Modified GALAXY Code: Interaction of Whirlpool Galaxy M51 and Dwarf Galaxy NGC 5195

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ABSTRACT

I compare the gravitational effect two galactic nuclei and a disk of stars have upon interaction to the observations of Whirlpool galaxy, M51, and neighboring dwarf galaxy NGC 5195. In this work I modify the GALAXY Code in Carroll and Ostlie 2007 with Velocity Verlet algorithm in order to determine the positions, velocities and accelerations of the stars and nuclei. In my simulation I find similar spiral features around $\boldsymbol{t \cong 216\ Myr - 228\ Myr}$ when using a softening-factor ($\boldsymbol{s_f}$) of 2.016 in my calculations. $\boldsymbol{s_f \lesssim 2}$ show little to no spiral features and $\boldsymbol{s_f \gtrsim 3}$ show no spiral features.

1. INTRODUCTION

Theoretical models of galaxy formation enable a better understanding of the observed morphological structure of galaxies. The Hubble sequence classifies galaxies by their intrinsic characteristics (Hubble, 1926). In the Hubble sequence, galaxies are distinguished by morphological structure such as ellipticals (E's), spirals and irregulars (Irr's). The sequence extends into two types of spiral galaxies: normal spirals (S's) and barred spirals (SB's)[1]. Lenticular galaxies are those that lie between ellipticals and spirals. They can be either normal (S0's) or barred (SB0's), see Figure 1. Spiral galaxies are noted by their beautiful spiral structure which can vary in number of arms. In particularly, a galaxy with two symmetric spiral arms is known as a Grand-Design Spiral (Carroll and Ostlie, 2007). The spiral arms in galaxies consist of O and B main-sequence stars[2] as well as active star forming regions due to self-gravitational instabilities within the stars (see Larson et al. 1978; Elmergreen 2011). This is the reason why many spiral galaxies observed consist of bright spiral arms.

Previous studies (e.g. Toomre 1977; White 1978; Barnes & Hernquist 1996; Naab, Jesseit & Burkert 2006; Naab et al. 2014) suggest that the morphological structure of galaxies are a direct consequence of galaxy merger events. In a recent study, Rodriguez-Gomez et al. 2017 studied ~18,000 galaxies in the Illustris cosmological hydrodynamic simulation (Genel et al. 2014) and find that galaxy mergers shape the morphological structure of massive galaxies[3]. The Whirlpool Galaxy (M51) is believed to have obtain its spiral structure upon interacting with it with neighboring dwarf galaxy NGC 5195 (Carroll and Ostlie, 2007), see Figure 2. Galaxy M51 has been measured to contain a mass of ~10^{11} $M_\odot$ with a diameter of ~26,400 pc (Cain 2015).

In this work I analyze the gravitational effect two galactic nuclei and a disk of stars have upon interaction. The results presented in this paper complement the observations of Whirlpool galaxy, M51, and its companion NGC 5195. I use a modified version of the GALAXY code (see Section 2) to reproduce the morphological structure of M51. The remainder of the paper is organized as follows.

[1] Composed of a central bar shape. Look at bottom branch in Figure 1.

[2] O type stars: Temperatures ~ 40,000K, Radius ~ $10R_\odot$, Mass ~ 50 $M_\odot$

B type stars: Temperatures ~ 20,000K, Radius ~ $5R_\odot$, Mass ~ 10 $M_\odot$

[3] Massive galaxies in this paper correspond to those with Masses $\boldsymbol{\gtrsim 10^{11}}$ $M_\odot$

Section 2 describes the model of our simulation. Section 3 compares results of my simulated model to observations of galaxies M51 and NGC 5195. Section 4 summarizes findings.

