Spontaneous formation of double bars in dark matter dominated galaxies

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Accepted xxxx Month xx. Received xxxx Month xx; in original form 2012 Nov. 29

ABSTRACT

Although nearly one-third of barred galaxies host an inner, secondary bar, the formation and evolution of double barred galaxies remain unclear. We show here an example model of a galaxy, dominated by a live dark matter halo, in which double bars form naturally, without requiring gas, and we follow its evolution for a Hubble time. The inner bar in our model galaxy rotates almost as slowly as the outer bar, and it can reach up to half of its length. The route to the formation of a double bar may be different from that of a single strong bar. Massive dark matter halo or dynamically hot stellar disc may play an important role in the formation of double bars and their subsequent evolution.

Key words: galaxies: structure – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: evolution – galaxies: halos

1 INTRODUCTION

A high fraction (> 60%) of disc galaxies in the local Universe are barred, including our Milky Way, and nearly 30% of barred galaxies host an inner, secondary bar, nested inside the main bar, i.e., are double barred (Erwin & Sparke 2002; Erwin 2011; Laine et al. 2002). The inner bars are likely to be old structures, as they are seen in the near-infrared (Mulchaey et al. 1997) and stellar population analysis gives rather old age estimates (de Lorenzo-Cáceres et al. 2012, 2013). There is observational evidence that the two bars in double barred systems rotate independently (Corsini et al. 2003). The observed common occurrence of double bars is not reflected in the present numerical models of bar formation. While a stellar disc with the Toomre parameter $Q \sim 1$ readily forms a single bar, which then grows within a Gyr to become a strong bar (such as the one in NGC 1300), long-term evolution of such a strong bar does not lead to the formation of a double bar on its own in purely stellar discs. Only a few N-body simulations have reported formation of double bars (Rautiainen & Salo 1999; Curir et al. 2006; Debattista & Sheri 2007), mostly when special initial conditions have been imposed.

In 2D simulations of Rautiainen & Salo (1999), with rigid bulge and halo, double bars form when the Toomre $Q$ parameter is increased in the central parts of the disc, and they can survive for the Hubble time. In sets of cosmological N-body models by Curir et al. (2006), double bars form when the mass of the disc is lowered. Debattista & Sheri (2007) showed that the inner bar developing from a rapidly rotating bulge, or a pseudobulge, survives many relative rotations of the bars. Such inner bar pulsates, and its pattern speed oscillates in accord with predictions from orbital analysis (Maciejewski & Sparke 1997, 2000). Another route to forming double bars relies on the presence of a dissipative (gaseous) component. In this scenario (e.g., Friedli & Martinet 1993), gas inflow in the large-scale bar stagnates in the inner kpc, leading to the formation of a disc there, which may become unstable and give rise to a smaller, secondary bar. However, in numerical realizations of this scenario, the inner bar lasts no longer than a few relative rotations of the bars (see sect.5.2 of Maciejewski & Athanassoula 2008, for a summary).

In this letter, we report spontaneous formation of double bars in a dark matter dominated stellar disc without any gas. We have performed a suite of simulations of dark-matter-dominated galaxies (Saha et al. in prep) in 3 dimensions that include a live halo. We noticed that in a few cases, structures resembling double bars form naturally in our simulations. In this paper, we present a model with such structure being most evident. It provides insight into factors decisive in formation of double bars, and explores self-consistent double bars of parameters markedly different from previous simulations.

2 INITIAL GALAXY MODEL

Equilibrium model of a galaxy is constructed using the self-consistent method of Kuijken & Dubinski (1995). The initial galaxy model consists of a live disc, halo and a classical bulge. The disc has an exponentially declining surface density with a
scale-length $R_d$, scale-height $h_z$, and mass $M_d$. In internal units, where G=1, these parameters take the following values: $R_d = 1$, $h_z = 0.03$ and $M_d = 1.58$. The outer radius of the disc is truncated at $0.6R_d$ with a truncation width of $0.3R_d$ within which the stellar density smoothly drops to zero. The live dark matter halo is modelled with a lowered Evans model \cite{evans1993} which has a constant density core. Such a cored halo is known to better represent the observed high resolution rotation curves in low surface brightness (LSB) galaxies \cite{kurzo2006}. The initial classical bulge is modelled with a King model \cite{king1966}. The mass of the dark halo is $M_h = 20.43$ and that of the classical bulge is $M_b = 0.153$. For relevant details on model construction, the reader is referred to \cite{saha2010, saha2012}. The initial Toomre $Q$ profile for the galaxy is such that $Q$ rises to a high value beyond about $5R_d$ and the same happens at radius below $\sim 1R_d$. At $2.5R_d$, the Toomre $Q$ reaches the minimum of $Q = 2.55$.

