Time Evolution of Dark Matter Bars in Weakly Barred Galaxies

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Abstract

Galactic bars have been known to influence both the channeling of matter towards the nucleus of the galaxy, and potentially influence massive black hole dynamics; however a relatively untested and contested field of study is the effects had on the dark matter halo of a galaxy. Linear perturbation theory applied to strongly barred galaxies, dictates that interactions between the orbits and their resonances with the galactic bar have been shown to induce dark-matter bar evolution. Through the transfer of angular momentum the bar drives evolution for all modes within the galaxy. The predicted dark matter bar is expected to lag somewhat behind the original stellar bar. Weakly barred galaxies on the contrary are less conducive to angular momentum transfer and potentially spurring dark matter evolution in galaxies. We present then a statistical Bayesian analysis of the M = 2 potential of a very high resolution direct N-Body simulation of a weakly barred galaxy generated via Schwarzchild method to match with observational data of NGC 4371 over the course of 600 Myrs. Results show that there is a weak dark matter presence in the M=2 region, with limited evolution showing a relationship between the matter and dark matter bars. However, this does not compute for smaller inner bars, nor does this significantly affect dark matter distributions.

1 Introduction

Galaxy bars are a dominant presence among galaxies, comprising 2/3 of those observed, ranging from weak to strongly barred. The exact formation of bars is the result of the formation of a non-axisymmetric potential from the other materials within the galaxy, creating a triaxial potential. The orbits that comprise these potential are called peridic orbits and take upon the following family of forms[1].

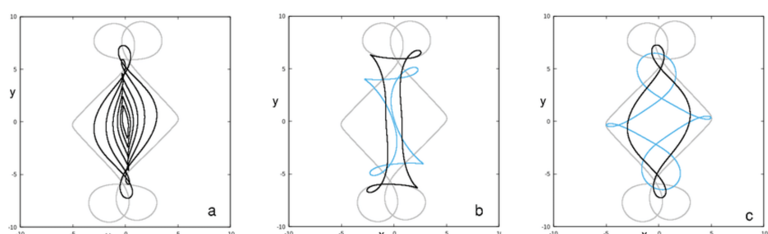

Figure 1: Various forms of peridic orbits, note that these are not the orbits that the individual stars and gas follow, but overlap to create what comprises the bar.

As seen above the orbits cross very close to the galactic center,a consequence of having a multiplicity of 2, which makes bars particularly important for material transport on galaxies. In a sense a bar induces its surroundings to become a bar as well. A less looked into consequence of this is how a bar may influence the dark matter halo surrounding a galaxy.

The evidence for an against an induced dark matter bar remains relatively inconclusive. Theory using linear perturbation theory, proposes that interactions between dark matter and the bar would lead to induced orbital instabilities on the former that drag the latter. Consequently, a dark matter bar would be formed that trails the stellar bar. However previous simulations with barred galaxies have acquired inconsistent results on the angular momentum change in bars. Though more recent idealized N-Body simulations have shown that there is some significant angular momentum transfer;

and that to get an accurate model of bar-halo dynamics, one requires simulations of 5×10^6 particles[2]. Additionally, other studies have shown that given the presence of a dark matter bar, there is a strong dependence on the strength of the original galactic bar[3]. Note, however, that in those simulations the potential was constant with respect to time, and concluded that weakly barred galaxies have a negligible dark matter presence.

To clarify and clean up any issues with previous research, this project is using a very high-resolution N-body simulation of a barred galaxy over the course of 600Myrs to observe the potential time evolution of the dark matter bar in a weakly barred galaxy.

2 Method and Motivation

2.1 Simulating a Galaxy

Through AMUSE and Schwarschild modeling, a weakly barred galaxy following observations of NGC 4371 was produced, with more than 5×10^6, particles of both dark and regular matter. Then we used Phi-GPU to model the evolution of the said galaxy over a fourth-order Hermite Integrator. The comparison can be seen below.

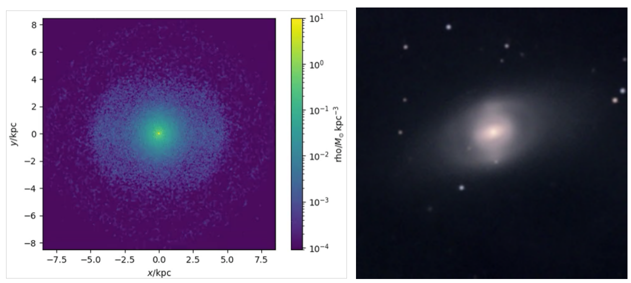

Figure 2: Our model[Left] of NGC 4371[Right], notice the faint weak bar in both.

