TIDALLY INDUCED BARS OF GALAXIES IN CLUSTERS

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ABSTRACT

Using N-body simulations, we study the formation and evolution of tidally induced bars in disky galaxies in clusters. Our progenitor is a massive, late-type galaxy similar to the Milky Way, composed of an exponential disk and a Navarro-Frenk-White-dark matter halo. We place the galaxy on four different orbits in a Virgo-like cluster and evolve it for 10 Gyr. As a reference case, we also evolve the same model in isolation. Tidally induced bars form on all orbits soon after the first pericenter passage and survive until the end of the evolution. They appear earlier, are stronger and longer, and have lower pattern speeds for tighter orbits. Only for the tightest orbit are the properties of the bar controlled by the orientation of the tidal torque from the cluster at pericenter. The mechanism behind the formation of the bars is the angular momentum transfer from the galaxy stellar component to its halo. All of the bars undergo extended periods of buckling instability that occur earlier and lead to more pronounced boxy/peanut shapes when the tidal forces are stronger. Using all simulation outputs of galaxies at different evolutionary stages, we construct a toy model of the galaxy population in the cluster and measure the average bar strength and bar fraction as a function of clustercentric radius. Both are found to be mildly decreasing functions of radius. We conclude that tidal forces can trigger bar formation in cluster cores, but not in the outskirts, and thus can cause larger concentrations of barred galaxies toward the cluster center.

Key words: galaxies; clusters: general – galaxies: evolution – galaxies: fundamental parameters – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: structure

1. INTRODUCTION

Barred galaxies constitute between ~30% and 70% of the galaxy population depending on the exact definition of the bar, morphological type, environment, etc. (Aguerri et al. 2009; Buta et al. 2010, 2015; Cheung et al. 2013 and references therein). Bars seem to be important for the internal evolution of galaxies, e.g., since they provide a means of transport for gas and stars, as well as for the redistribution of angular momentum, and so are able to profoundly influence the structure of the host objects (e.g., Athanassoula 2013). As a result, bars are expected to be the driving force behind the formation of inner galactic structures, such as star-forming rings (Buta et al. 2004), and they also contribute to the build-up of bulge-like structures, i.e., the so-called pseudobulges (e.g., Fathi & Peletier 2003; Chung & Bureau 2004; Kormendy & Kennicutt 2004; Athanassoula 2005).

With the advent of large, often high-resolution, photometric surveys like the Spitzer Survey of Stellar Structure in Galaxies (S3G, Sheth et al. 2010; Kim et al. 2015) or the Calar Alto Legacy Integral Field Area (CALIFA) Survey (Sánchez et al. 2012), it became possible to not only study the properties of individual barred galaxies in much more detail, but also to assess the statistical properties of barred galaxies. Observational studies of barred galaxies focus either on a large number of objects to obtain statistical information on their properties across a number of parameters, or they can be detailed studies of a smaller number of objects (e.g., Aguerri et al. 2015; Seidel et al. 2015) or even single galaxies (e.g., Gadotti et al. 2015). The former are useful, e.g., for comparison with high-redshift objects, while the latter can be used to perform detailed comparisons with simulations.

Numerical simulations have shown that bars can form spontaneously from the dynamical instabilities inherent in self-gravitating axisymmetric disks (e.g., Efstathiou et al. 1982; for a review see Athanassoula 2013). The purely self-gravitating disks of early simulations were instantly susceptible to bar formation, with added spherical potential delaying but not preventing it (Ostriker & Peebles 1973; Athanassoula 2002). Bars were also found to grow more slowly in hotter disks, i.e., those characterized by higher velocity dispersions (Athanassoula & Sellwood 1986; Athanassoula 2003). Bar growth (in mass, length, and strength) is predicted to be due to the transformation of stellar orbits in the disk from circular to elongated as a result of the angular momentum loss of the involved stars. At the same time as the bar strength increases, its pattern speed is expected to decrease (e.g., Athanassoula 2003; Villa-Vargas et al. 2009). An important episode in the secular evolution of a bar is that of buckling instability leading to the formation of a boxy/peanut shape (Combes et al. 1990; Raha et al. 1991), and usually occurring about 1–2 Gyr after the formation of the bar (Martinez-Valpuesta et al. 2006).

Another channel for the formation of bars in galaxies may be related to interactions with other galaxies of similar, larger, or smaller size. It has been demonstrated that interactions with a perturber can lead to the formation of a tidally induced bar in a galaxy (e.g., Gerin et al. 1990; Noguchi 1996; Miwa &
Noguchi 1998; Berentzen et al. 2004; Mayer & Wadsley 2004; Lang et al. 2014; Goz et al. 2015. Recently, Łokas et al. (2014) investigated the evolution of a tidally induced bar in a dwarf galaxy orbiting a Milky Way-like host; a good candidate for such a bar is the Sagittarius dwarf (Łokas et al. 2010). Tidally induced bars could also form as a result of the interaction of normal-size or dwarf galaxies with a cluster-like potential (Byrd & Valtonen 1990; Mastropietro et al. 2005). In particular, Mastropietro et al. (2005) have shown that bars are an intermediate stage in the evolution of low-mass galaxies under strong cluster tidal fields from late- to early-type objects. If such a mechanism were indeed dominant in clusters, then we should observe an increased fraction of barred galaxies toward the cluster center.

