dark matter component in the dark matter subhalo is passed through without merger and a dark-matter-deficient galaxy is formed.

In the case of the weak feedback model, the energy injected into the gas by the supernova feedback is lost by radiative cooling before it is converted to kinetic energy, so the gas remains at the collision interface. Compared to the weak feedback model, the strong feedback model simulation results in a more extended stellar system because the energy injection from stellar particles to gas particles makes the strong outflow and most of the

https://doi.org/10.1017/S1743921322004562 Published online by Cambridge University Press

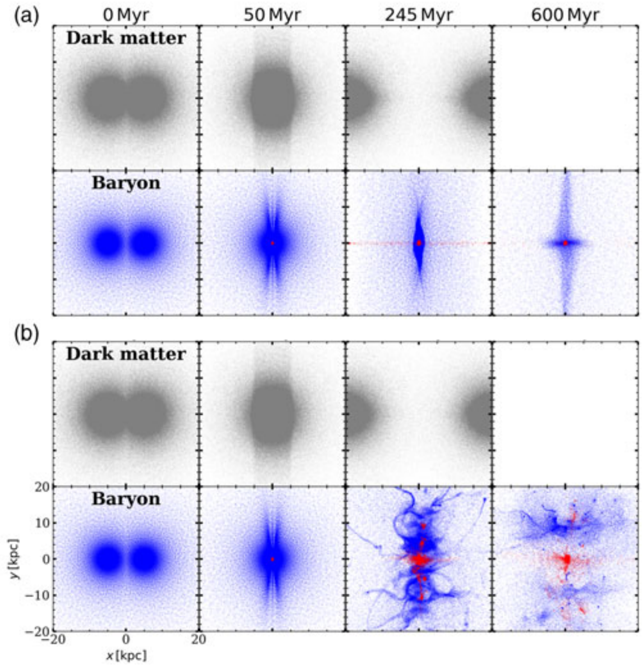

Figure 1. Snapshots of the head-on collision between dark matter subhalos with $10^9\,M_\odot$ for a collision velocity of $100\,km\,s^{-1}$ in weak feedback model (a) and strong feedback model (b). The gray, blue, and red dots represent dark matter, gas, and stars, respectively. From left to right, $t = 0$, 50, 245, and 600 Myr, respectively. The gray, blue, and red points represent dark matter, gas, and stars, respectively.

gas is ejected from the system. This suggests that the strength of the feedback affects the formation process of the ultra-diffuse galaxies. Both simulation results showed star formation rates of a few $M_\odot\,yr^{-1}$ at the time of the collision, but the star formation histories differ significantly thereafter. The star formation rate rapidly decreases in the strong feedback model, but not so much in the weak feedback model. Finally, galaxies with stellar masses of $\sim 10^8\,M_\odot$ and $\sim 10^7\,M_\odot$ are formed in the weak and strong feedback models, respectively.

Acknowledgements

Numerical computations were performed with computational resources provided by the Multidisciplinary Cooperative Research Program in the CCS, University of Tsukuba. This work was supported by JSPS KAKENHI Grant Numbers JP21J21888, JP20K04022.

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