Our model satisfies both the prerequisite for an accurate simulation for halo-bar interactions, and a lengthy time analysis of the bars in question. Ideally our data should provide evidence of some noticeable distinction in the dark matter distribution overall, and around the galactic plane for weakly barred galaxies. Additionally any results show that bars may play a role in the evolution of dark matter in galaxies.

2.2 Finding a Bar

To analyze the galaxy we used pynbody, a python module designed to analyze N-body simulation data. To distinguish the presence of the bar from the rest of the galaxy we'll be using a fourier map, which isolates all particles whose orbits that lie in the m=2 potential (The bar region). To eliminate any issues with the presence of other m=2 structures such as spiral arms, the radius of this analysis was limited to 3kpc.

Using the properties of the radial bins of pynbody, we can find the greatest amplitudes of the m=2 orbits at each radius and determine the bar from those points. The following section will go into how the bar was analyzed over time.

3 Analysis Techniques

3.1 Monte Carlo's

When producing the distribution of the greatest amplitude points, the result is fairly unphysical, since each object is placed into radial bins with varying numbers of particles. To accomdate for the uncertainty of the bins, we ran a Monte Carlo simulation of %30 for 60 trials (20 for regular matter), where the minimum requirement for each bin is also %30 . From the data we determined the covariance matrix, and as a result the standard error of each point. This would go on to be the sample weights in our regression later, introducing more physical results to the simulation.

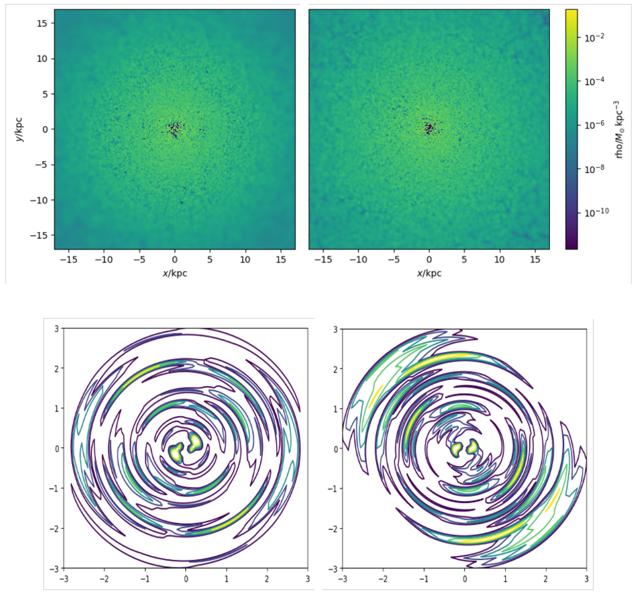

Figure 3: t = 0 and 218 [Left and Right] for dark matter distribution, before and after fourier mapping [Above and Below].

3.2 Regressions

From direct observations of the bar, three distinct bars can be noticed. See the image below for clarification

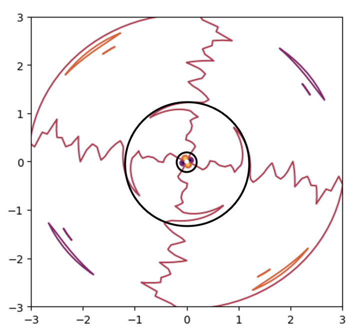

Figure 4: 3 bars of NGC 4371, first two circled, final one is the largest

This is relevant since the model being used is RidgeCV regression given by scikit-learn. RidgeCV is a linear regressor that both constrains the coefficients and uses cross validation to prevent overfitting. However since regions closer to the center would generally have lower uncertainties, (Smaller radius means smaller x and y errors, this cross-validation would still prefer the inner region, contaminating the result.

The way we fix this is by taking the mode of a posterior distribution we make, which is of the form

$$Score(R) = \frac{ModelScore(R) \times \ Prior}{Evidence}$$

Where our Prior is our observation that the smallest bar ends at 8th bin and the intermediate bar ends at 20bin, so it becomes a uniform distribution between those points.

The prior can be tested more through varying what the minimum radius should be, however that is very sensitive since any linear regression of 2 points would have a very strong model score.

For this analysis we will only look at the two largest bars due to the generally erratic movement of the smallest one, and the relative lack of data points.

A final fix needed for our regression is that they prefer to fit functions over fitting general lines, so to cover all 180º, each timestep a corresponding x and y model will fit the data and whichever produces the better model is chosen.

3.3 Angles & Time Series

With our optimal radii for each time step, we can accurately plot a linear regression. Note that we use the original stellar bar to calibrate the results, since we are comparing the dark matter results to them.