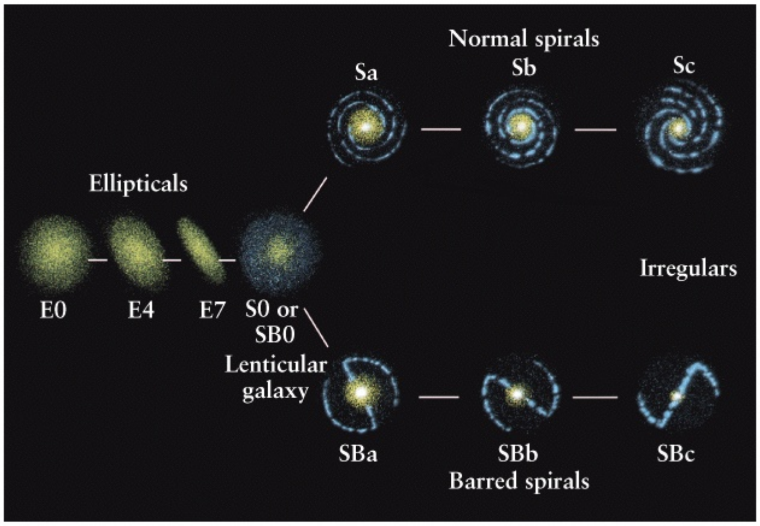

Figure 1: Diagram of the Hubble sequence. Please note the Hubble sequence does not represent the evolutionary sequence of a galaxy, rather it is a diagram showing observational morphological structures of galaxies.

Figure 2: Grand Spiral Galaxy M31 (enclosed by white hexagon) with companion galaxy NGC 5195 (enclosed by green oval).
Image credit: vdHoeven/NASA/JPL-Caltech/R. Kennicutt (Univ. of Arizona)/DSS Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

2. SIMULATION MODEL

The GALAXY Code presented in Carroll and Ostlie, 2007 is similar to the galaxy interaction code in Toomre & Toomre (1972). The GALAXY Code calculates the gravitational effect two galactic nuclei and a disk of stars experience upon interaction. In the program two galactic nuclei with masses M_1 and M_2 are treated as point masses.

At $t = 0$ $\boldsymbol{yr}$ in the simulation, M_1 is surrounded by a disk of stars that obey circular Keplerian orbits and M_2 is located ~21,000 pc away, from the center of M_1. The disk of stars is composed of 10 rings with 25 stars each. The separation between each ring is 1,300 pc and the radius of each ring can be found by:

$$r_{ring} = i\ x\ 1{,}300\ pc \qquad (i = interger) \tag{1}$$

where $\boldsymbol{i}$ is an integer corresponding to the $\boldsymbol{i}^{th}$ ring, counting from the center. This is done in order to preserve the approximate diameter (see Introduction) of M51. The gravitational influence between stars is neglected, therefore do not affect the motions of the nuclei or each other. There is no friction involved in the system leaving each star to feel gravitational effects from both nuclei. With these assumptions, my model is then composed of a simple two-body system between the nuclei and a n-number three-body system running in parallel. The number of three-body systems in the program depend on the number of stars.

The positions, velocities and accelerations of each star and nuclei are calculated using the Velocity-Verlet algorithm rather than the modified Euler-Cromer algorithm Carroll and Ostlie 2007 suggest. I find the acceleration of each star using Newton's Law of gravity:

$$a_x = \frac{GM_1}{r_1^3(t)}\left[X_1(t) - x_{1,2,3\ldots i}(t)\right] + \frac{GM_2}{r_2^3(t)}\left[X_2(t) - x_{1,2,3\ldots i}(t)\right] \tag{2}$$

where

$$r_{1,2}(t) = \sqrt{\left[X_{1,2}(t) - x_{1,2,3\ldots i}(t)\right]^2 + \left[Y_{1,2}(t) - y_{1,2,3\ldots i}(t)\right]^2 + \left[Z_{1,2}(t) - z_{1,2,3\ldots i}(t)\right]^2 + s_f^2}$$

$X_{1,2}$, $Y_{1,2}$, $Z_{1,2}$ correspond the x, y, and z position of each nucleus. The subscript 1,2 correspond to nuclei M_1, M_2, respectively. $x_{1,2,3\ldots}$, $y_{1,2,3\ldots}$, $z_{1,2,3\ldots}$ correspond to the x, y, and z position of each star where the subscripts 1,2,3…$\boldsymbol{i}$ correspond to different stars. s_f^2 in $r_{1,2}^3(t)$ is known as the "softening" factor and is used in order to avoid overflow or zero (really small) accelerations. I determine s_f through trial and error and verifying simulation snapshots to observations (Figure2).

