Morphological Modeling of NGC 6240

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Abstract

The amount of dark matter present in a galaxy merger influence its tidal morphology. Classical galaxy mergers like NGC 7252 possess elongated twin tidal tails, but such distinct features are absent in NGC 6240. We propose that this absence is explained by tail material falling back into the galaxies under gravitational influence of massive dark matter halos. Our goal is to see if a sufficiently large halo enables us to construct an acceptable model for NGC 6240. We may infer new information about dark matter and the impacts of dark matter halos, based on the results of the model.

To rapidly examine possible models for NGC 6240, we employ the Identikit program. Identikit uses specialized N-body simulations to interactively approximate tidal interactions with arbitrary encounter geometry. Each of these simulations has a specific mass model, galaxy mass ratio, pericentric separation, and eccentricity. We perform numerous simulations with the aforementioned parameters to examine different scenarios of NGC 6240. Specifically, we use models that have a relatively massive halo which previously were shown to re-accreted tidal material. Then we investigate different time steps, disk orientation, and viewing angle to obtain a model that matches the observed morphology and position-velocity diagram of NGC 6240. In addition to the Identikit simulation, we use self-consistent simulation as a point of comparison.

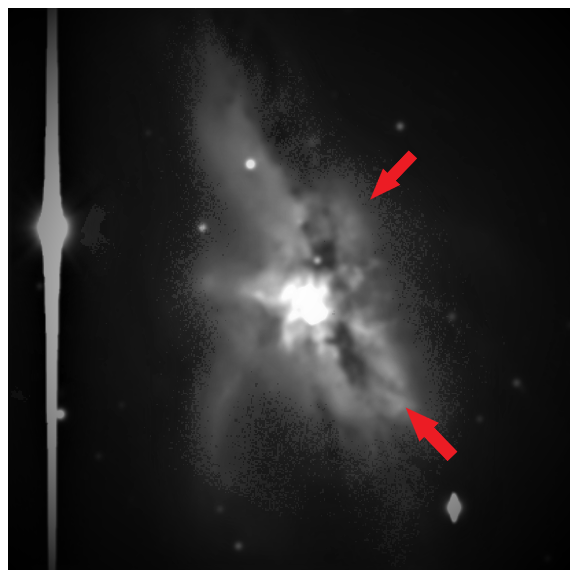
After exploring the parameter space, we found two candidate models that matched the key features found in NGC 6240's morphology. The self-consistent simulation produced similar results to the Identikit simulation. The PV diagram have some resemblance to the velocity data, but not enough to be certain it is accurate. The loops present in the morphology was successfully recreated via rapid re-accretion of tidal material. Thus we have shown that creating NGC 6240 look-alike through a large halo is possible.

1 Introduction

Galaxy interactions result when a galaxy's gravitational field disturbs another galaxy. Dark halos facilitate galaxy interactions since they create a large cross section for other dark halos to interact with it. As the galaxies interact, the dark halo's gravitational field forces rest of the galaxies into an interaction. The morphology of these galaxy interactions is sensitive to the strength of these gravitational fields. Galaxy mergers are the most violent type of galaxy interaction where two or more galaxies collide to form a new galaxy. When a merger occurs, the two galaxies will not have enough momentum to separate and will fall back into each other.

Early test-particle simulations by Toomre and Toomre (1972) showed that the long bridges and tails of interacting galaxies can arise as a result of brief but intense tidal interactions. Subsequently, self-consistent simulation allowed researchers to explore details of merger morphology and orbit decay. This self-consistent property is key to accurately modeling mergers.

(a) NGC 7252



(b) NGC 6240

Figure 1: 1a is NGC 7252, a textbook example of a galaxy merger. 1b is an image of NGC 6240, with possible tidal loops indicated by arrows.