Unfortunately, there is at present no clear evidence for such a relation, although early studies seemed to support this hypothesis. An analysis of the clustercentric distances of barred galaxies in the Coma cluster by Thompson (1981) showed that a significantly larger fraction of barred galaxies are located at the cluster core than at larger clustercentric distances. In a study of the Virgo cluster, Andersen (1996) found that barred disk galaxies are more centrally concentrated than unbarred disks. More recently, Barazza et al. (2009) studied the bar fraction in clusters at moderate redshifts z = 0.4–0.8 and found that the bar fraction decreases strongly with distance if normalized by the cluster virial radius.

However, other studies seem to have reached less firm or even conflicting conclusions. For example, Méndez-Abreu et al. (2010) studied the bar fraction in the Coma cluster (based on a sample of 190 galaxies spanning a 9 magnitude range) and found no dependence on clustercentric distance, suggesting that the environment is not the most important factor and plays a secondary role in bar formation and/or evolution. Lansbury et al. (2014) analyzed bars in S0 galaxies in Coma (using SDSS DR8 data) and found an increase in the bar fraction toward the cluster core, but at a low significance level. In another study, Cervantes Sodi et al. (2015) find (from the analysis of SDSS DR7 data) that the bar fraction is not directly dependent on the group/cluster environment, but is a strong function of stellar mass.

In general, external factors in bar formation are difficult to quantify. In order to aid in such an endeavor, in this paper, we study in detail the tidal evolution of a massive late-type disky galaxy similar to the Milky Way. By evolving the galaxy in a Virgo-like cluster for 10 Gyr on four distinct orbits, we investigate the influence of tidal forces of varying strength on the bar formation and evolution. As a reference case, we also analyze the bar properties in the same model evolved in isolation. Note that our purpose here is to investigate the effect of the tidal force of the cluster as a whole and not the effect of the short-term encounters between individual galaxies that may also influence the formation and evolution of bars in cluster galaxies. However, this second process is expected to be less important for the normal-size galaxies we consider here than for dwarfs or low surface brightness objects (Moore et al. 1999).

The paper is organized as follows. In Section 2, we describe the simulations used for this study. Section 3 presents a general description of the evolution of the galaxies in the cluster including the main characteristics such as kinematics and shape. Later, in Section 4, we investigate in more detail the properties of the bars formed during the evolution: their surface density distribution, bar mode strength, and pattern speed, as well as buckling instability. Finally, in Section 5, we use a few hundred simulation snapshots at varying clustercentric radii sampled from four simulations to create a toy model of the cluster galaxy population in which we measure the expected fraction of barred galaxies as a function of radius and attempt a comparison with observations. The discussion follows in Section 6.

2. THE SIMULATIONS

The initial conditions for our simulations consisted of N-body realizations of the Virgo cluster and a Milky Way-like progenitor generated via the procedures described in Widrow & Dubinski (2005) and Widrow et al. (2008). The procedures allow for the creation of N-body models of galaxies and halos very near equilibrium. The Virgo cluster was approximated as a single-component (Navarro et al. 1997, Navarro-Frenk-White (NFW)) spherical dark matter halo of $10^9$ particles with parameters estimated by McLaughlin (1999) from the combined analysis of X-ray and kinematic data and renormalized by Comerford & Natarajan (2007) to match our definitions of the virial mass and concentration (following Lokas & Mamon 2001). Namely, our Virgo cluster has a virial mass of $M_v = 5.4 \times 10^{14} M_{\odot}$, a concentration of $c = 3.8$, and an isotropic velocity distribution. In order to make the cluster mass finite, we introduce a smooth cutoff in the density profile at the scale of the virial radius (2.1 Mpc) so that the total mass is equal to the virial mass.

We compared the line-of-sight velocity dispersion profile of such an N-body realization to the presently available kinematic data for galaxies in the region of Virgo from the NED database. We find that the velocity dispersion profile of the generated model (although based on parameters aiming to reproduce the present properties of the cluster) falls significantly below the presently measured profile. This means that our model may be considered as a good approximation for the average gravitational potential in the Virgo cluster over the last few Gyr, rather than just the present-day maximum value. Once the evolution of the mass content of the clusters (and in Virgo in particular) is known in more detail, the results presented here can be mapped to a given epoch in the evolution of the cluster. Note also that the Virgo cluster is not a very massive cluster, and we may expect typical, more massive clusters to be even more effective in inducing bars as their tidal forces will be stronger.

As our model of the progenitor galaxy, we adopted a rather large, late-type galaxy similar to the Milky Way. We have used a model close to the model MWb of Widrow & Dubinski (2005), with just two components: an NFW dark halo and an exponential disk, but with no classical bulge. Each of the two components was made of $10^9$ particles. The dark matter halo had a virial mass of $M_{\text{halo}} = 7.7 \times 10^{11} M_{\odot}$ and concentration $c = 27$. The disk had a mass of $M_{\text{disk}} = 3.4 \times 10^{10} M_{\odot}$, a scale-length of $R_0 = 2.82$ kpc, and a thickness of $z_0 = 0.44$ kpc. Both components were smoothly cut off at the appropriate scales. The minimum value of the Toomre parameter of this realization was $Q = 2.1$, and so we expect the model to be stable against bar formation for at least a few Gyr.