At $t = 0$ yr, each star has a fixed position and I assume they are at rest. With these initial conditions I determine the present velocity and position of each star with Equations 3 and 4.

$$v_x(t) = v_x(t-1) + a_x(t-1)\Delta t \tag{3}$$

$$x(t) = x(t-1) + v_x(t-1)\Delta t \tag{4}$$

For the nuclei I do the same. The acceleration for nuclei M_1 and M_2 are:

$$A_{1,x} = \frac{GM_2}{r_o^3(t)}\left[X_2(t) - X_1(t)\right] \tag{5}$$

$$A_{2,x} = \frac{GM_1}{r_o^3(t)}\left[X_1(t) - X_2(t)\right] \tag{6}$$

where

$$r_0(t) = \sqrt{[X_1 - X_2(t)]^2 + [Y_1(t) - Y_2(t)]^2 + [Z_1(t) - Z_2(t)]^2 + s_f^2}$$

and $X_{1,2}$, $Y_{1,2}$, $Z_{1,2,}$ and s_f^2 have similar meaning as in Equation 2. At $t = 0$ yr, I assume M_1 is at rest, and at the origin, while M_2 is given an initial speed. The present velocity and position of the nuclei are:

$$V_{1,x}(t) = V_{1,x}(t-1) + A_{1,x}(t-1)\Delta t \tag{7}$$

$$V_{2,x}(t) = V_{2,x}(t-1) + A_{2,x}(t-1)\Delta t \tag{8}$$

$$X_1(t) = X_1(t-1) + V_{1,x}(t-1)\Delta t \tag{9}$$

$$X_2(t) = X_2(t-1) + V_{2,x}(t-1)\Delta t \tag{10}$$

2.1 CODE UNITS

To speed up the calculations, Carroll and Ostlie 2007 suggest the following units.

- $1\ unit\ of\ mass = 2x10^{11}$ $M_\odot$
- $1\ unit\ of\ distance = 500\ pc$
- $1\ unit\ of\ time = 1.2\ Myr$
- $1\ unit\ of\ speed = 400\ \frac{km}{s}$

These units also make the gravitational constant, $\boldsymbol{G}$, and $\boldsymbol{\Delta t}$ equal 1 in the equations above.

3. SIMULATED RESULTS AND OBSERVATIONS

Figure 3 shows a snapshot of our system at $t = 0\ \boldsymbol{yr}$. In code units, NGC 5195 is located at $(-30,30,0)$ with initial velocity $(0,0.34,0.34)$, and M51 is at rest on the origin. The Velocity Verlet algorithm in Section 2 updates future positions, velocities and accelerations of stars and nuclei using initial conditions at $t = 0\ \boldsymbol{yr}$. In the code, M51 has a mass of 5 and NGC 5195 has a mass quarter of the mass of M51.

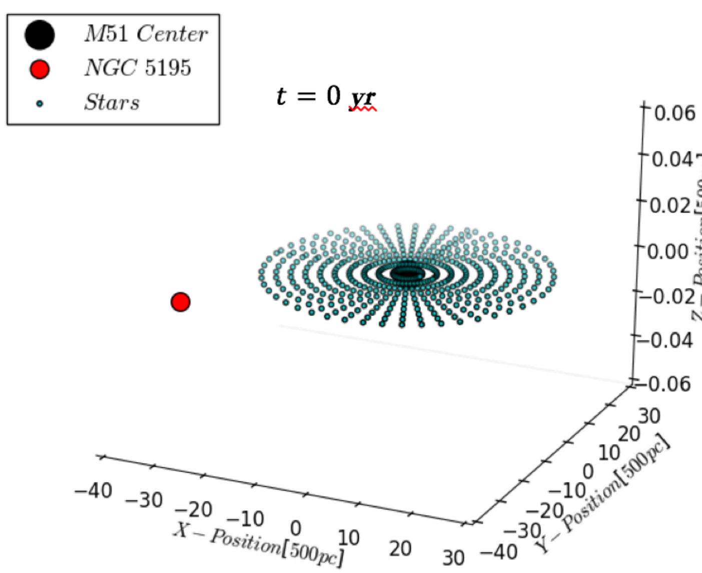

Figure 4. Snapshot of the simulation at $t = 0\ \boldsymbol{yr}$. The red dot and black dot correspond to the center of mass of NGC 5195, and M51 respectively. The cyan dots are the stars.

With a $\boldsymbol{s_f}$ **of 2.016**, the spiral features of M51 begin to appear around $\boldsymbol{t > 100\ (120\ Myr)}$. At $\boldsymbol{t < 100}$ I see no spiral features as the rings of stars are breaking apart, see Figure 5. A small clip of the simulation can be found in the link below[4]. I determine my simulation resembles the observations in Figure 2 at $\boldsymbol{t \cong 180\text{-}190\ (216\ Myr - 228\ Myr)}$, see Figure 6.