Classic merger remnants like NGC 7252 have long tidal tails, but there are a subgroup of mergers, such as Arg 220 and NGC 6240, which lack these distinctive features. In figure 1, we compare the morphology of both mergers. The object of our study, NGC 6240, is an ultra-luminous infrared starburst galaxy in the Ophiuchus system with dual AGN $\sim$ .9 kpc from each other (Rubinur et al. (2018)) at $z = 0.02448$ (Downes et al. (1993)). The lower nuclei is approximately three times more luminous than the upper nuclei in the $.2KeV - 10KeV$ band (Yoshida et al. (2016)). Figure 1b shows NGC 6240's structure is highly disturbed and difficult to interpret due its "butterfly" morphology (Yoshida et al. (2016)). We believe the "loops" marked in Fig. 1(b) are due to tidal material re-accreted from the stubby tails visible above and below the bright central regions of this galaxy. There are currently no models that reproduce the abbreviated tails and loop-like features.

The morphology of an interacting system is sensitive to the amount and distribution of dark matter (Barnes (2016)). Mergers with low-mass halos easily produce the elongated tails seen in classical mergers like NGC 7252. However, systems with more massive halos tend to produce short-lived tails that soon fall back into the center. Thus, if a model contains too little or too much dark matter, the observed tidal feature may not be replicated. The aim of this paper is to see if a massive dark halos can create a model that replicates the disturbed tidal features observed in NGC 6240.

Our project uses the Identikit 1 Modeling program(Barnes and Hibbard (2009)) to construct a model of NGC 6240. The Identikit approach is similar to standard merger approach with one key difference, discussed in the method section. Identikit reduces the number of simulations we need to run and simplifies the job of inspecting models. Once we have the simulation finished, we use the Identikit image viewer to adjust the parameters to find a suitable model.

Here is an outline of our paper. Section 2 describes our method along with the observational data used, Identikit 1 software, and potential galaxy models. Section 3 discusses our results and their possible implications. Here we review the different parameter we used in our search and which parameters reproduced the morphology. Section 4 will be our conclusion.

2 Method

2.1 Observational Data

Our project uses an optical image of NGC 6240 as a template to match our model to the prominent tidal features. This image is an R-band optical image of NGC 6240 taken by Subaru's Suprime-Cam. We were unable to perform data reduction on a raw image from Subaru's database due to software errors on our end so we utilized a reduced image from Masafumi Yagi(Yoshida et al. (2016)). The image has undergone overscan subtraction, flat-field correction, distortion correction, and atmospheric dispersion correction using Subaru's

Suprime-Cam data reduction photometry pipeline.

From the stellar absorption line data taken on NGC 6240 with Muse (thanks to George Privon, private communication), we construct stellar line of sight velocity and dispersion maps. Plots of these velocity fields are shown in Figure 2. The velocity fields suggest the upper region is inclined towards the viewer, sections of the lower region is inclined away from the viewer, and the remaining sections of the merger lie face-on. We use information from Muse's data cube to construct position-velocity space diagrams, as seen in Figure 3. The projection's purpose is to be used in Identikit 1 as a set of visual constraints. These additional constraints will verify whether we identify a feasible set of parameters or a set of parameters resembling the morphology, but not the velocity.

