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Inner bars also buckle. The MUSE TIMER view of the double-barred galaxy NGC 1291

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ABSTRACT

Double bars are thought to be important features for secular evolution in the central regions of galaxies. However, observational evidence about their origin and evolution is still scarce. We report on the discovery of the first Box/Peanut (B/P) structure in an inner bar detected in the face-on galaxy NGC 1291. We use the integral field data obtained from the MUSE spectrograph within the TIMER project. The B/P structure is detected as bi-symmetric minima of the h_4 moment of the line-of-sight velocity distribution along the major axis of the inner bar, as expected from numerical simulations. Our observations demonstrate that inner bars can follow a similar evolutionary path as outer bars, undergoing buckling instabilities. They also suggest that inner bars are long-lived structures, thus imposing tight constraints to their possible formation mechanisms.

Key words: techniques: spectroscopic – galaxies: evolution – galaxies: individual: NGC 1291 – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION

de Vaucouleurs (1975) described a rarity in the centre of NGC 1291. He detected, for the first time, an inner bar which follows the same lens-bar-nucleus pattern of the outer bar. Nowadays, we know that bars within bars are not an oddity, with recent observations suggesting that ~30 per cent of all barred galaxies host an inner bar (Erwin 2004, 2011; Buta et al. 2015). The importance of inner bars is not restricted to their high incidence. In particular, they are thought to be an efficient mechanism for transporting gas to the galaxy central regions, possibly fueling active galactic nuclei (AGNs; Shlosman, Begelman & Frank 1990; Maciejewski et al. 2002) and affecting the formation of new stellar structures (de Lorenzo-Cáceres et al. 2012; de Lorenzo-Cáceres, Falcón-Barroso & Vazdekis 2013). Still, little is known about the origin of inner bars and now, 40 yr later, NGC 1291 strikes again providing a new piece of evidence to unveil the formation of the central regions of galaxies.

The current scenarios leading to the build-up of an inner stellar bar include: (i) gas inflow through the outer bar (Friedli & Martinet 1993) induces the formation of an inner gaseous bar that then forms stars (Heller, Shlosman & Englmaier 2001; Shlosman & Heller 2002; Englmaier & Shlosman 2004), or (ii) gas inflow through the outer bar creates an inner stellar disc, which becomes dynamically cold, and forms an inner stellar bar (Wozniak 2015). The latter scenario has also been worked out in dissipationless simulations where a dynamically cold stellar inner disc is imposed at the beginning of the simulation (Rautiainen & Salo 1999; Rautiainen, Salo & Laurikainen 2002; Debattista & Shen 2007; Shen & Debattista 2009; Saha & Maciejewski 2013; Du, Shen & Debattista 2015). Besides the different origins, the most striking difference between these models is the fate of the inner bar. In the current models, stel-

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lar inner bars built up of previously formed gaseous inner bars are short-lived, lasting only a few galaxy rotations. Similarly, past models of inner bar formation where the inner stellar disc was formed from gas inflow along the outer bar, proved to be short-lived due to the destructive effect of the central mass concentration. However, Wozniak (2015) recently challenged this picture with new simulations showing inner bars could be long-lived. Therefore, it is crucial to find not only new inner bars, but also a way to observationally quantify their lifetime, in order to help constrain these theoretical scenarios further.

Unlike inner bars, the so-called galaxy outer (or main) bars can be easily formed in numerical simulations once a dynamically cold disc is settled (see Sellwood 2014, for a review). The formation and evolution of these bars can be followed with exquisite detail in numerical simulations, and they generally behave as long-lived structures (Combes et al. 1990; Debattista & Sellwood 2000; Athanassoula 2003; Kraljic, Bournaud & Martig 2012), but see Bournaud, Combes & Semelin (2005). A crucial epoch during the life of a bar occurs when its central region grows in the vertical direction during the buckling phase. During this phase, generally ocurring after the bar is completely formed and lasting about 1−2 Gyr, the bar creates a Box/Peanut (B/P) structure in its central regions (Combes & Sanders 1981; Athanassoula et al. 1983; Martinez-Valpuesta, Shlosman & Heller 2006). The B/P structures are readily recognizable in edge-on galaxies, where their characteristic shapes stand out of the disc plane (Lütticke, Dettmar & Pohlen 2000; Yoshino & Yamauchi 2015; Ciambur & Graham 2016). The high incidence of B/P structures provides observational evidence that bars generally survive for, at least, several galaxy rotations thus suggesting they are long-lived structures with a minimum age since their assembly of ∼2–3 Gyr.