We place the progenitor galaxy on a few typical, eccentric orbits in the Virgo cluster with an apocenter to pericenter distance ratio of $D_{\text{apo}}/D_{\text{peri}} = 5$ (Ghigna et al. 1998). The values of the apo- and pericenters were chosen to cover a wide range of distances where most of the galaxies in Virgo are
observed. Our tightest orbit with $D_{\text{peri}} = 0.1$ Mpc is the smallest possible that can still be considered unaffected by the central galaxy, while our most extended orbit reaches the outskirts of the cluster. In all of our simulations, the disk of the progenitor was coplanar and exactly prograde with the orbit. We performed four such simulations, referred to as S1–S4, with identical initial conditions except for the orbit sizes. As a reference case, we have also evolved our progenitor galaxy in isolation and will refer to this simulation as S5. The orbital parameters of the simulations are summarized in Table 1. The second and third columns of the table list the apocentric and pericentric distances, the fourth column gives the radial orbital period, the fifth column provides the number of pericenter passages occurring within the time during which we followed the evolution, and the last column shows the color coding to be used throughout the paper.

The evolution of the system in each simulation was followed for 10 Gyr using the GADGET-2 N-body code (Springel et al. 2001; Springel 2005) with outputs saved every 0.05 Gyr. The adopted softening scales were $\epsilon_D = 0.1$ kpc and $\epsilon_H = 0.7$ kpc for the disk and halo of the galaxy, while $\epsilon_C = 14$ kpc was adopted for the halo of the Virgo cluster, respectively. This large softening of the host (of the order of 5 scalelengths of the galaxy disk) was set so as to minimize the effect of the rather large mass of the cluster particles on the evolution.

### Table 1

| Simulation | $D_{\text{apo}}$ (Mpc) | $D_{\text{peri}}$ (Mpc) | $T_{\text{orb}}$ (Gyr) | $n_{\text{peri}}$ | Line Color |
|------------|-------------------------|-------------------------|------------------------|------------------|------------|
| S1         | 0.5                     | 0.1                     | 1.3                    | 9                | red        |
| S2         | 0.75                    | 0.15                    | 1.9                    | 6                | green      |
| S3         | 1.0                     | 0.2                     | 2.5                    | 4                | cyan       |
| S4         | 1.5                     | 0.3                     | 3.7                    | 3                | blue       |
| S5         | ...                     | ...                     | ...                   | ...              | black      |

3. EVOLUTION OF THE GALAXIES

#### 3.1. Orbital Evolution

The orbital evolution of the galaxies in the cluster during 10 Gyr is illustrated in Figures 1 and 2. In each simulation, the initial position of the progenitor was set at the coordinates $(X, Y, Z) = (-D_{\text{apo}}, 0, 0)$ kpc of the simulation box and the velocity vector of the galaxy was toward the negative $Y$ direction. Figure 1 shows the orbits of the simulated galaxies in projection onto the orbital plane $XY$. Figure 2 compares the distances (upper panel) from the cluster center and the orbital velocities (middle panel) of the galaxies in the cluster. The radial orbital periods for the different simulations (between the first two apocenters) are listed in the fourth column of Table 1. The galaxies experience a different number of pericenter passages: nine, six, four, and three, respectively, for S1 to S4. Note that some orbital decay is seen in the orbits as a result of dynamical friction, and so the apo- and pericenter distances as well as the orbital periods decrease in time.

The lower panel of Figure 2 shows the logarithm of the tidal force experienced by the stars of the progenitor galaxy approximated as $r M (<D)/D^3$ (and expressed in $M_\odot$ kpc$^{-2}$), where $r$ is the distance from the progenitor center and $M(<D)$ is the mass of the cluster contained within the galaxy’s distance.
from the cluster center, \( D \), as it moves on its orbit. For the calculation, we adopted \( r = 7 \) kpc, a scale-length found below to correspond to the typical length of the bar. We note that although the mass of the cluster contained within \( D \) is significantly smaller for the tighter orbit, the \( D^{-3} \) dependence of the tidal force on distance prevails and the tidal force is systematically stronger for tighter orbits than for more extended ones, both at pericenters and apocenters.

The values of log \( TF \) at the first pericenter passage vary from 7.2 for simulation S4 to 7.8 for S1. These values can be compared with those characteristic for the configurations applied in the study of Miwa & Noguchi (1998). They used close to point-mass perturbers of 1 and 3 times the mass of the perturbed galaxy and pericenter distances of 40 kpc. These values translate to log TFs of 7.3 and 7.8 in our units. Miwa & Noguchi concluded that these two values bracket the transition between two regimes of tidal bar formation: when the tidal perturbation is relatively weak, the bar properties are determined mostly by the internal structure of the perturbed galaxy, while a sufficiently strong tidal perturbation washes out the intrinsic structure of the target galaxy and creates a bar with properties determined by the parameters of the tidal encounter. Comparing these values with ours, we may expect that in simulation S4, where the tidal force is weak and below the range, the bar will be very weakly affected by tides, while for the tighter orbits S1–S3 we should see bars with different properties.

### 3.2. Evolution of Kinematics

In order to measure the global kinematic properties of the stellar component of the galaxies as a function of time, we calculated the direction of the principal axes of the inertia tensor of the stars within 7 kpc from the galactic center and rotated the stellar distribution to align the coordinate system with the principal axes so that the \( x \) coordinate is along the major axis, \( y \) is along the intermediate axis, and \( z \) is along the shortest axis. The choice of a radius of 7 kpc, corresponding to about \( 2.5 R_b \), was motivated by the typical length of the bars in the later stages of the evolution and will be justified below when we discuss the properties of bars in more detail. We then introduce a standard system of spherical coordinates and calculate the mean velocities and dispersions of the stars (see Łokas et al. 2014 for details).