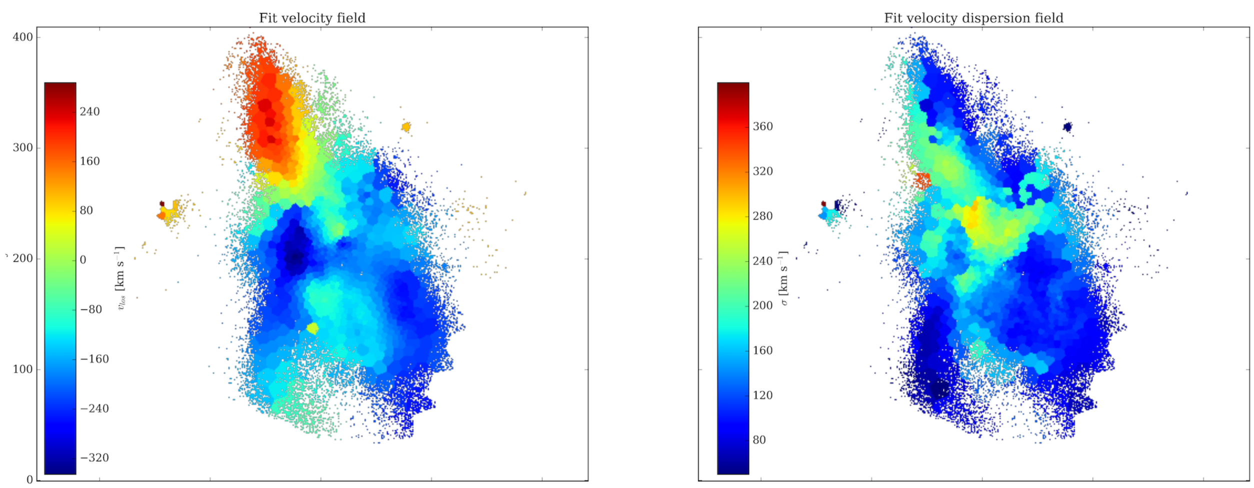


Figure 2: This is a stellar velocity field and dispersion field derived from absorption line data. The absorption line data is taken from Muse observation on NGC 6240.

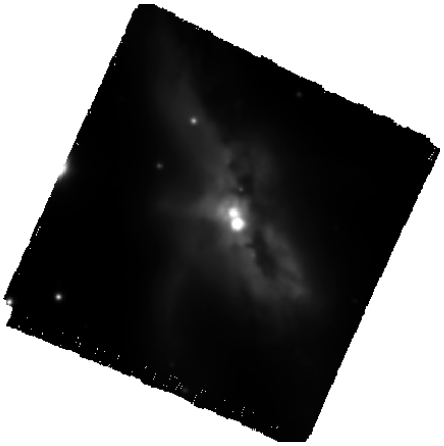
2.2 Galaxy Model

Our galaxy model consists of a bulge, disk, and a dark halo with profile parameters taken from Barnes (2016). The bulge is described by a Jaffe (1983) density profile of bulge mass M_b and scale radius a_b as seen in Equation 1.

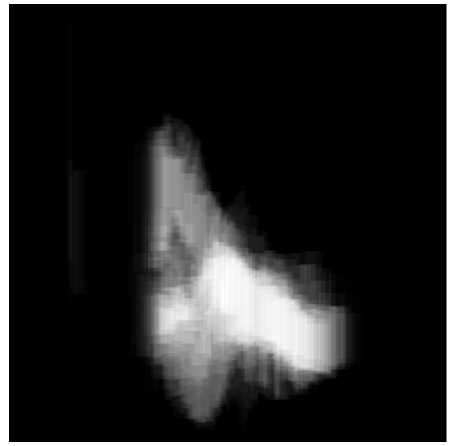
$$\rho_b(r) = \frac{M_b a_b}{4\pi r^2 (a_b + r)^2} \tag{1}$$

The disk is described by a exponential isothermal profile of disk mass M_b, inverse scale length α_d and scale height z_d as seen in Equation 2.

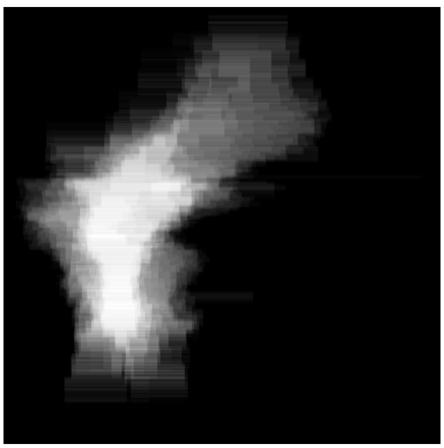
$$\rho_d(R, z) = e^{-R\alpha_d} sech^2(z/z_d) \frac{M_d}{4\pi\alpha_d^2 z_d} \tag{2}$$



(a) XY Projection



(b) XV Projection



(c) VY Projection

Figure 3: 3a is the stellar velocity field along our line of sight in pixel coordinate, 3a is a velocity vs pixel's x position plot and 3c is pixel's y position vs velocity plot. All three plots are spatially mapped Identikit friendly projection used in our matching.