The detection of B/P structures in low-inclination galaxies is a far more difficult task due to projection effects, but it is also extremely rewarding since it allows for a direct comparison between the bar and the B/P properties. Three main diagnostics (two photometric and one kinematic) have been proposed to identify B/P structures in non edge-on galaxies: (i) barlenses: this method is based on detecting a central, close to circular, isophotal contour in the central region of the galaxy that it is associated with the presence of a projected B/P structure (Laurikainen et al. 2011; Athanassoula et al. 2015; Laurikainen & Salo 2017); (ii) boxy centre + spurs: this is similar to the previous criterion, but concerns more inclined galaxies and it is based on the detection of boxy isophotes in the galaxy central region followed by narrower and offset (with respect to the bar major axis) isophotes in the outer parts (spurs; Erwin & Debattista 2013, 2017); (iii) kinematic features in face-on galaxies: the detection of symmetric double minima of the fourth-order (h_4) Gauss–Hermite moment of the line-of-sight velocity distribution (LOSVD) along the major axis of the bar, which was shown to be a signature of the presence of a B/P structure (Debattista et al. 2005; Méndez-Abreu et al. 2008b, 2014)

In this letter, we show the first detection of a B/P structure in an inner bar, namely that of NGC 1291. We use the high-quality stellar kinematics provided by the MUSE spectrograph within the TIMER project (Gadotti et al. 2018, hereafter Paper I) to trace the presence of symmetric double h_4 minima along the major axis of the inner bar of NGC 1291. In Section 2, we describe the main stellar structures present in this double-barred galaxy. Section 3 describes the observation and stellar kinematic measurements. The results are shown in Section 4 along with the corresponding discussion. Our conclusions are summarized in Section 5.

2 NGC 1291: PROPERTIES AND STELLAR STRUCTURES

NGC 1291 is a nearby galaxy at 8.6 Mpc (mean redshift-independent distance from NED; http://ned.ipac.caltech.edu/). It is a relatively massive ($M_\star = 5.8 \times 10^{10}$ $M_\odot$) and face-on galaxy with an inclination of 11 deg when measured using the semi-axes ratio of the 25.5 mag arcsec^{-2} isophote at 3.6 μm. Recently, Buta et al. (2015) morphologically classified this galaxy as (R)SAB(l,bl,nb)0+. This indicates that it is a lenticular, double-barred galaxy with an outer ring, a lens, and a barlens.

We performed a two-dimensional photometric decomposition of NGC 1291 using the 3.6 μm image provided by the Spitzer Survey of Stellar Structure in Galaxies (S^{4}G, Sheth et al. 2010). To this aim, we applied a modified version of GASP2D (Méndez-Abreu et al. 2008a, 2017, 2018) upgraded to account for the complex structural mixing of this galaxy. Details on the methodology to decompose double-barred galaxies can be found in de Lorenzo-Cáceres et al. (in preparation). We found that NGC 1291 can be successfully described with six structural components: an outer and inner bar modelled with a Ferrers profile with effective (total) radii 36.7 (131.5) and 15.5 (29.0) arcsec, respectively, a central bulge with Sérsic index $n = 2.9$ and effective radius $r_e = 9.8$ arcsec, an inner exponential disc surrounding the inner bar, a lens related to the outer bar described using a Sérsic surface brightness distribution with $n = 0.6$, and a faint exponential outer disc.