Figure 3 illustrates the kinematic properties of the stellar components as a function of time for the five simulations. The upper panel shows the rotation of the stars around the minor axis \( v_y \). As expected from previous studies of the tidal stirring of galaxies, in general, rotation decreases with time, i.e., the streaming motion of the stars is replaced by random motions, as confirmed by the increasing one-dimensional (1D) velocity dispersion of the stars seen in the second panel. During the first 5 Gyr of evolution, the dependence on the orbit is clearly monotonous: the effect is strongest for the tightest orbit (S1) and weakest for the most extended orbit (S4). After that, the trend of decreasing rotation and increasing dispersion is not so clearly present for S1. The rotation can both decrease and increase at a given pericenter passage depending on the orientation of the bar at this moment. This is the same effect as was discussed for tidally induced bars in dwarf galaxies by Łokas et al. (2014, see their Figure 11): the bar is sped up if the tidal torque acts in the same direction as bar’s rotation, while it is slowed down if the torque acts in the opposite direction. As a result, at the end of the evolution, S2 is more evolved than S1 in the sense of having lower rotation and higher velocity dispersion. This is simply due to the more “favorable” orientation of its bar at pericenter passages. Let us also note that the evolution on the most extended orbit (S4) is very similar (even slightly slower) to the case of the galaxy evolving in isolation (S5). This means that at this most extended orbit, the tidal force is too weak to significantly affect the evolution.

The last panel of the Figure shows the behavior of the anisotropy parameter \( \beta \) (defined in the standard way as \( \beta = 1 - (\sigma_2^2 + \sigma_3^2)/(2\sigma_1^2) \), where the second velocity moment \( \sigma_\phi^2 = \sigma_\phi^2 + v_\phi^2 \) includes rotation). For all of the simulations, the anisotropy increases in time from negative values corresponding to tangential orbits (due to the initial rotation) toward more positive values corresponding to more radial orbits. For S1 and S2 where rotation is strongly diminished, the anisotropy is mildly radial, while for the remaining cases the orbits are close to isotropic or weakly tangential (S4) at the final stages of evolution.

### 3.3. Evolution of Shape

Figure 4 describes the evolution of the shape of the stellar component within 7 kpc. The upper panel of the Figure plots the intermediate to longest axis ratio \( b/a \), the middle panel the shortest to longest axis ratio \( c/a \), and the bottom panel the
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4. PROPERTIES OF THE BARS

4.1. Surface Density Distributions

Figure 5 illustrates the final outcome of the simulations in terms of the surface density distribution of the stellar component of the galaxies. The images were created by aligning the stellar components with the principal axes determined as before from the distribution of stars within 7 kpc from the center. The results for simulations S1–S5 are shown in rows. The columns (from the left to the right) contain the projections along the shortest (z), intermediate (y), and longest (x) axes of the stellar component, i.e., they correspond to the face-on, edge-on, and end-on views of the bars. The bar along the x axis is clearly visible in all cases.

The shape of the bar is, however, significantly different in S1 and S2 (the two tightest orbits) than in the remaining simulations: it shows a distinct boxy/peanut shape characteristic of a strong bar, not only in the edge-on view but also in the face-on view, while in S4 and S5 the isodensity contours are more elliptical, characteristic of weaker bars. Orbit S3 produces a bar with a shape intermediate between the two. Note that while the surface density contours of the bars formed in simulations S3–S5 would be well fit by the generalized ellipses proposed by Athanassoula et al. (1990), the shapes of the bars in simulations S1–S2, especially in the outer parts, could be better approximated by curves similar to Cassini ovals.

4.2. Bar Modes and Pattern Speeds

The strength of the bar can be characterized by one number: the module of the Fourier $m = 2$ mode of the surface distribution of the stars. We calculated this parameter for each output of the five simulations projecting all of the stars along the shortest axis and taking into account all of the stars within a radius of 7 kpc. The results are shown in the upper panel of Figure 6. Confirming the impression from the surface density distributions discussed in the previous subsection, we find the bar to be strongest in the case of simulations S1 and S2. Note, however, that the rather similar final stages of the two simulations are reached by significantly different paths. In the case of S1, the bar mode grows most strongly up to $A_2 = 0.5$ during the first 5 Gyr to remain more or less on a similar level in the later stages of evolution. On the other hand, for the remaining simulations S2–S5, this growth is more monotonic and stable, but at the end of the evolution S2 even overcomes S1, reaching $A_2 \approx 0.54$.

In the lower panel of Figure 6, we plot the pattern speed, i.e., the angular velocity of the bar measured during the last 5 Gyr, that is, after the bar is formed in all of our simulations. As expected, the stronger the bar is in terms of $A_2$, the lower its pattern speed. This correlation, known to exist for bars formed in isolation (Athanassoula 2003), is therefore also confirmed for our tidally induced bars. Again, we find an approximately monotonic dependence of the bar properties on the extent of the orbit of the galaxy: bigger tidal forces on tighter orbits produce stronger bars with lower pattern speeds.

Interesting information about the bar properties can be obtained if we go beyond single-value measurements and study the profiles of bar modes as a function of the cylindrical radius in the galaxy, $A_2(R)$. Examples of such profiles for the final outputs of the five simulations are shown in Figure 7. The curves possess characteristic shapes, with a maximum typical of bars formed in isolation and similar to tidally induced bars in dwarfs (Łokas et al. 2014).