The dark halo is described by a Navarro et al. (1996) or NFW profile of halo mass M_h and scale radius a_h. To make the mass of the model finite, we taper the density profile at radius b_h. Equation 3 holds true when $r \leq b_h$, while for $r > b_h$ we use the equation provided in Springel and White (1999) to produce an exponential drop beyond the taper radius. Our simulation is consistent with the conventional assumption we live in a ΛCDM cosmological model.

$$\rho_h(r) = \frac{M_h(a_h)}{4\pi(ln(2) - .5)r(a_h + r)^2} \tag{3}$$

The halo concentration is $c_h = \frac{b_h}{a_h}$.

Mergers with sufficiently massive dark halos generally have their tails fall back into the bulge soon after the first encounter and thus does not form extended tails (Dubinski et al.

(1996)). The parameter ϵ can be described as $\epsilon = \frac{v_e^2}{v_c^2}$ where v_e is escape velocity and v_c is circular velocity where radius $r = 2\alpha_d^{-1}$. ϵ is a measure of tail accretion rate. When $\epsilon \geq 6$, the tidal tails present after the first encounter often accrete into the galactic center before the second encounter occurs.

2.3 Modeling Method

A merger simulation is characterized by a minimum of 16 parameters which describe the initial orbit, disk inclinations, viewing angle, time, physical unit scaling and center of mass as described in Privon et al. (2013). The initial orbit is described by eccentricity e, idealized pericentric separation along the orbital plane p, and the mass ratio μ. Each galaxies' spatial orientation is determined by an orbital inclination angle i between the angular momentum vector and zenith and an azimuth angle ω equivalent to the argument of periapse.

Once the simulation is run, we begin the process of matching by choosing an output time t. The viewing angles $(\theta_x, \theta_y, \theta_z)$ describe our viewing direction with respect to the orbital plane. The length scaling L and velocity scaling V are used to scale the model quantities to physical units. The system's center of mass are described as (M_x, M_y) for plane of the sky and M_v for velocity, concluding all 16 sets of parameters. In addition, the galaxy models have their own parameters, described in Section 2.2.

In standard merger simulations the bulge, disk, and dark halo are represented by massive particles. The models are constructed from a self consistent N-body numerical simulation where we are required to describe an initial orbit and the disks' inclination. After stating the initial conditions, the simulation is advanced over a specific time step using a treecode (Barnes and Hut (1986)). This process results in a model where its viewing angle, scaling parameters and center of mass are arbitrarily decided in the viewer. However, this process only yields one possible set of disk orientations among many. We lack sufficient information regarding NGC 6240's initial state to narrow down the possible combination. Thus, this method would be too time consuming to explore every choice of initial orbit and disk orientation. However, after we obtain a set of disk angles from Identikit simulations, we use them to construct a self-consistent simulation. This is done to add another constraint to our modeling process.

The Identikit approach uses a spherical distribution for the galaxy's disk instead of the regular disk used in the standard approach. Simulations for various initial orbits are advanced over a specified time step and the collection of simulations are stored as a catalog. The spherical disk distribution allows us to account for all possible disk orientations. In the

Identikit interface, we select an angular momentum vector so test particles corresponding to the chosen vector appear in the rendered model. The remaining test particles are erased, leaving behind a typical disk. This program provides the flexibility to dynamically modify the disk orientation in real time as we inspect for the observed features. Using this method, we only need to perform one numerical simulation for a given initial orbit.

