Spectral analysis of stellar orbits in a tidally induced bar

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Using numerical analysis of fundamental frequencies we study the orbital structure of a tidally induced bar formed in a simulated dwarf galaxy orbiting a Milky Way-like host. We find that only about 10% of stars have frequencies compatible with x_1 orbits, the classical periodic orbits in a barred potential. The rest of the stars follows box orbits parallel to the bar, with varying degree of elongation.

1 Introduction

Bars are common features of disk galaxies in the present Universe. The estimated fraction of barred galaxies depends on the criteria used and ranges from $1/4$ to $2/3$ (Cheung et al., 2013, and references therein). Some of the dwarf galaxies in the Local Group possess a bar as well (e.g. the Large Magellanic Cloud) or are supposed to have one (e.g. the Sagittarius dwarf, see Łokas et al., 2010). Such bars may result from the tidal interaction of initially disky dwarf irregular galaxies with a bigger host as an intermediate stage on the way to their transformation into dwarf spheroidal galaxies, as envisioned by the tidal stirring scenario (Kazantzidis et al., 2011). Recently, Łokas et al. (2014) described in detail the formation and evolution of such a bar in a dwarf orbiting in the gravitational field of the Milky Way.

An important aspect of the bar dynamics is the study of its orbital structure to determine what types of orbits contribute to the density distribution of a bar. It is believed that x_1 periodic orbits (in the notation of Contopoulos & Papayannopoulos, 1980), which are parallel to the bar, form the backbone of the bar (for a review see Athanassoula, 2013). This conjecture is supported by the classification of orbits in terms of $(\Omega - \Omega_{\mathrm{p}})/\kappa$, where Ω is the angular frequency, κ is the radial frequency of the orbit and Ω_{p} is the bar pattern speed. In the inner part of the bar particles with $(\Omega - \Omega_{\mathrm{p}})/\kappa = 1/2$ dominate (Athanassoula, 2002), which is interpreted as the prevalence of x_1 orbits.

2 Methods

We reanalyzed the simulation of Łokas et al. (2014) which described the interaction of a dwarf galaxy with a Milky Way-like host. The dwarf model consisted of an NFW (Navarro et al., 1995) dark matter halo of mass 10^9 $M_\odot$ and a stellar disk of mass 2×10^7 $M_\odot$. The host galaxy model was made of an NFW halo of mass 7.7×10^{11} $M_\odot$ and a stellar disk of mass 3.4×10^{10} $M_\odot$. The orbit of the dwarf was eccentric, with the apocenter and pericenter of, respectively, 120 and 25 kpc. The dwarf was
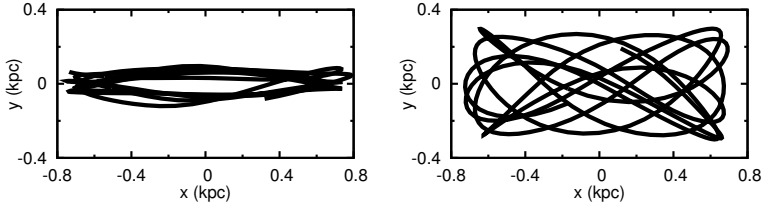
Fig. 1: *Left:* Orbit of x_1 type, which has $\omega_y/\omega_x = 1$. *Right:* Typical box orbit, with $\omega_y/\omega_x \approx 1.6$. Both orbits have a mean radius of about 0.5 kpc.

initially placed at the apocenter and its evolution was followed using publicly available N-body code GADGET2 (Springel, 2005), using 4×10^6 particles in total.

As described in Łokas et al. (2014), during the first pericenter passage a bar is formed in the disk of the dwarf. The length of the bar is about 2 kpc. At the following pericenters the bar is shortened and thickened. For our analysis of the orbits we used only the period between the first and the second pericenter, when the bar is the strongest. At this period, the bar rotates steadily for about 1.6 Gyr so it is possible to use a rotating reference frame, such that the x, y and z axes are aligned with, respectively, the major, the intermediate and the minor axis of the bar. During this period of interest, we saved positions of the particles every 0.005 Gyr to obtain 320 simulation outputs to probe the orbits.

We used the numerical analysis of fundamental frequencies (see e.g. Valluri & Merritt, 1998) which involves performing discrete Fourier transform of the time series of a given coordinate, e.g. $x(t)$. We searched for the maximum of such a discrete spectrum and then refined the determination of the location of the true peak of the Fourier spectrum. We designate the frequency of the peak as ω_x.

3   Results

In Figure 1 we show two typical shapes of orbits found in our simulation. One of them (see the left panel of the Figure) is an x_1-type orbit, which is very elongated and circulates in the same direction as the bar rotates. The second one (see the right panel) is a box orbit, also elongated with the bar, but not as much as the x_1-type orbit.

We calculated the ω_x and ω_y frequencies for 10^5 orbits with the mean distance from the center of the dwarf in a range of 0.2 – 0.8 kpc. The lower boundary was set by the resolution of the simulation, whereas the upper one by the lowest frequency we were able to resolve. The x_1-type orbits, which have mean distance from the center of 0.8 kpc, extend along the bar up to $x \approx 1.2$ kpc, thus our analysis refers to the inner half of the bar. Figure 2 presents a histogram of frequency ratios ω_y/ω_x for the analysed set of orbits.

The orbits clustered around $\omega_y/\omega_x = 1$ are x_1-type orbits, however they contribute less than 10% to the total number of orbits. The orbits in the range $\omega_y/\omega_x = 1.2$–1.9 have boxy shapes. The ones around $\omega_y/\omega_x \approx 1.3$ are almost square-like. Then, the larger ω_y/ω_x, the more elongated is the orbit. The ones at $\omega_y/\omega_x \approx 1.9$ are almost as elongated as the x_1 orbits.
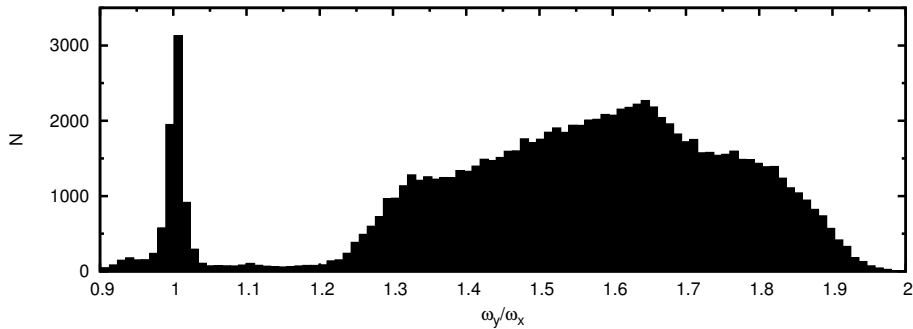
Fig. 2: Histogram of frequency ratios ω_y/ω_x for 10^5 orbits with the mean radius of $0.2 - 0.8$ kpc.

4   Summary

We followed the orbits in a tidally induced bar in a simulated dwarf galaxy orbiting the Milky Way. We computed fundamental frequencies of the particle orbits in the bar. Only about 10% of the orbits belong to x_1 type, whereas the majority of the orbits have boxy shapes, with varying degree of elongation. Our results are thus in agreement with the recent findings of Patsis & Katsanikas (2014), who emphasized the importance of box orbits in bars.

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