An even more complete characterization of the bar properties, previously applied, e.g., by Athanassoula et al. (2005) and Saha & Maciejewski (2013), can be obtained by combining the dependence on distance and on time to produce maps of $A_2$ mode profile evolution such as those shown in Figure 8. Here, we combined measurements such as those shown in Figure 7 for 201 outputs of each simulation to create contour plots with...
Figure 5. Surface density distributions of the stars in the simulated galaxies at the end of the evolution for our five simulations (rows) and along different lines of sight: the shortest (z), intermediate (y), and longest (x) axes of the stellar component (columns from left to right). The surface density measurements were normalized to the log of maximum value $\Sigma_{\text{max}} = 3.3 \times 10^3 M_\odot \text{kpc}^{-2}$ occurring for the line of sight along the x axis for S2. Contours are equally spaced in log $\Sigma$ with $\Delta \log \Sigma = 0.05$. 
contours spaced by 0.1 in $A_2$. Such diagrams can be used to visually determine both the bar strength and bar length depending on the preferred definition of these quantities. For example, the first maximum value of $A_2$ along the radial variable can be adopted as a measure of the bar strength at a given time and some lower fixed value (e.g., half the maximum) at a larger radius as a measure of the bar length (see the discussion in Section 8 of Athanassoula & Misiriotis 2002).

The diagrams allow us to grasp the full history of bar formation and evolution in the five simulations. Slightly after the first pericenter passage, which occurs at 0.7, 0.95, 1.25, and 1.9 Gyr for simulations S1–S4, respectively, the disks are stretched, causing an increase of $A_2$ at large distances. As expected, the galaxy at the tightest orbit (S1) is affected most strongly and down to lowest radii. For this case, the evolution is rather complicated: initially, a small bar with a radius of about 3 kpc forms that only later grows to reach a typical scale of the order of 7 kpc and even larger. The intermediate stages of this evolution involve the formation of spiral arms, rings, and oval disks. Interestingly, for this simulation, the bar appears longest and strongest between 4.5 and 5.5 Gyr, i.e., during one full orbit between the fourth and fifth pericenter passage.

**Figure 6.** Evolution of the bar mode $A_2$ measured for stars within the radius $r = 7$ kpc (upper panel) and the pattern speed of the bar (lower panel) as a function of time.

**Figure 7.** Profiles of the bar mode $A_2(R)$ at the final outputs of the simulations.

**Figure 8.** Evolution of the bar mode profiles $A_2(R)$ in time. The five panels from top to bottom show the results for simulations S1–S5, respectively.
passage. After this period, the bar is shortened and weakened until the seventh pericenter at 7.7 Gyr when it starts to grow again. As discussed in Section 3.2, this behavior is due to particular orientations of the bar with respect to the tidal torque at pericenters. When the torque speeds up the bar, it makes it weaker, while the opposite is true for the torque slowing down the bar, which makes it stronger. We note that at the end of evolution, the bar in S1 is significantly longer than 7 kpc, as confirmed by Figure 7, whether we estimate the length as the radius where the first minimum occurs (∼14 kpc) or as the radius where $A_2$ falls down to half the maximum value (∼12 kpc).

For the remaining simulations, on more extended orbits, the situation is similar in the sense that a small bar forms first and then grows to a size of at least 7 kpc, but this generally happens later, in a more steady manner and the bar at the end is weaker. In all cases, the disk is stretched at the first pericenter passage, but at larger radii for more extended orbits. However, we always see perturbations (regions of slightly higher $A_2$) propagating toward the center of the galaxy that seem to seed the bar. These perturbations are stronger and propagate faster for tighter orbits.

The galaxy evolved in isolation (S5) remains stable against bar formation for the first 3 Gyr. After this time, a bar starts to develop and grows uniformly in a manner similar to the most extended orbit (S4). However, the growth in S5 is slightly faster and the final bar is a little stronger and longer than for S4. This behavior is probably due to the fact that, contrary to S5, the galaxy in S4 is subject to a tidal force, however mild, that affects and perturbs the outer parts of the disk forming tidal extensions. Only after that does a perturbation from the outer part travel toward the center to seed the bar.

Table 2 summarizes the properties of the bars at the end of evolution. The columns of the Table list (from the second to the sixth) the value of the maximum of the bar mode profile $A_{2,\text{max}}$ (see Figure 7), the length of the bar $a_b$, the pattern speed $\Omega_p$, the corotation radius $R_{\text{CR}}$, and the ratio $R_{\text{CR}}/a_b$. The corotation radii were estimated from the comparison between the circular frequency and the pattern speeds of the bars in the final simulation outputs, as shown in Figure 9. Note that mass loss due to tidal stripping is relatively mild in these simulations as all curves are close to the original one (well approximated by the black line corresponding to the galaxy evolved in isolation).

In particular, even the galaxy on the tightest orbit (S1) still contains 40% of the initial mass within 40 kpc at the end of evolution. The length of the bar was estimated as the cylindrical radius where the value of $A_2(R)$ drops to $A_{2,\text{max}}/2$ or, if a well-defined minimum of the profile occurs at a smaller radius, then this radius was adopted as the bar length. In most cases, the ratio $R_{\text{CR}}/a_b$ is of the order of 2, indicating that our bars are slow. Our strongest bar in S2 is even slower with a ratio equal to 3.4.