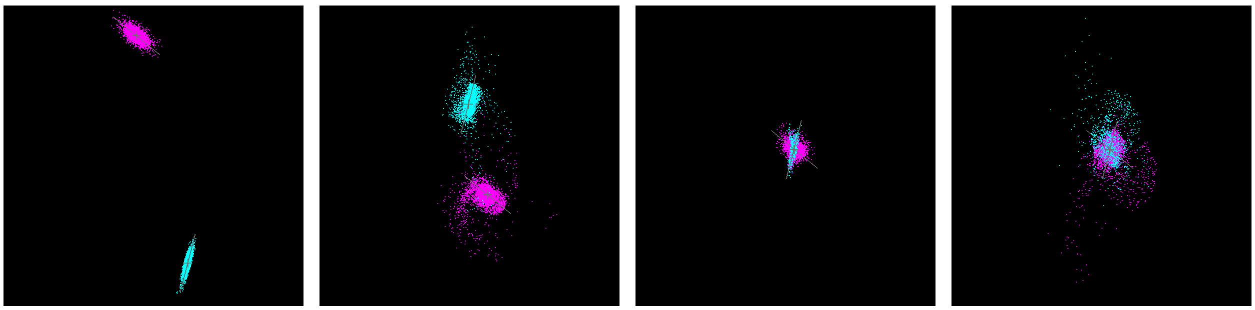
In the Identikit viewer, we select an initial orbit from the catalog to visualize on the viewer. The viewer displays the simulated model with XY, XV and VY projections. We manually adjust disk inclinations and view angle to search for features resembling those observed in Figure 3. To test our hypothesis that tidal tails fall back due to the gravitational field, we focus on models which include massive dark halos. Disturbed features have higher probability of forming when μ is approximately 1 so our model will focus on $\mu = 1$. Normally the two simulated galactic centers are locked to the nuclei's optical location, however the nuclei in NGC 6240 are too close together to designate a fixed separation without causing large variation in morphology when altering the disk inclination by a small angle. Our modeling process concludes when we obtain a set of parameters that create a model closely resemble the observed morphology and kinematics.

3 Result and Discussion

We adopt eccentricity $e = 1$, mass ratio $\mu = 1$ and $f_L = .05$ for all our simulations. We simulated two different candidate mass models for the progenitors of NGC 6240. The AGN of NGC 6240 are too close in proximity for us to effectively constrain their position without significant modification of morphology for small increment of change. Thus, we manually adjust the model's center so it is approximately over the galactic center.

3.1 Models of NGC 6240

Our first model used parameters $c_h = 16$ and $\alpha_d a_h = 3.0$, yielding $\epsilon = 6.13$. For our first model, we investigated the model for pericentric separation $\frac{p}{a_h}$ of .4, .5 and .625. While we explored the parameter space, we found the loop features forms after the first encounter and remains until after the second encounter as we suspected. We found a model with pericentric separation of $\frac{p}{a_h} \geq .625$ provide enough time for the progenitor galaxies to form two loops each, resulting in four loops overall. Ultimately we decided the difference caused by pericentric separation will not cause a major difference in the morphology. We found the lower tail and upper loop could replicated with good accuracy for all three separation. From the three choice of pericenter that we have explored so far, the model with $\frac{p}{a_h} = .4$ is shown to be the best fit. When $\frac{p}{a_h} = .625$, the upper tail extension does not follow the morphology and the lower loop was wider than expected. For $\frac{p}{a_h} = .5$ the upper tail trails off towards the end while the bottom loop is slightly skewed too much downward. At $\frac{p}{a_h} = .4$, the upper tail is a good fit while the bottom loop is slightly better align. In Figure 4, we showcase the different stages of the model's evolution in Identikit, including the final configuration.