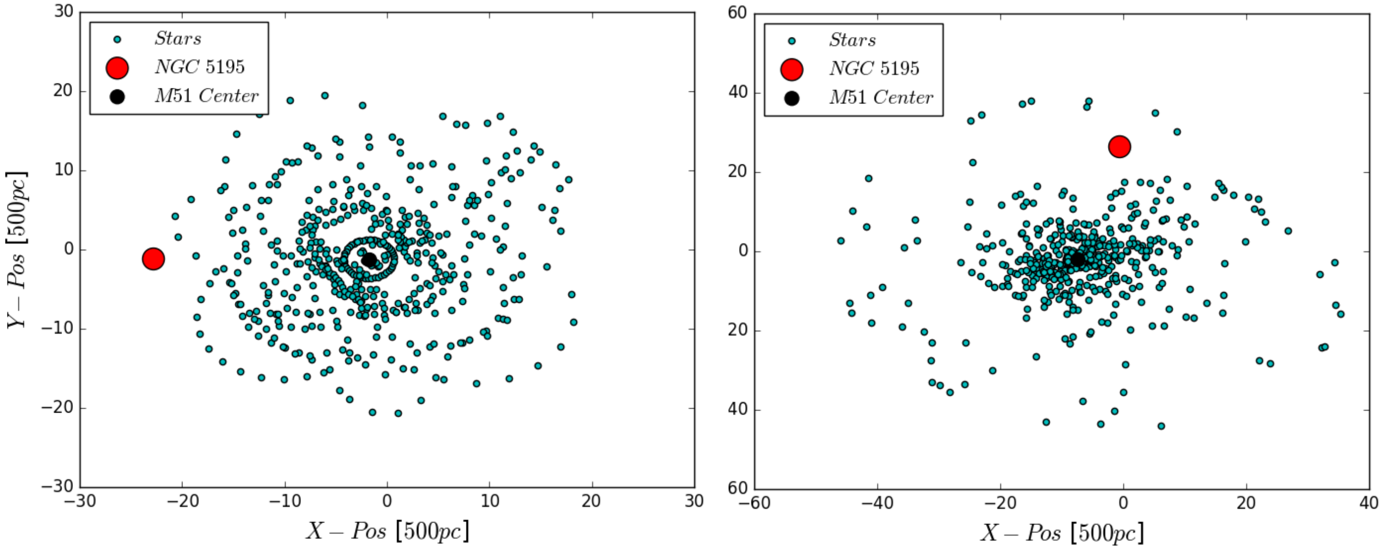

Figure 5. Left: Snapshot of the simulation at $\boldsymbol{t = 71}$ (*85.2 Myr*)**.** Right: Snapshot of the simulation at $\boldsymbol{t = 141}$ (*169.2 Myr*)**.**

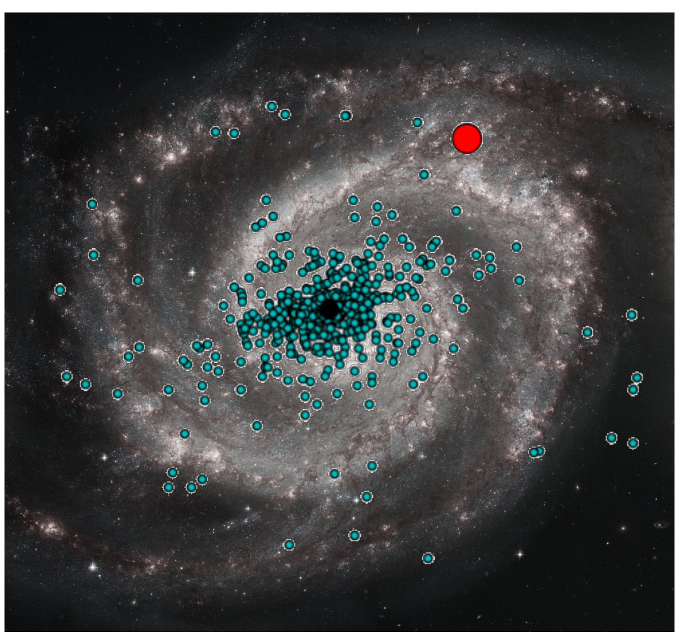

Figure 6. Overlay of simulation snapshot at $\boldsymbol{t = 182}$ ***(219.6 Myr)*** on-top of observation in Figure 2. Color scheme is similar to the Figures above. Notice how simulation snapshot traces the spirals of M51.

