Numerical Simulation of Milky Way Galaxy and Sagittarius Dwarf Galaxy Collision

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September 2016

Abstract. The Milky Way has its own system of dwarf satellite galaxies, which have much lower mass. Interaction between the Milky Way and its satellites can impact the structure. Sagittarius Dwarf Galaxy is one of the nearest and brightest Milky Way's satellite galaxies. But it has been torn apart because of potential of the Galaxy. In this paper, we investigate a few models of Milky Way collision with its satellite. Sagittarius Dwarf Galaxy will be constructed as spherical and disk dwarf galaxy. We also included the stars, gaseous, and dark matter as the building blocks of the dwarf galaxy in calculation of this tidal interaction. The calculation was performed using N-body and Smoothed Particle Hydrodynamic program, GADGET-2 code.

1. Introduction

First model of galactic formation called ELS model was proposed by Eggen et al. [1]. In this model, rotating spherical gas cloud collapsed and formed a galaxy. The rotating gas cloud then formed either disk or elliptical galaxy depend on rotational velocity. This model could not explain the various ages of cluster on halo galaxy. Another model of galactic formation proposed that galaxy was formed by aggregation of collapsed cloud fragments, called protogalaxy. This interaction could form a bigger galaxy.

Galactic formation models have led us to think about our galaxy, Milky Way. \( \Lambda \) Cold Dark Matter (\( \Lambda \text{CDM} \)) theory said that Milky Way must had tens or hundreds of dwarf galaxy forming an observed halo galaxy. In fact, the observed satellite galaxy of Milky Way were not that much. It was probably due to the domination of dark matter in our halo. The evidence of that interaction was the existence of the satellite galaxies and observed star streams around our Galaxy. Sagittarius Dwarf Galaxy (SDG) was one of the big satellite galaxy of Milky Way.

This paper is constructed as follows. In Section 2, we describe our simulation, including the initial condition and method. In Section 3 we show the result of the
Table 1. Potential Parameter of Milky Way Galaxy.

| Parameter     | Value                      |
|---------------|----------------------------|
| **Bulge**     |                            |
| Mass, $M_b$   | $9.489 \times 10^9 M_\odot$|
| Scale Length, $b_0$ | 0.23 kpc                  |
| **Disk**      |                            |
| Mass, $M_d$   | $6.626 \times 10^{10} M_\odot$|
| Scale length, $a_d, b_d$ | 4.22 kpc, 0.292 kpc        |
| **Halo**      |                            |
| Virial Mass ($M_{200}$) | $3.299 \times 10^{12} M_\odot$|
| Characteristic radius($r_s$) | 45.02 kpc                |

simulation fitted with the observational data, and discuss the result. Finally, in Section 4 we summarize our work.

2. Computational Model

Milky Way model consists of bulge, disk, and halo with Hernquist, Miyamoto-Nagai, and NFW (Navarro, Frenk and White) profile potential respectively. Milky Way potential is considered fixed, with total mass is $\sim 10^{12} M_\odot$. Stars, gaseous, and dark matter was also included in the calculation of this model.

Similar with Milky Way, SDG models consist of bulge and halo with Hernquist and NFW potential respectively. We used two model of SDG. First SDG model have spherical form with additional Plummer potential. Second SDG model have disk form with additional Miyamoto-Nagai potential. Detail composition of Milky Way and SDG mass were shown in the table 1 and 2.

Table 2. Potential Parameter of Sagittarius Dwarf Galaxy.

| Parameter     | Value                      |
|---------------|----------------------------|
| **Spherical** |                            |
| Model         |                            |
| Mass          | $4 \times 10^6 M_\odot$     |
| I Scale length| 0.45 kpc                   |
| Particles     | 21000                      |
| **Disk**      |                            |
| Model         |                            |
| Mass, $M_d$   | $4 \times 10^6 M_\odot$     |
| II Scale length, $a_d$ | 0.23 kpc                  |
| Particles     | 21000                      |
| **Bulge**     |                            |
| Mass, $M_b$   | $5.3 \times 10^7 M_\odot$   |
| Scale length, $b_0$ | 0.23 kpc                 |
| Particles     | 5000                       |
| **Halo**      |                            |
| Virial Mass ($M_{200}$) | $8.03 \times 10^8 M_\odot$|
| Characteristic Radius ($r_s$) | 4 kpc                    |
| Particles     | 4774                       |
N-body/SPH simulation was performed using cosmological simulation code, GADGET-2\cite{2}, with initial condition of particle distribution was generate using open source DICE\cite{3} code. We used GADGET-2 to simulate $2 \times 10^5$ particles in Newtonian space and ignores the cosmological space expansion. Initial position of SDG was derived by simulate point mass particle backward from current position of SDG ($X_{gal}, Y_{gal}, Z_{gal} = (19.41, 2.69, -6.9)$; $v_x, v_y, v_z = (248.8, -44.1, 172.9)$) to 5 Gyr ago. This simulation produced an orbit of SDG with eccentricity, apogalactic, and perigalactic are 0.5, 43.9, and 14.4 respectively. N-body/SPH simulation started from apogalactic position of the orbit.