In Fig. 1 we show the circular velocity curve for the galaxy model under consideration. The model galaxy is dark matter dominated right from the central region. This is a norm amongst most LSB galaxies \cite{deblock2001}. However, rotation curves in LSB galaxies usually show a slow rise, while the circular velocity curve in our model rises sharply in the inner region. Such a sharp rise is seen in giant LSB galaxies which often contain a bulge-like component \cite{beijersbergen1999, lelli2010}. Our galaxy model has some resemblance to these giant LSBs, but unlike them it contains no gas; hence caution is advised if our results are to be used in studies of LSB galaxies. If we set the unit of length to $R_d = 4.0$ kpc and the circular velocity at $R = 2.1R_d$ to 220 km s$^{-1}$, then the units of time, mass and velocity are 42 Myr, $8.08 \times 10^9 M_\odot$, and 93.2 km s$^{-1}$, respectively. Dimensional values in the remainder of this paper are given in this standard scaling. Thus, in our standard scaling, the disc, bulge and halo masses are $M_d = 1.27 \times 10^{10} M_\odot$, $M_h = 0.124 \times 10^{10} M_\odot$, and $M_b = 1.65 \times 10^{10} M_\odot$, respectively. For any other mass unit $M_0$ and length unit $R_0$, the time unit is $42$ Myr $(R_d/4$kpc$)^{1.5}(M_0/8.08 \times 10^9 M_\odot)^{-0.5}$ and the velocity unit is $93.2$ km s$^{-1}(R_d/4$kpc$)^{-0.5}(M_0/8.08 \times 10^9 M_\odot)^{0.5}$. Note that scale lengths of giant LSB discs are typically 10 kpc or more \cite{beijersbergen1999}, but for such scaling the simulated evolution time exceeds Hubble time.

The simulation was performed using the Gadget code \cite{springel2001}, with a tolerance parameter $\theta_{tol} = 0.7$, and the maximum value of the integration time step $\sim 0.03$, corresponding to 1.2 Myr. A total of 2.2 Million particles were used to represent the galaxy model with 1.05 Million each for the disk and halo and 0.1 Million for the bulge.

3 RESULTS

The set of images presented in Fig. 2 represents density of the stellar component at different times throughout the run, projected onto the disc plane. The radial variation of the $m = 2$ Fourier component of the stellar density as a function of time is presented in Fig. 3. In order to estimate the extent of the bars, and to measure their orientation, we fitted ellipses to the density field on a set of images such as in Fig. 2, and derived their ellipticity and the position angle (PA) in the same way as it is done for the observational data. In Fig. 3 we show the ellipticity and the PA as a function of the semi-major axis (SMA) obtained using the IRAF ELLIPSE fitting routine. If a bar is present, the PA of the major axis should be nearly constant over a range of sizes, with ellipticity reaching local maximum within this range. By matching the radial variation of the PA and the peak in the ellipticity, we assign an average value of the PA to each bar with an average error of $\sim 10^5$. When the inner bar is not exactly perpendicular to the outer one, spiral features start from the end of the inner bar, making the measurement of the PA of the bar difficult. In this situation, we recheck our automated measurement of assigning a PA by eye. In measuring the length of the bar, we follow the algorithm described by \cite{erwin2005} for deriving $L_{bar}$ there. This is the upper limit for the length of a bar.

3.1 Formation of two bars

We follow the evolution of an initially axisymmetric stellar disc embedded in a dark matter halo, which gravitationally dominates the stellar component throughout the extent of the disc. Since the stellar disc is initially hot, it does not form a bar readily. There is no clear non-axisymmetric structure in the disc till $t=48$ in Fig. 2 which corresponds to 2 Gyr, but a short open spiral can be noticed at $t=72$ (3 Gyr) in Fig. 2. The PA of the fitted ellipses at this time, shown in Fig. 3 increases almost monotonically with radius, hence the two bars are not well defined yet. However, there are two local maxima in ellipticity with values higher than 0.2, and the $m=2$ Fourier component in Fig. 2 also shows two maxima at $t = 72$. These two maxima, albeit with much lower amplitude, can be traced back to $t = 48$ at least, with the maximum corresponding to the outer bar forming first. Thus in our model two independent structural components are present from early stages of the run, which then develop into two bars. At later times, the two maxima in Fig. 3 correspond to the two bars.

As the asymmetry grows in strength, the spiral transforms into two well defined bar-like structures that appear almost simultaneously over time between $t = 72$ and 96 (3 and 4 Gyr). At $t = 96$, the two bars are nearly perpendicular to each other. Although there is still a spiral transition between the bars, the ellipse PA shown in Fig. 3 is roughly constant within the inner (up to 0.75 SMA length) and the outer bar (up to 1.5 SMA length). The outer bar has a clear boxy isophote.
3.2 Rotation of two bars

After $t = 48$, the snapshots in Fig. 2 are shown every 24 time units (corresponding to 1 Gyr), which is approximately two rotation periods of the outer bar (see below). The sequence clearly demonstrates that the inner bar rotates with respect to the outer bar. However, we find that the inner bar definitely is a very slowly rotating structure: it takes several rotations of the outer bar for the relative angle between the bars to change considerably. During the period of 5 Gyr (between $t = 96$ and $t = 216$), the inner bar has rotated only once inside the outer bar, going from one state when the two bars are orthogonal to the next one.