Another feature differentiating the evolution in the five simulations is the formation and survival of tidally induced spiral arms. In all cases, tidal extensions in the form of two-handed spirals are formed at pericenters. In the case of S1, however, the spiral arms are short-lived and are quickly dispersed to form extended tidal tails. Once the stars in the outer parts are stripped, no spiral arms are formed and the whole stellar component is contained in the bar, as confirmed by low values of $A_2$ at $R > 13$ kpc in the maps shown in Figure 8. In the case of S2–S4, the material in the spiral arms formed at the pericenter remains in the vicinity of the galaxy for some time. The arms wind up to form tighter structures but survive for much longer, especially in the case of simulation S4. We will discuss the properties of such tidally induced spiral arms in more detail in a follow-up paper (see also Semczuk & Łokas 2015).

4.3. Buckling

Another interesting phenomenon occurring during the evolution of the bars is that of buckling instability. An example of the edge-on view of the bar in simulation S1 at 4.95 Gyr from the start clearly showing the distortion due to buckling is presented in Figure 10. One more example is seen in the middle panel for simulation S3 in Figure 5. It turns out that bars buckle in all of our simulations, but later in the evolution for more extended orbits. We find that a good signature of buckling is the presence of non-zero streaming velocity along the shortest axis of the bar, which is best measured using cylindrical coordinates.

The upper panel of Figure 11 plots the absolute value of the mean streaming motion along the vertical (shortest) axis $v_z$ as a function of time. All simulations show a significant signal in this parameter, up to about 15 km s$^{-1}$, corresponding to
were performed in cylindrical coordinates for stars within 7 kpc.

Figure 10. Example of the buckling instability occurring for simulation S1 at 4.95 Gyr after the start of the simulation. The plot shows the surface density distribution of the stars viewed edge-on, perpendicular to the bar major axis. Asymmetries in the stellar distribution, characteristic of buckling, are clearly seen.

In the lower panel of Figure 11, we plot the evolution of the mean velocity along the shortest axis and the corresponding velocity dispersion as a function of time. The measurements for the dark matter particles show an opposite behavior. In this case, the \( z \)-component of the angular momentum of stars (upper panel) and dark matter (middle panel) measured for particles within 14 kpc from the center of the galaxy as a function of time. Clearly, in general, the angular momentum of stars decreases systematically with the most significant changes occurring at pericenter passages.

4.4. Angular Momentum Transfer

Transfer of angular momentum from the disk to the halo via resonances is believed to be the main mechanism behind the formation and evolution of bars in isolation (Athanassoula 2003). Here, we check whether a similar phenomenon may be at work for tidally induced bars. Figure 12 plots the \( z \)-component of the angular momentum of stars (upper panel) and dark matter (middle panel) measured for particles within 14 kpc from the center of the galaxy as a function of time. Clearly, in general, the angular momentum of stars decreases systematically with the most significant changes occurring at pericenter passages.

As expected, the behavior is qualitatively similar to that of the rotation velocity shown in the upper panel of Figure 3. The smaller timescale oscillations, particularly visible in the case of S4, are due to spiral arms. These oscillations are not present in S5, which indeed does not have transient spirals (see Figure 8). Note, however, that on average S4 and S5 have nearly identical angular momentum evolutions, which indicates that contrary to bars, these transient spirals do not significantly contribute to the angular momentum exchange between the disk and the halo.

The measurements for the dark matter particles show an opposite behavior. In this case, the \( z \)-component of the angular momentum grows with time and more so for tighter orbits. For
measurements, especially for S1, but also for S2 and S3, because the dark matter component then experiences strong tidal torques.

This means that for tighter orbits, some angular momentum is transferred outside the gravitationally bound body of the evolving galaxy. However, after 10 Gyr, only 10% of stars from within the 30 kpc radius are stripped even for the tightest orbit S1. This small number of stripped stars is unable to carry away a significant amount of angular momentum. Therefore, it must be transferred to the dark matter component first. The dark matter halo, being more extended, is more heavily stripped by tidal forces and the angular momentum can be carried away by its particles.

5. BAR FRACTION IN THE CLUSTER

We have demonstrated that, on average, bars form faster and are stronger for tighter orbits. We may therefore expect galactic bars to be stronger and more frequent near centers of clusters. Here, we attempt to predict the dependence of the bar fraction on the distance from the cluster center. For this purpose, we construct a toy model of the Virgo cluster using all of the 800 simulation outputs we have available from our four runs on different orbits S1–S4 (200 per simulation, excluding the initial configurations). We therefore assume that for the last 10 Gyr, our toy Virgo cluster constantly accreted galaxies, 4 of them every 0.05 Gyr, each on 1 of the 4 orbits we considered. Combining the simulation outputs in this way, we obtain a sample of galaxies at a variety of distances from the cluster center and at different evolutionary stages. We verified that the projected density distribution of such a sample of galaxies can be approximated by a power law not very different from the actual distribution of galaxies in Virgo.