3. Result and Discussion

![Figure 1](image_url)  

**Figure 1.** Result of N-body simulation of Milky Way and SDG interaction in equatorial coordinate projection after 4, 7, and 8 Gyr. Top, middle, and bottom figure show the simulation result of Milky Way and Model I (spherical SDG), Model II (disk SDG), semi-disk SDG respectively. Cyan, red, yellow, blue, and green colors respectively show particle of Milky Way’s plane from simulation, simulation result for particle member of SDG, observed SDG by Law et al. \cite{4}, leading and trailing tail of SDG by Majewski et al. \cite{5}.

Simulation result of Milky Way and SDG interaction was shown in figure 1. As comparison, we also performed a simulation of interaction Milky Way and mixed spherical and disk SDG, or semi-disk SDG (see bottom part of figure 1). Observational
Figure 2. Data fitting of simulation result with leading stellar stream by Belokurov et al. [6]. Red color shows simulation result of SDG. "x" symbols show mean of simulation data in range of RA every 5°. Blue color show observed leading tail by Law et al. [4]. Mean data of observed SDG by Belokurov et al. [6] show in "o" symbol. Data of Law et al. [4] and Majewski et al. [5] was used to confirm the result (yellow, blue, and green colors in figure 1).

In simulation result, star stream was formed after SDG has orbited Milky Way for \(~4\) Gyr. This result agreed with the reported age of SDG by Bellazzini et al. [7]. They reported that SDG star stream population was started to be formed while progenitor SDG was colliding with Milky Way in 3-4 Gyr. However, the best fit simulation result with observational data was obtained after 7 Gyr interaction (see center and right part of figure 1). Then, the simulation star stream was fully followed the feature of observed stream along with equatorial coordinate, while SDG was dominated by M giant star population with age \(\geq 5\) Gyr (5.5-9.5 Gyr), and average 8 Gyr (Bellazzini et al. [7]).

Another report (Ibata et al. [8]; Law & Majewski et al. [9]; and Pennarubia et al. [10]) said that SDG was torn apart and formed stellar stream after interacted for 3 Gyr with progenitor total mass of \(~10^8 M_\odot\). The mass fraction was dominated by
baryon particles (star and gas). Meanwhile, Gibbons et al. reported that SDG stellar stream was formed -as observed now- after interacting for 4 Gyr with progenitor SDG total mass of $10^{10} M_\odot$ and 90% of the mass fraction dominated by dark halo. In this simulation, the mass fraction of progenitor SDG was too large so the stream was formed much longer (more than 4 Gyr) then expected.

$$\chi^2_X = \sum_i \left( \frac{X_{\text{obs},i} - X_{\text{simulation},i}}{X_{\text{simulation},i}} \right)^2$$  \hspace{1cm} (1)

$$\chi^2_{\text{sum}} = \chi^2_{RA} + \chi^2_{\text{dec}} + \chi^2_{\text{distance}}$$  \hspace{1cm} (2)

Stellar stream feature in the observed area by Belokurov et al. [6] presented in the simulation result after 7 Gyr. Trend of the stream was similar with observational data. The fitting data was calculated using equation (1). From the equation (1), $X$ is the mean of position (RA, declination, or galactocentric distance). Observational data ($X_{\text{obs}}$) derived from Belokurov et al. [6]. Total of $\chi^2$ calculated by summing up $\chi^2$ of RA, dec, and distance (equation 2). The best fit of the simulation result was derived after 8 Gyr of the interaction Milky Way and disk SDG, with $\chi^2 = 38.4$.

4. Summary

We have reported the simulation of Milky Way and Sagittarius Dwarf Galaxy interaction using cosmological simulation code, GADGET-2. Initial conditions of particle distribution in the galaxy was generated using open source code DICE. We used a fix model of Milky Way that composed of bulge, disk, and halo (included dark halo). For the Sagittarius Dwarf Galaxy (SDG), we considered two models, spherical and disky SDG. Initial position of SDG was derived by simulating the SDG orbit backward in 5 Gyr from current position. The simulation was performed using $\sim 2 \times 10^6$ particles until 8 Gyr forward. The tidal stream was formed after SDG orbiting the Milky Way 4, 7, and 8 Gyr.

From 2 (+1) models, tidal stream of disky SDG after orbiting Milky Way 8 Gyr fitted with observed star stream with $\chi^2 = 38.4$. Nevertheless, the tidal stream was formed after certain times. It might be happened due to the overestimated mass fraction and length scale of the SDG bulge. Varying initial position and mass fraction of SDG are necessary for next studies to get better result.

Acknowledgments

RPA gratefully acknowledge the financial support from DIKTI fresh graduate scholarship and FMIPA ITB for this research.

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