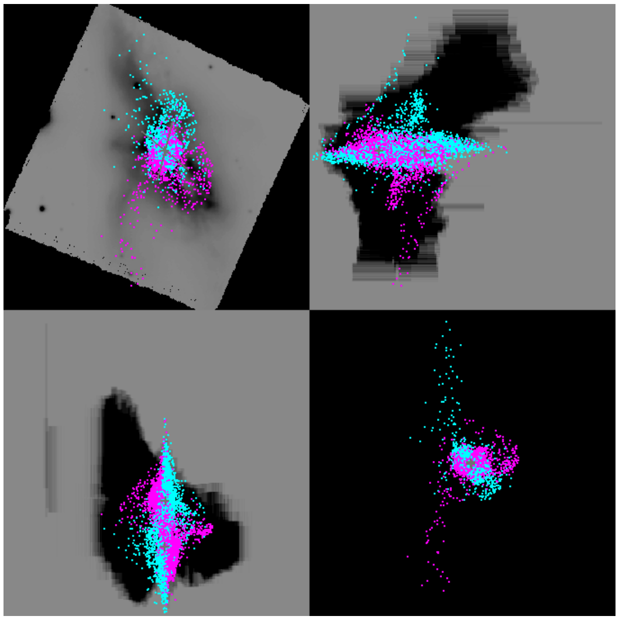


(a) Initial Separation (b) 1st Passage (c) 1st Apastron (d) Before 2nd Passage

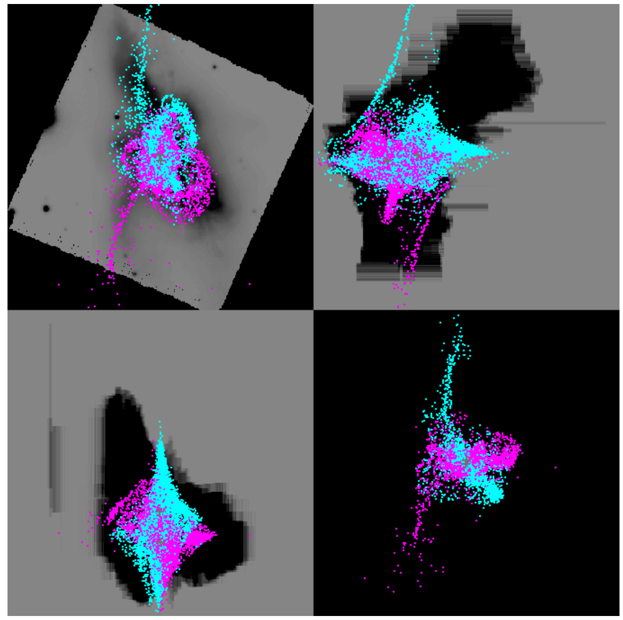
Figure 4: These are images of the first model throughout multiple timestep.

Figure 5a is our first model of NGC 6240 where $\frac{p}{a_h} = .4$. Our model used viewing angle of $(\theta_x \theta_y, \theta_z) = (110.9, 111.4, 8.5)$. The cyan galaxy disk have $i = 26.2$ and $\omega = 104.3$ while the purple galaxy disk have $i = 41.3$ and $\omega = 259.4$. The velocity phase diagram XV and VY constructed by the model does not align with our velocity data, although there are sections of key interest that does line up. This model does not quite replicate the merger's upper section, notice how the upper section extends out at the incorrect point and curves at the wrong angle. In addition, the model's lower loop feature fails to curl around the merger's lower loop properly.

We created a self-consistent version of the model by rounding the viewing angle, disk inclination and argument of periapse from their Identikit equivalent to the nearest 5s. These simulation used the same density profiles as their Identikit counterparts. If we look at our self-consistent model in 5b, we find the model does not follow the tails well nor the end of the lower loop. The tails of the self-consistent simulation captures the same trend as it's Identikit counterpart. However, there are noticeable deviations from the Identikit simulation. While the Identikit simulation's tails have some resemblance to morphology, the self-consistent simulation's tails and extensions are not well lined up with the morphology.