In order to quantify the rotation of the two bars, the PA of the outer bar, $\Phi_p$, and of the inner bar, $\Phi_s$, were calculated every 0.3 time units in the inertial frame. During every such interval, the PA of each bar increases by about $10^\circ$. In Fig. 3 we show how the phase difference of the two bars, $\Phi_s - \Phi_p$, evolves with time. This difference increases monotonically, which means that the inner bar rotates faster than the outer bar. Past $t = 190$, the difference becomes linear with time. In Fig. 3 we plot the pattern speed of each bar as a function of time. They are derived by fitting consecutive straight lines to $\Phi_p(t)$ and $\Phi_s(t)$ data points over every period when each bar rotates by $360^\circ$ in the inertial frame. These measurements are sufficiently accurate to imply that changes in pattern speed over time are real, though there is no clear regularity in these changes. The pattern speeds of the two bars are different only by $\sim 10^\circ$ at the most. After $t = 190$, the rotation period of the outer bar is $T_p = 2\pi/\Omega_p \approx 12$ time units.

Although past $t = 96$ the two bars are separate entities, as demonstrated by nearly constant PA of fitted ellipses in Fig. 3 there is a spiral structure between them visible in Fig. 2. When the two bars are moving away from alignment at $t = 136$, towards be-
coming perpendicular at $t = 216$, this spiral is trailing. It turns to a leading spiral as soon as the bars get past the perpendicular arrangement at $t = 216$, and are on their way to become parallel again. Thus the spiral is always trailing when the bars are getting out of alignment, and leading when they are getting back to alignment. The spiral structures are nearly absent when the two bars are perpendicular to each other. These characteristics are different from a spiral emerging at the ends of a bar that is driven by that bar, as in that case the spiral should always be trailing. The spiral in our model may be caused by the orientation of orbits in the potential of the two bars, like in model02 of Maciejewski & Small (2010), when the loops (maps of orbits) form a trailing spiral when the bars are leading the alignment, and a leading spiral when they are coming back to the alignment. When the bars are parallel or perpendicular, the loops are aligned, and therefore they do not form a spiral shape. The spiral structure may influence the dynamics of the two bars, and may indicate that the two bars are dynamically coupled, although in a different way than having resonances overlapping or pattern speeds commensurate.

### 3.3 Evolution and dynamics of two bars

The strength and size of the two bars increase with time, as can be seen in Fig. 3 and Fig. 4. Both of these quantities can be reliably measured when the two bars are orthogonal to each other, i.e. at $t = 96$ and 216. Between these two times, the length of the inner bar increases by two-fold: from $0.75 R_d$ to $1.55 R_d$ (see Fig. 3). In the same time period, the length of the outer bar grows monotonically from $1.5 R_d$ to $2.1 R_d$. Thus the length ratio of the bars appears to increase from 0.5 at $t=96$ to 0.75 at $t = 216$. However, at relative bar positions other than orthogonal, the estimate of the length of the inner bar returns lower values, possibly because of the presence of a spiral structure connecting the bars, and then the length ratio remains close to 0.5. The amplitude of the peak in ellipticity associated with the inner bar grows from 0.4 at $t = 96$ to almost 0.7 at $t = 216$ (see Fig. 3), i.e., by a factor of ~ 1.5. The ellipticity of the outer bar is lower than that of the inner one: at $t = 96$ and 216 it is about 0.3, although it reaches 0.5 at $t = 168$ and 240. The increase of strength and size of the bars is moderated by the relative position of the bars: $A_2$ within the outer bar is reduced when the bars are orthogonal, and $A_2$ within the inner bar is reduced when the bars are parallel (Fig. 3). The inner bar is growing stronger particularly after $t = 144$, as it grows in size and its $A_2$ increases. This is because of the combination of the secular and the periodic change caused by moving away from alignment.

Having confirmed that the two bars are independent structures, one would like to know their dynamics: are they slow or fast bars, and what resonances they generate. Pattern speed of the outer bar decreases from about $\Omega_P = 0.58$ at $t = 136$ to $\Omega_P = 0.50$ at $t = 237$. Comparing these values with the azimuthal frequency curve in Fig. 6 we have the corresponding corotation radii at 3.6 and 4.1 $R_d$. On the other hand, the length of the outer bar increases in the same time interval from 1.66 to 2.25 $R_d$. Thus the outer bar is slow, in the sense that it extends to only about 0.5 of its corotation radius, with this ratio increasing from 0.46 to 0.55. As the pattern speed of the inner bar is similar to that of the outer bar, the inner bar extends to even lower fraction of its corotation radius, with the ratio around 0.3.

