Studying Barred Galaxies by Means of Numerical Simulations

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Abstract We will describe two morphological structures of barred galaxies with the help of numerical simulations. The first one is a feature seen in face-on barred galaxies, the ansae, probably very important dynamically speaking.

The second one, are the Boxy/Peanut bulges in disc galaxies. They have been associated to stellar bars, and are a result of the secular evolution of barred galaxies. We analyse their properties in a large sample of N-body simulations, using different methods to measure their strength, shape and possible asymmetry, and then intercompare the results. Some of these methods can be applied to both simulations and observations. In particular, we seek correlations between bar and peanut properties, which, when applied to real galaxies, will give information on bars in edge-on galaxies, and on peanuts in face-on galaxies.

1 Introduction

Optical studies have established that about 1/3 of all disk galaxies are strongly barred, and another 1/3 moderately barred (e.g., Sellwood & Wilkinson 1993). Near infrared (NIR) imaging, a more efficient way to detect the old stellar population of bars, has increased the observed bar fraction even further to more than 80% (Eskridge et al. 2000; Knapen, Shlosman & Peletier 2002; Grosbøl, Pompei & Patsis 2002).

We will show, some examples on how the numerical simulations can help us to understand some aspects of these barred galaxies.

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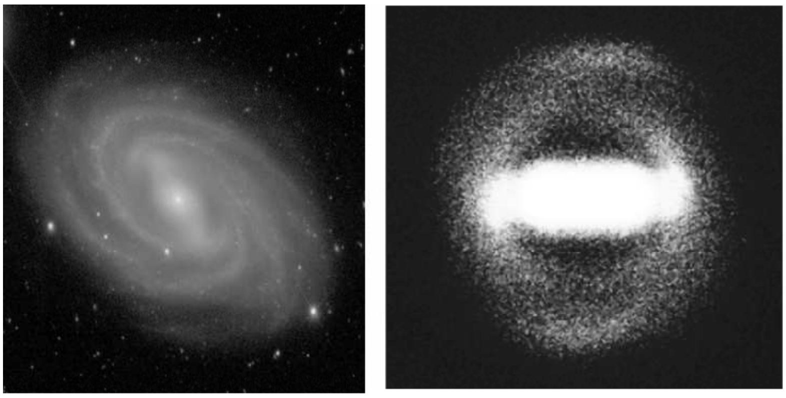

Fig. 1 *Left:* Example of the ansae in an observed galaxy, M106.*Right:* Face-on view of a simulated galaxy (the standard model) at time $\tau \sim 9.4$ Gyr. The ansae can be clearly observed at the ends of the bar.

2 Face-on view. The case of Ansae in barred galaxies

We focus in a morphological feature at the outer region of the bar. Ansae can be described as a pair of density enhancements at the ends of the bar (Fig. 1), sometimes also referred to as *condensations* in older work (e.g., Danby 1965) or symmetric density knots (see Martinez-Valpuesta, Knapen & Buta 2007). More examples of ansae can be found in the literature(e.g., NGC 4262, NGC 2859 and NGC 2950; Sandage 1961; Athanasoula 1984). Ansae can be seen also in numerical simulations of barred galaxies, at later stages of their evolution (Athanassoula & Misiriotis 2002, Martinez-Valpuesta et al. 2006). We can see as an example Fig. 2.

We present a statistical analysis (from Martinez-Valpuesta, Knapen & Buta 2007) of the presence of ansae in barred galaxies based in The de Vaucouleurs Atlas of Galaxies (Buta, Corwin & Odewahn 2007). We select all the barred galaxies from the Atlas. Assuming that the sample of galaxies collected in the Atlas is random in the sense that the presence or absence of ansae did not influence the selection process of galaxies in the catalogue. Based on the detailed description for each galaxy as given in the Atlas, we then separated all galaxies with and without ansae, and collected the statistics as a function of morphological type (Fig. 2).

The statistical analysis shows how ansa bars are more predominant among early type barred galaxies. In simulations, the ansae in bars appear at later stage of their evolution, when the bar is already fully evolved, and already has at least one buckling (Martinez-Valpuesta et al. 2006). If we compare the observations and simulations, we can think about early type galaxies, as those that are quite evolved.