(a) Identikit Simulation

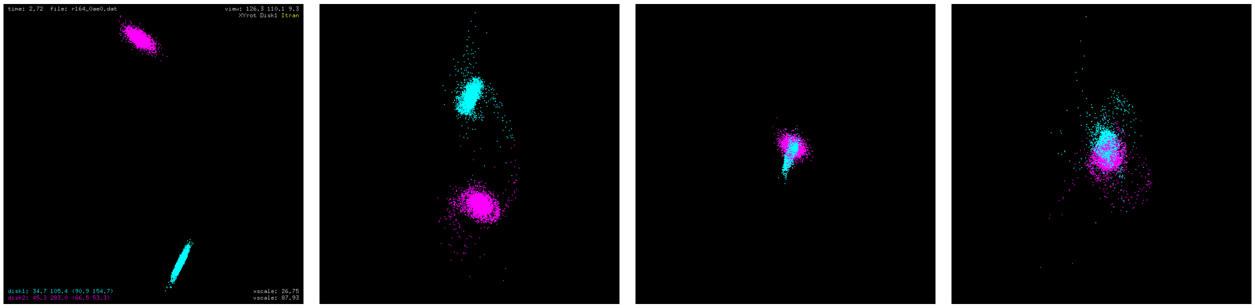


(b) Self-Consistent Simulation

Figure 5: 5a is the Identikit simulation while 5b is the self-consistent simulation for the first model

The second model used $c_h = 8$ and $\alpha_d a_h = 4.8$, yielding $\epsilon = 6.95$. From our first model results, we decided to work with only one pericentric separation, $\frac{p}{a_h} = .4$. In comparison to the first model, our second model re-accrets the tidal material much quicker, resulting in two loops for each galaxy. Interestingly, while we were exploring the parameter space, we found there are disk orientations where the extra loop is hidden. In Figure 6, we showcase the different stage of the model's evolution similar to what we did in our first model. In comparison to our first model, the loop features are better replicated in our second model. The upper tail matches the morphology pretty well, but the lower tail extends in a different direction.

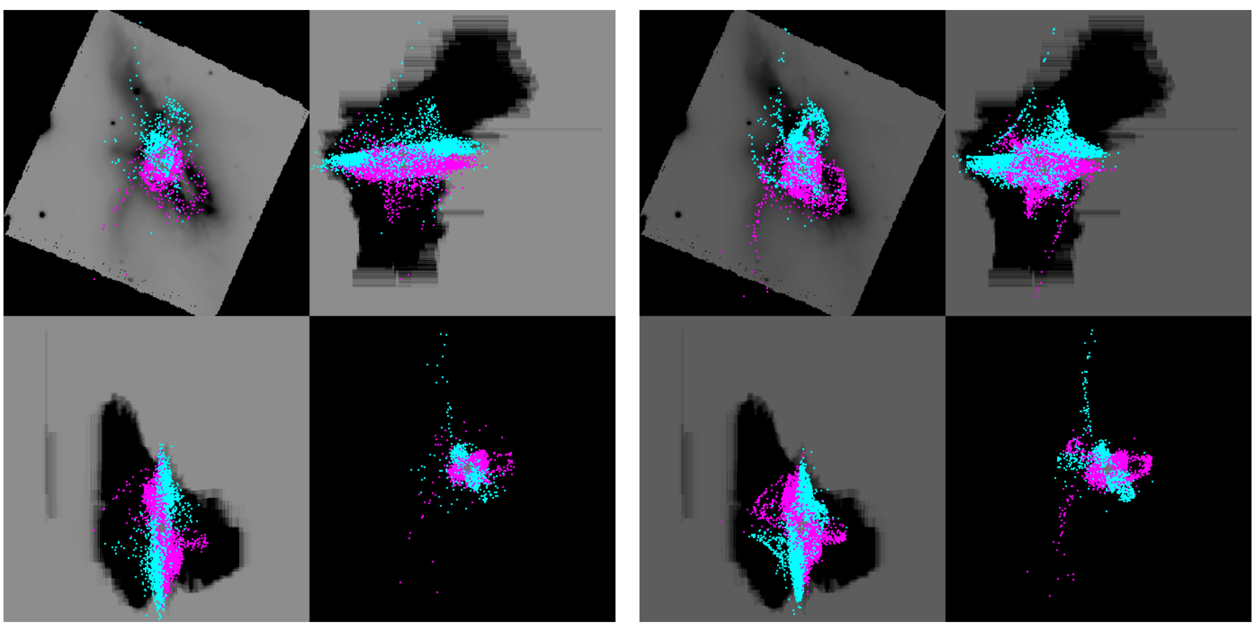
The self-consistent simulation for the second model matches the morphology extremely well, excluding the upper tail. If we examine figure 7b, we find the upper tail completely deviates from expectation. In comparison to it's Identikit counterpart, the loops are more pronounced, but the tails do not agree with each other very well. The self-consistent simulation fixed the Identikit simulation's lower loop, but fails to replicate the upper loop.