We then assume that an imaginary observer is able to measure exactly the properties of the bars, in particular the strength of the bar mode \( A_2 \) using stars within 7 kpc for all galaxies in the sample, as we have done in previous sections. We then have a sample of 800 galaxies with known distances and \( A_2 \) values. We now translate the three-dimensional distances to the projected ones assuming that the cluster is observed along the X, Y, and Z axes of the simulation box. Binning the galaxies in projected radius into 8 bins of 100 galaxies each, we calculate the mean value of \( A_2 \) and the fraction of galaxies with a strong bar (\( A_2 > 0.3 \)) in each bin. The results for the quantities calculated in this way are shown in Figure 13 for the three lines of sight. The average strength of the bar (upper panel) shows a clear trend of values decreasing with distance from the cluster center. The bar fraction (lower panel) also shows a general trend to decrease with radius, although it varies strongly with distance and depends on the line of sight. The case of the decreasing bar fraction is least convincing for the observation along the Y axis (magenta line) where it is fairly constant with radius within the distance of 0.6 Mpc.

Given this rather idealistic realization of the Virgo cluster, we expect that detecting such trends in real data may be even more difficult. Recall that we have used just a single model of a progenitor galaxy and one initial orientation of its disk with respect to the orbit (exactly prograde). Varying these parameters would result in a sample of barred and unbarred galaxies whose average properties are very difficult to estimate. We have verified, however, by running the simulations on orbits S2 and S3 with exactly retrograde disk orientations that
bars formed in such configurations are similar to those in isolation, i.e., such disk orientations do not speed up the formation of bars. For the mildly prograde and perpendicular orientations of the disk, we expect some enhancement in the bar strength, but much weaker than for the exactly prograde configurations. In both panels, the three lines correspond to measurements along the three axes of the simulation box: $X$ (brown), $Y$ (magenta), and $Z$ (orange).

![Figure 13](image.png)

Figure 13. Average value of the bar mode $A_1$ (upper panel) and the bar fraction (lower panel) as functions of the projected distance from the cluster center. The bar fraction is defined as the fraction of galaxies with $A_2 > 0.3$. In both panels, the three lines correspond to measurements along the three axes of the simulation box: $X$ (brown), $Y$ (magenta), and $Z$ (orange).

bars formed in such configurations are similar to those in isolation, i.e., such disk orientations do not speed up the formation of bars. For the mildly prograde and perpendicular orientations of the disk, we expect some enhancement in the bar strength, but much weaker than for the exactly prograde cases (Lokas et al. 2015). Therefore, if galaxies are accreted by clusters with random disk orientations, then we may expect the average bar strength and bar fractions to decrease with respect to what we showed in Figure 13.

It would be essential to compare the predictions to real data. Unfortunately, although Virgo is one of the closest and best-studied clusters, no uniform morphological classification of its member galaxies has been performed to date, although one may be available soon within the Next Generation Virgo Cluster Survey (Ferrarese et al. 2012). We have therefore selected probable Virgo members from the NED database using the velocity criterion $-1000 \, \text{km} \, \text{s}^{-1} < v < 3000 \, \text{km} \, \text{s}^{-1}$ that corresponds to a $\sim 3\sigma$ cut and removes obvious interlopers. Such a selection yields a sample of 1168 galaxies with morphological classification (barred versus unbarred) up to 2.9 Mpc from the cluster center. The morphological types given by the NED database were verified and in some cases supplemented using the data from LEDA and Galaxy Zoo.

Calculation of the fraction of barred galaxies as a function of radius gives values of the order $0.1$–$0.15$ almost independently of radius out to 2 Mpc. There is thus no strong variation of the bar fraction visible in the data. Also, the value found is significantly lower than our prediction in the lower panel of Figure 13. However, if we take into account that our toy model only includes disky galaxies and none of them undergo a full transformation into a spheroidal/elliptical object, the comparison would be more meaningful if we used only late-type galaxies in Virgo. Selecting only spirals and S0s with firm morphological classification (in the same velocity range), we end up with a much smaller sample of 356 galaxies within 2.9 Mpc. The fraction of objects classified as barred among those turns out to be much higher and varies in the range of $0.25$–$0.45$ depending on binning. This value agrees quite well with our prediction for the central part of Virgo, but still no clear trend with radius is visible.

We have already remarked that the prediction may be an overestimate due to the narrow class of orbital configurations considered. Also, the data we have used are far from uniform and complete as the NED database is a compilation of information originating from different studies and surveys. Comparison with the data in the case of the Virgo cluster may also be hampered by the particular properties of the cluster itself. First, the cluster is known to be non-spherical and departing from equilibrium. However, the most important feature from our point of view may be the fact that it is composed of a few distinct groups. It may very well be that the presence of such groups obscures or even destroys the dependence of the bar fraction on the distance from the cluster center as the galaxies may have evolved in group rather than cluster environment in the first place.

6. DISCUSSION

We studied the formation and evolution of tidally induced bars in late-type galaxies similar to the Milky Way orbiting in a Virgo-like cluster. We placed our progenitor galaxy on four different orbits in the cluster and also evolved it in isolation as a reference case. Bars form in the galaxies in all our simulations and we find an approximately monotonic dependence of the bar properties on the strength of the tidal force experienced during the evolution. The bars form earlier and are stronger and longer for galaxies more affected by the tidal force from the cluster. All of our bars experience extended periods of buckling instability, but again this occurs earlier on tighter orbits. The formation time and properties of the bar in the model evolved in isolation are very similar to those in the galaxy on the most extended orbit, and so for this orbit no enhancement in bar strength was seen. We therefore conclude that tidal interactions can trigger and influence bar formation in the cluster center but not in the outskirts. Our results agree with those of Miwa & Noguchi (1998), who estimated the range of tidal forces that should result in strongly tidally modified bars. This range turns out to correspond to the values of tidal force experienced by our galaxies on tighter orbits.