We calculate the angle with the slope of our linear fit, since:

$$\phi = \arctan(m)$$

Here m is the direct coefficient of the x model and the inverse of the y model.

When collected for each time, we can use astroml's LombScargle function to do a Fourier analysis of the data. Through this we can find the greatest periodic component, since the angle should be periodic, and we can compare the overlap of the final results.

4 Results

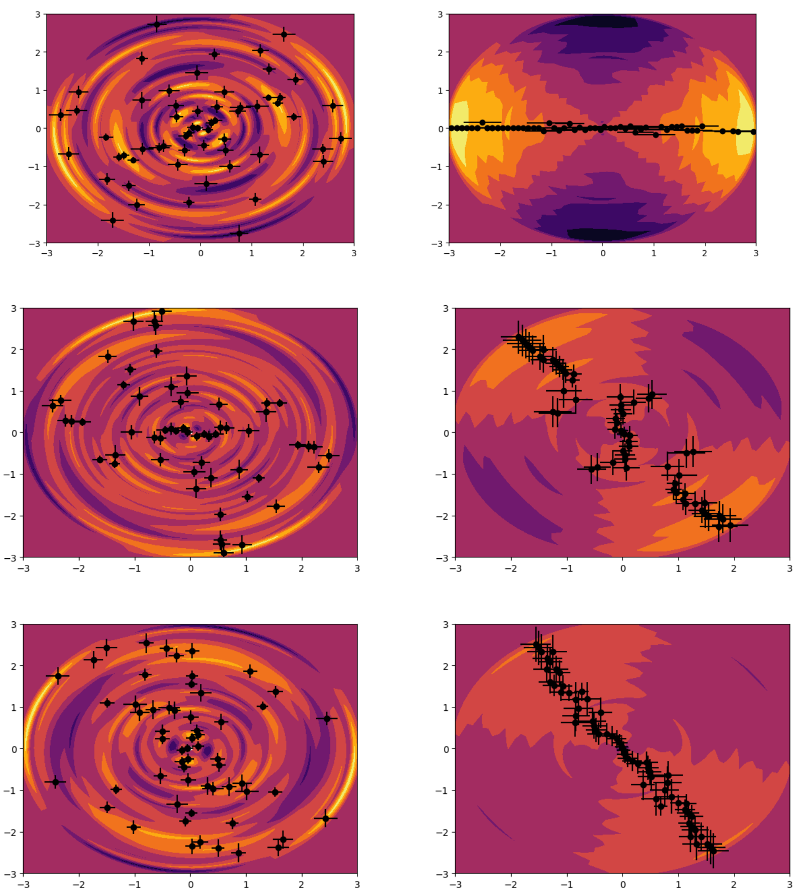

Figure 5: t = 0, t = 200, and t = 445 for the dark matter and matter bar locations, notice the increasing accuracy over time

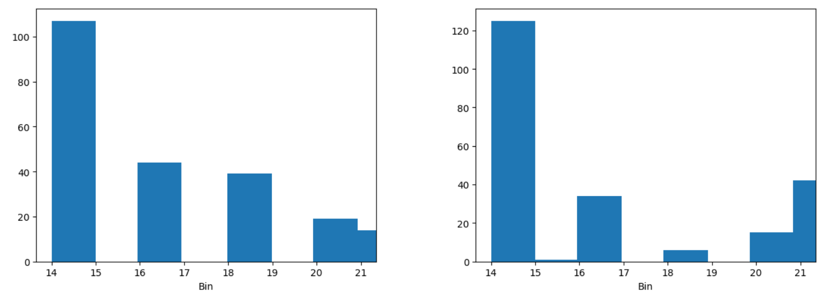

Figure 6: Optimal R comparision, DM on left, Stellar on Right

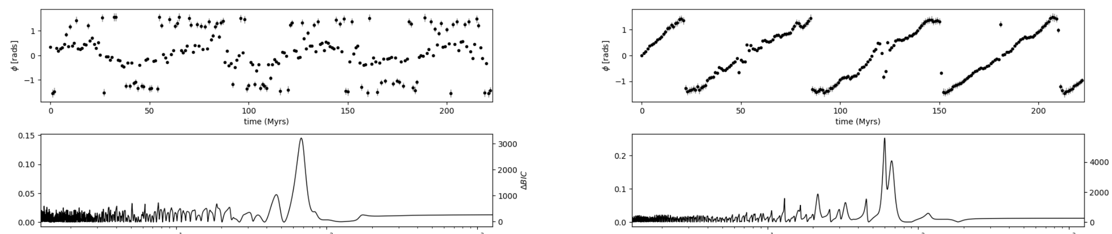

Figure 7: Time Series Analysis of DM [Left], and Matter [Right], notice that the peak for Dark Matter is 135.58, and for stellar its 119.72 (Note data is halved during analysis), log(False Call)is less than -14