In order to determine the presence of the Inner Lindblad Resonance (ILR), in Fig. 5 we plot the axisymmetric approximation to the $\Omega - \kappa/2$ curve derived from the rotation velocity, accompanied by the same curves derived from tangential velocity on the major axis of each bar, which relaxes the assumption of axial symmetry. These curves do not differ much, which is expected in a model dominated by nearly spherical dark matter halo. Over the $\Omega - \kappa/2$ curves, we overplot the range of pattern speeds associated...
with each bar throughout the run. Our measurements are consistent with either no ILR or a weak single ILR at around $1 - 1.2R_d$, thus the inner bar cannot have its backbone built out of orbits related to the $x_2$ orbits in the outer bar. Further work is needed to establish orbital support of double bars like the ones in the model presented here. The possible absence of an ILR makes the disc favourable to grow a bar through the swing amplification of waves as it allows the feedback loop to complete [Toomre, 1981]. On the other hand, since our bars form slowly in an initially rather stable disc (high Toomre’s $Q$), and since they do not extend to their corotation radii, the mechanism proposed by Lynden-Bell [1973] may play a role in their formation. However, neither of these mechanisms anticipated formation of multiple bars.

4 DISCUSSION AND CONCLUSIONS

In this paper, we presented a model of a stellar disc, which spontaneously forms two bars that is markedly different from systems simulated previously: the gravitational potential is dominated by the dark halo (Fig. 1), the inner bar is large (Fig. 2), and the angular velocities of the bars are almost equal (Fig. 6).

All numerical simulations of double bars to date assume gravity dominated by stars in the region where the bars form. If Toomre’s $Q$ is low, then the outer bar forms rapidly, and an additional process is needed to induce the formation of the inner bar. On the other hand, double bars can form spontaneously in pure N-body models when the disc is poorly coupled by its self-gravity, which has to compete with the gravity of the massive halo or with thermal motions [Rautiainen & Saito, 1999] were able to obtain double bars in their Model IV, in which they increased the Toomre parameter $Q$ in the central parts of the disc to $Q = 3$, from $Q = 1.5$ in the otherwise identical Model I, which returned a single bar only. In sets of cosmological N-body models by Curir et al. [2006], double bars form when the disc-to-halo mass ratio is smallest in each set. Only single bars form in more massive discs in those models. Our simulations presented in this paper confirm this trend, because they form double bars in the disc with high $Q$, which is dominated by dark matter halo. These findings indicate that the route to the formation of double bar may be different from that of a single strong bar, and the dark halo or hotter disc may play an important role. Bar formation in our simulation scaled to younger, smaller discs proceeds faster, but further work is needed to study evolution of such spontaneously formed double bars once the disc grows more massive.

In the majority of numerical models, both purely stellar and with a gaseous component, the pattern speed of the inner bar is significantly larger than that of the outer bar [Friedli & Martinec, 1993; Rautiainen & Saito, 1999; Debattista & Sherr, 2007; Heller et al., 2007]. Our model shows that an inner bar with the angular velocity similar to that of the outer bar is also possible. Since throughout the evolution of our model, the two bars can be in any relative orientation (Fig. 2), the observed random orientation of the two bars [Buta & Crocker, 1993; Friedli & Martinec, 1993] does not have to imply that pattern speeds of the bars differ significantly.

The inner bar in our model is large – it is about half of the size of the outer bar for most part of the run. This is more than the typical size ratio of the bars, being 0.12 [Erwin & Sparke, 2002], but size ratios up to 0.4 have been observed (NGC 3358, Erwin, 2004). An inner bar supported by orbits inside the ILR of the outer bar cannot be too large [Maciejewski & Spinks, 2000], but in our model the outer bar may have no ILR, hence other orbits, without such size constraint, must support the inner bar here.

In summary, the model of double bars presented here indicates that (1) formation of double bars may proceed under different conditions and in a different way than the formation of a single strong bar – it may need dynamically hot stellar disc, possibly dominated by the dark halo; (2) inner bars as large as half of the length of the outer bar can last for a Hubble time or longer; (3) the difference between pattern speeds of the two bars can be minimal, yet the two bars can be observed in any relative orientation.

ACKNOWLEDGEMENT

We would like to thank the anonymous referee for pointing out that coupling of the disc by its self-gravity may play a role in formation of double bars, the remark that we incorporated in the revised text, and Peter Erwin for useful discussions. K.S. acknowledges support from the Alexander von Humboldt Foundation. WM acknowledges the ESO Visiting Fellowship, which allowed to initiate this project.

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