Our tidally induced bars turn out to be quite slow in terms of the ratio of the corotation radius to the bar length, which we find to be of the order of 2 or higher, while the typical observed values are of the order of unity (i.e., most of the observed bars are fast). They also appear to be slow when compared to the bar pattern speed of the Milky Way, which is estimated to be of the order of $\Omega_b \approx 50 \, \text{km} \, \text{s}^{-1} \, \text{kpc}^{-1}$ (Gerhard 2011), while our fastest bars have $\Omega_b$ below 15 in the same units. While Miwa & Noguchi (1998), who simulated the formation of tidal bars as a result of encounters between two galaxies, also found their tidal bars to be rather slow, in our case the speed of the bar seems unrelated to the tidal origin. Note that all of our bars are similarly slow, even the one formed in isolation, and so their speed is rather due to the initial configuration. In addition, our bars are much longer and stronger than the real Milky Way bar, and so they must have lower pattern speeds. The trend of stronger bars having lower pattern speed is the same in our bars as in those formed in isolation.
Only for the tightest orbits does tidal evolution lead to the formation of a distinctive boxy/peanut shape at the end of the simulations. Here, we agree with Noguchi (1996) and Miwa & Noguchi (1998), who observed that tidal bars have different, more boxy shapes than bars formed in isolation. On the other hand, Athanassoula & Misiriotis (2002) found that the shapes of the bars can be different even if they form in isolation and suggested that this is related to the fraction of dark matter in the galaxy center and the amount of angular momentum transferred from the disk to the halo. Since all of our progenitors have the same structural properties initially, it seems that the shape is indeed controlled by the amount of angular momentum transferred, whether it is caused by the different initial structure or is induced by tides.

We verified that the mechanism behind the tidal bar formation in the configurations discussed here, i.e., a normal-size galaxy evolving in a cluster environment, is the transfer of angular momentum from stellar to dark matter particles of the galaxy. Only after the dark matter halo is stripped by the tidal forces is the angular momentum transferred outside the galaxy. Note that this is significantly different from the case of a dwarf galaxy orbiting the Milky Way discussed by Łokas et al. (2014) where the stellar angular momentum was carried away by the stars stripped from the dwarf and feeding the tidal tails. Here, very little stripping of the stellar component takes place, and so a different mechanism must be at work. This mechanism, the transfer of angular momentum from the stars to the dark matter halo, is thus the standard one that has been invoked as the process responsible for bar formation in isolated galaxies (Athanassoula 2003; Debattista et al. 2006; Martinez-Valpuesta et al. 2006).

Additional differences between the tidally induced bars in dwarfs and in normal-size galaxies studied here include the fact that, in the dwarf, the buckling is very weak and the bar structure is rather simple, while here the stellar component undergoes a number of rapid variations, including extended periods of buckling, and the formation of the bar is accompanied by the presence of short-lived substructures like rings, spiral arms, or even bars embedded within weaker bars or oval disks. This is especially the case for the tighter orbits. On the other hand, on more extended orbits, we witness the formation of strong and long-lived spiral arms. The observational properties of these tidally induced bars and spiral arms will be discussed in more detail in follow-up papers.

The problem of the evolution of disky galaxies in cluster-like environments has been addressed in a number of past studies. For example, Mastropietro et al. (2005) studied the evolution of disky dwarf galaxies and their transformation into early-type objects. They reported the formation of tidally induced bars in some of their configurations. On the other hand, Gnedin (2003) and Smith et al. (2015) did not get bars as a result of tidal interactions in their studies. The difference in the outcome of their simulations and ours can be traced to different initial configurations: their disks are rather hot and thick from the start (in the case of Smith et al. 2015) or become such when evolved in isolation (Gnedin 2003), and thus are more stable against bar formation. In contrast, in our case, the thickness and the vertical velocity dispersion of the stellar component remains constant in time until the bar buckles.

Using all of our simulation outputs, we constructed a toy model of the population of galaxies in a Virgo-like cluster in order to estimate the expected average strength of the bar and the fraction of barred galaxies as a function of clustercentric distance. We predict both quantities to be mildly decreasing functions of radius. We have also attempted a preliminary comparison with the data using a morphologically classified sample of galaxies in Virgo from NED but were unable to confirm the expected trends. The difficulty lies in the lack of a proper data set with uniform morphological classification and depth, but also in the presence of substructure in Virgo that may obscure the trends.

An obvious caveat of the results presented here is the lack of a dissipational component in our simulations, as including gas dynamics and star formation is known to have some influence on bar formation in galaxies (Debattista et al. 2006; Athanassoula et al. 2013). In particular, Athanassoula et al. (2013) find that in the presence of a significant gas fraction in the disk, bars form later and are weaker. However, the gas component in normal-size galaxies is probably not dominant at the time they are accreted by a cluster and, in addition, the gas is expected to be stripped by ram pressure rather quickly after the galaxies are accreted if they plunge deep enough inside the cluster, as is the case for our orbital configurations (Quilis et al. 2000). Therefore, in less than one orbital time, the dynamics of the galaxies is expected to be essentially collisionless. We are thus confident that our simplified approach is able to grasp the basic evolution of disky galaxies in clusters and the process of formation of tidally induced bars in them.

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