5 Discussion & Summary

Looking below at a close up of the LombScargle distributions we can see that the periods of both of the larger bars in NGC 4371's simulation have similar periods, additionally these are the most significant periods compared to the others, with extremely low false-positive probabilities [Give them here]. Additionally, given that they have similar optimal radii, we can say that there is some relationship between them. Note that looking at the complete distribution shows that the dark matter bar does not completely trail the stellar one; however some fraction of the dark matter distribution may. Looking at the distribution of dark matter over time in this galaxy

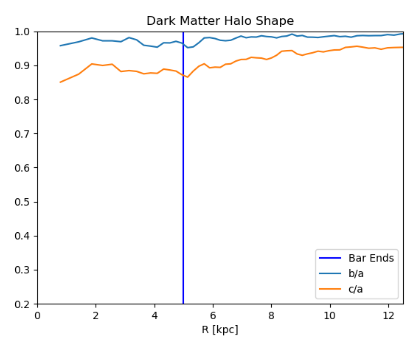

Figure 8: Shape of Dark matter at each radius near end of simulation t = 300.

The shape remains generally spherical even within the region where the bar is prominent, so the influence the bar has on the overall distribution is negligible. Any matter that gets close to the galactic plane however is susceptible to the flow of the bar, and as seen when fitting the data, the velocity of the bar does decrease over time.

The smaller bar has much more difficulty being fit than the larger one, likely because they lack as many data points to get a consistent shape. See that the galactic bar does have a similar shape to the large bar, just noisier, same with the dark matter. However more work has to be put in on how to best fit the smallest regions of the bars.

To summarize the results of this project, there has been shown to be a semblance of a relationship between the strongest points of the M=2 potential of the dark matter and stellar components of a galaxy. Over time these points follow similar trajectories, though the massive amounts of particles in the dark matter distribution creates a large amount of noise making the bar less discernible.

Weakly barred galaxies, just like strong ones seem to induce an albeit weak bar

References

[2]K. Holley-Bockelmann, M. Weinberg, N. Katz, Bar-xinduced evolution of dark matter cusps, Monthly Notices of the Royal Astronomical Society, Volume 363, Issue 3, November 2005, Pages 991–1007, https://doi.org/10.1111/j.1365-2966.2005.09501.x

[3]Marostica, D. A., Machado, R. E. G., Athanassoula, E., & Manos, T. (2024). The Response of the Inner Dark Matter Halo to Stellar Bars. Galaxies, 12(3), 27. https://doi.org/10.3390/galaxies12030027

[1]Pastras, Stavros & Patsis, P. & Athanassoula, E.. (2022). Gasflows in Barred Galaxies with Big Orbital Loops—A Comparative Study of Two Hydrocodes. Universe. 8. 290. 10.3390/universe8050290.

6 Appendix

Figures unable to fit into above section

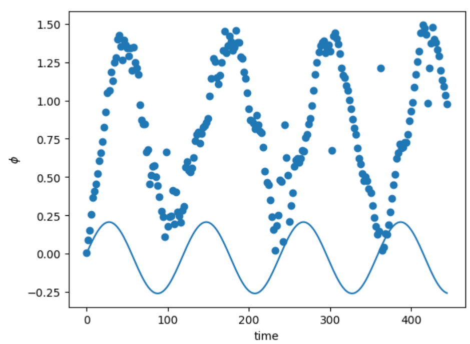

Figure 9: Fit of angle for galaxy, took absolute value of phi for better reference.

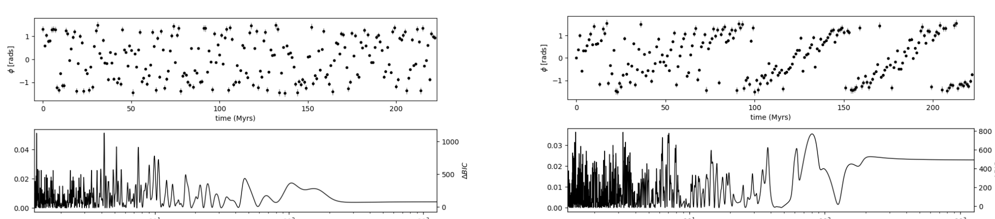

Figure 10: Noisy time series of the small bars, notice that they are somewhat similar but not significant enough to be noticeable.