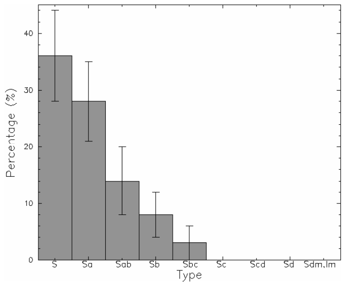

Fig. 2 Histogram of ansa bars among barred galaxies. Data from Martinez-Valpuesta et al. 2007

3 Edge-on view. Boxy/Peanut bulges

By means of simulations and theoretical studies it has become clear in the last decades that bars are not flat morphological features but that they have a vertical structure, the Boxy/Peanut bulges (Combes & Sanders 1981, Combes et al. 1990).

We use 200 simulations from E. Athanassoula to corroborate that bars grow strongly, together with bulges that they produce. For that we developed and used different methods, allowing as to have a clear quantification of the peanut strength and the bar strength, among other properties of bars and Boxy/Peanut bulges.

3.1 Methods for measuring bar and peanut strength. Correlation

In this section we introduce several methods for measuring the properties of the bar and the B/P feature. In order to measure the bar strength we use the typical Fourier decomposition and take the amplitude of the second component. We can do this globally or radially, i.e. calculating withing the bar region or calculating it in different cylindrical shells.

$$A_{m,r} = \frac{1}{M_k \pi} \sum_j m_j e^{im\theta_j}, \quad m = 2, \tag{1}$$

$$C_{m,r}(R) = |\sum_{j=1}^{N_s} m_j e^{im\theta_j}|, \quad m = 2, \tag{2}$$

and N_s being the number of particles in the given cylindrical shell of radius R.

In principle, for each given snapshot, we only consider the disk particles, position the bar major axis parallel to the x-axis and view, therefore, the bar side-on. Our main and new method to measure the B/P strength is by means of the Fourier decomposition again. We divide the edge-on snapshot of the bar in columns (of x, z

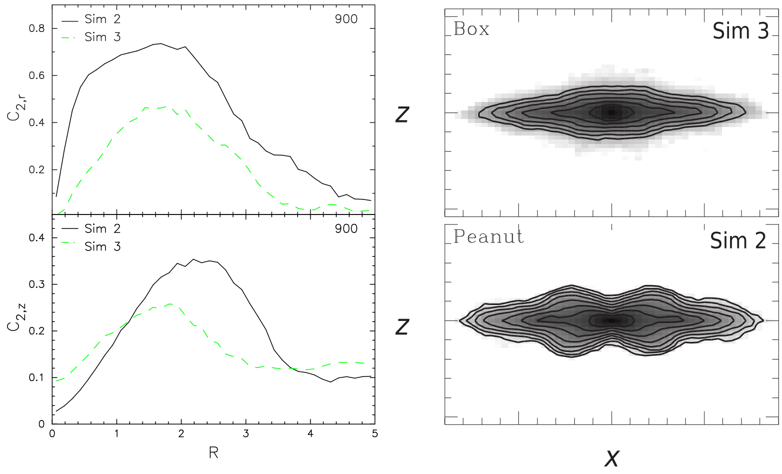

Fig. 3 *Right figure*: In the *top panel* figure we show the strength of the bar vs. radius for both simulations. In the *lower panel* we show the corresponding strength of the B/P bulge. *Left figure*: The *top panel* correspond to the edge-on view of Sim. 3, boxy type and in the *lower panel* the Sim. 2, strong peanut bulge.

components) at each given x.

$$C_{m,z}(x) = |\sum_{j=1}^{N_s} z_j e^{imz_j/(5z_0)}|, \qquad m = 1,2 \tag{3}$$

with N_s the number of particles per column or cut, and z_0 the scale height of the initial exponential disk. As an example of these methods for measuring the bar strength and the B/P bulge strength, we show them in Fig. 3.1, for two different simulations. One in which the B/P bulge is of type more peanut or X-shaped, i.e. strong, Sim 2, and one where the bulge is more boxy, i.e. weak B/P bulge.

The next main methods that we apply in our analysis are the standard statistical methods. We again apply them to the snapshot viewed edge-on. For measuring the strength of the peanut we can use the median, and standard deviation. The skewness and mean can be used to measure the strength of the buckling event, i.e. the asymmetry reached during the vertical instability. The shape of the bulge can be measured with the kurtosis.