(a) Initial Separation (b) 1st Passage (c) 1st Apastron (d) Before 2nd Passage

Figure 6: These are images of the second model throughout multiple timestep.

Figure 7a is our Identikit simulation for the second model of NGC 6240. This model uses viewing angle of $(\theta_x\theta_y, \theta_z) = (126.3, 110.1, 9.3)$. The cyan galaxy disk have $i = 34.7$ and $\omega = 105.4$ while the purple galaxy disk have $i = 45.3$ and $\omega = 283.4$. The velocity phase diagram XV and VY for the second Identikit model follows the diagram more closely than the first one. This model's upper region with relatively high accuracy while the lower tail does not follow the curve. The loops of this model do better in replicating the morphology than the first model.



(a) Identikit Simulation (b) Self-Consistent Simulation

Figure 7: 7a is the Identikit simulation while 7b is the self-consistent simulation for the second model

3.2 Discussion

From our result, we conclude that it is possible to create a lookalike model of NGC 6240 and the second model is a better fit than our first model. The tails and loops in our second model are more in line with the morphology than the first model. In addition, the second model recreates the small bump at the left center. A trend we notice in our velocity diagram, specifically the XV diagram, is the upper and lower peak corresponds with the tails. Our model has some success with matching the lower tail, but the upper tail is difficult to match. We find the upper tail on the velocity does not curve hard enough and the body's velocity does not extend long enough. Our PV diagram has resolution of $\sim 100km/s$ so the features on the PV diagrams are not extremely reliable. Thus we do not stress too much importance on the velocity diagrams. As a result, we believe we did an adequate job in creating the possible models for NGC 6240.

We created self-consistent versions and compared them to their Identikit counterparts. If we look at figure 5b we find the loops to be well matched, but the two tails point of origin and extension does not fit well. Model 1's self-consistent simulation and Identikit simulation does resemble each other pretty well. On the other hand, figure 7b does a sufficient job in recreating the loops and lower tail, but the upper tail deviates greatly from what we expect in the Identikit model.

Although we have shown it is possible to create lookalikes of NGC 6240, we can not say we found a sure-fire model. According to findings from Kollatschny et al. (2020), NGC 6240 is a triple nucleus system, which would invalidate our process of modeling NGC 6240 as a double nucleus system. However, Larson et al. (2020) paper suggest the third nucleus could actually be an extra nuclear clump. We believe this object is an extra nuclear clump rather than a third nucleus since we find two galaxy sufficient to recreate the overall morphology. Our model does not attempt to reproduce the current nuclear positions accurately. We have not determined proper scaling parameters to match our models to physical scale of NGC 6240.

4 Conclusion

In our paper, we use sufficiently large halo to see if we could construct a model that resembles NGC 6240's morphology. Utilizing observational data from Muse and Subaru, we crafted a XY and PV diagram. These diagrams represent the morphology and velocity data we want to replicate. Our project use Identikit simulation to quickly explore the parameter space for feasible models. We included self-consistent simulation based off the Identikit simulations to use as another set of constraint. Although the velocity data could not be recreated, the loops and upper tail from our best model is acceptable match for our purpose. The large halo used in the simulation showed loops could be formed through rapid accretion of the tail material. Thus we may conclude that sufficiently large halo does enable us to construct an acceptable model of NGC 6240.

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