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[4] Clip of Simulation: **https://www.youtube.com/watch?v=CeBztndJCHM&feature=youtu.be**

Figure 7 show the different morphologies created when using $\boldsymbol{s_f = 1.0}$ and $\boldsymbol{s_f = 3.5}$. When using a $\boldsymbol{s_f}$ **of 1.0** the rings fail to fully deform due to the small accelerations of the stars. Increasing the $\boldsymbol{s_f}$ enhances the spiral structure in our simulation and a $\boldsymbol{s_f}$ **of 2.016** yield the promising results in Figure 6. Using a $\boldsymbol{s_f}$ **of 3.5** result to high accelerations within the nuclei leaving no spiral structures.

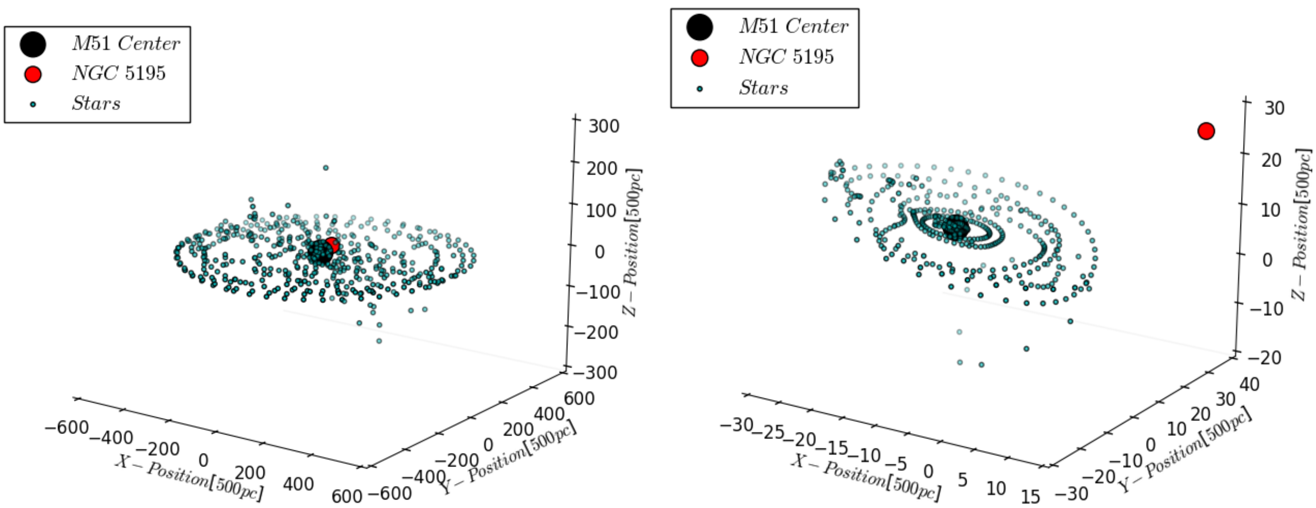

Figure 7. Both left and right images correspond to the snapshot at $\boldsymbol{t = 182}$ ***(219.6 Myr)*** but different $\boldsymbol{s_f}$. Left: $\boldsymbol{s_f = 1.0}$ Right: $\boldsymbol{s_f = 3.5}$

4. CONCLUDING REMARKS

In this paper I analyze morphological structure of the Whirlpool galaxy, M51. In my simulation, the spiral structure of M51 was created upon interaction with its neighboring dwarf galaxy, NGC 5195. My main results are the following:

- The spiral arms of M51 seems to be created upon interaction with NGC 5195 around simulation times of $\boldsymbol{t \cong 180\text{-}190\ (216\ Myr - 228\ Myr)}$ with a $\boldsymbol{s_f}$ **of 2.016.**
- $\boldsymbol{s_f \lesssim 2}$ yield small accelerations between the stars and nuclei, resulting in “conservation” of ring like structures instead of spirals.
- $\boldsymbol{s_f \gtrsim 3}$ yield high accelerations between the nuclei, resulting in no spiral features.

In this simulation I only consider the gravitational effects experienced by the system. More realistic results can be accomplished by using hydrodynamic simulations like those in Hopkins et al, 2014, 2017.

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