It is clear from Fig. 3.1 (*right panels*), that our methods to calculate the strength of the B/P bulge correlate nicely. In case of application to real observed highly inclined galaxies, these methods can be apply indistinctly. Even more interesting is the correlation arising when comparing the strength of the bar with the strength of the B/P bulge, measure with the kurtosis and with $C_{2,z}$, as can be seen in Fig. 4. Note

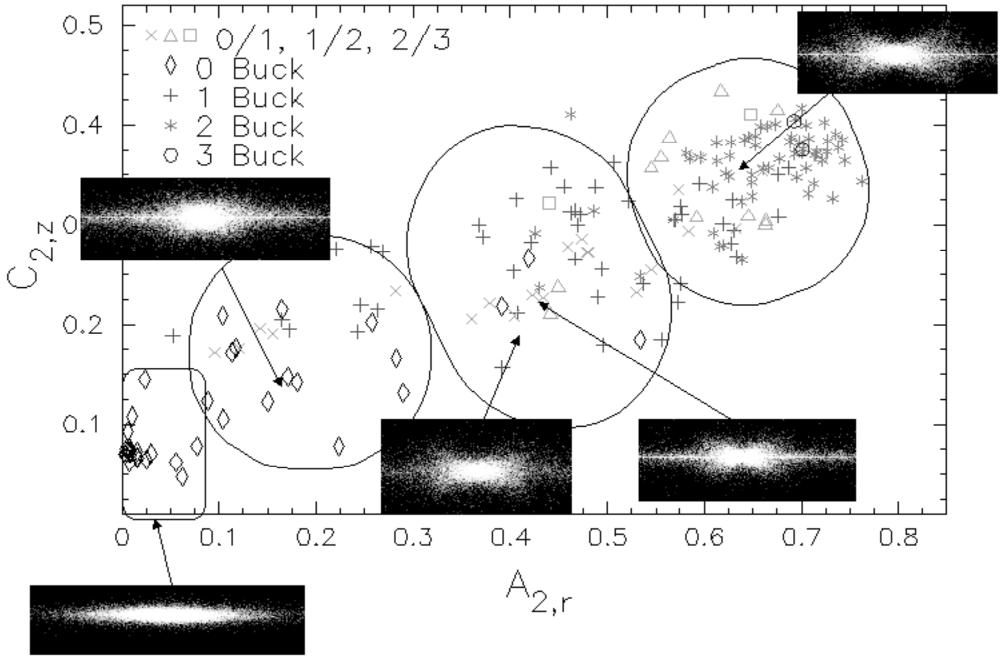

Fig. 4 We show the peanut strength calculated with our parameter $C_{2,z}$ vs. the bar strength calculated by means of $A_{2,r}$. There is a clear correlation. The different symbols correspond to the number of buckling events during the bar evolution. Notice how bars with two buckling are mainly very strong bars, and very strong peanut bulges.

in this figure how some simulations undergo several buckling events, as previously seen in (Martinez-Valpuesta, Shlosman & Heller 2006).

4 Conclusions and Future Work

By means of barred numerical simulations and the study of them, we can explain two different aspects of barred galaxies. Firstly, the galactic bars could be growing when presenting ansae. Secondly, strong bars tend to evolve forming strong Boxy/Peanut bulges.

More in detail, we have assessed the frequency of occurrence of ansae and our conclusion, based on a sample of 267 barred galaxies, is that ansae are very much concentrated in early-type galaxies. The highest fraction of ansae is found in strongly barred lenticulars, with $\sim 40\%$ of SB0 galaxies showing ansae. The overall fraction among S0 and Sa galaxies is around a third. Our next steps will focus in studying the orbits of the ansae in simulation to study if growing bars, capture new material by means of the ansae. Thus, observed galaxies showing ansae in their bars could be secularly growing.

Finally, we present different methods to calculate the strength of the bar and the strength of the B/P bulge. We find nice correlations between the different methods. The most important correlation relates the strength of the bar with the strength of the B/P bulge. Thus strong bars have stronger B/P bulges. We can also extrapolate from our Fig. 4, the strength of the bar is related to the number of buckling events. The stronger the bar gets, the more number of buckling events can have. Applying different tools to identify and measure the buckling events, we have found interesting relations between the buckling events and the dark matter halo initial conditions (Athanassoula & Martinez-Valpuesta 2008, in preparation).

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