Bar sizes for NGC 1291 have been previously reported in the literature. Erwin (2004), using measurements based on azimutally averaged ellipticity profiles, obtained a lower (upper) limit of 17 (24) and 89 (140) arcsec for the inner and outer bar, respectively. Herrera-Endoqui et al. (2015) measured the bar lengths using a visual inspection of the S^{4}G images. They found values of 19.3 and 97.2 for the inner and outer bar, respectively. Using photometric decompositions, Salo et al. (2015) measured a total outer bar size of 158 arcsec. Despite the well-known differences in the bar size when using different methods (Michel-Dansac & Wozniak 2006), our values are in relatively good agreement with the literature, and they represent the most accurate modelling of the stellar structures in NGC 1291 performed so far. In addition, the stellar structure inventory obtained from the photometric decomposition agrees well with the visual classification provided in Buta et al. (2015), and resembles the *Russian Doll* pattern described earlier by de Vaucouleurs (1975) as a repeated lens-bar-nucleus pattern. The main difference is that we do not find the presence of a barlens, but an inner disc surrounding the inner bar as indicated by the stellar kinematic map. We do not include, in our photometric decomposition, either the outer ring or the *ansae* (symmetric enhancements at the ends of the stellar bar) observed in the inner bar. Fig. 1 shows a 3.6 μm S^{4}G image of NGC 1291 where these stellar structures are visible.

3 TIMER OBSERVATIONS OF NGC 1291

The TIMER project is a survey employing the MUSE integral-field spectrograph to study the central 1 arcmin × 1 arcmin of a sample of 24 nearby ($d < 40$Mpc) barred galaxies with nuclear rings and other central structures such as nuclear spiral arms, inner bars, and inner discs (see Paper I). One of the project's main goals is to study the star formation histories of such structures to infer the cosmic epoch of the formation of the bar and the dynamical settling of the main disc of the host galaxy. The methodology was demonstrated with a pilot study of NGC 4371 (Gadotti et al. 2015).

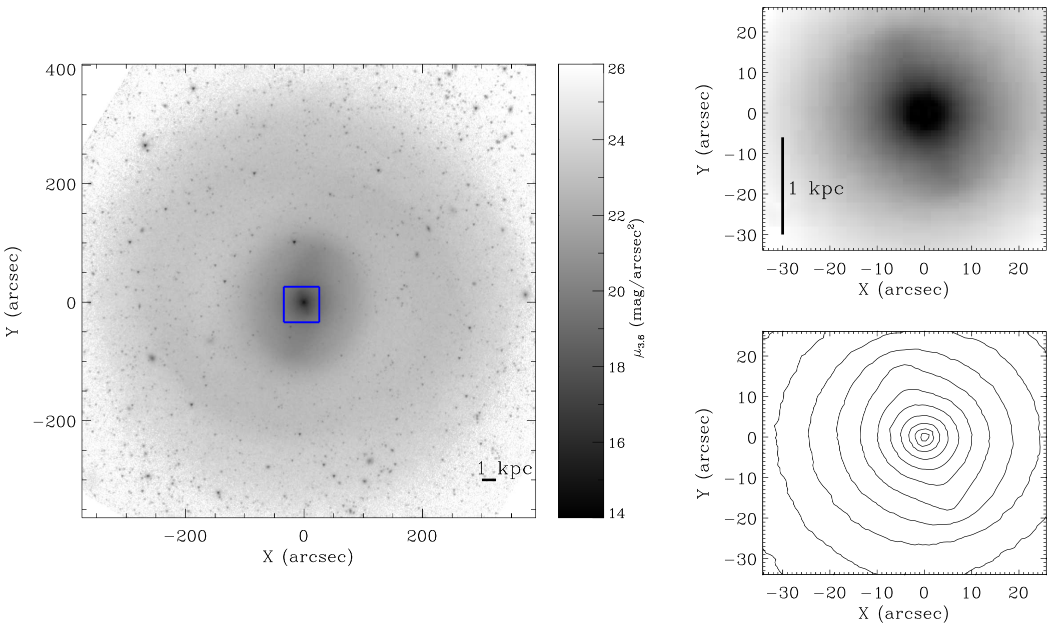

Figure 1. S^{4}G 3.6 μm images of NGC 1291. The left-hand panel shows the main outer structures described in Section 2, i.e. the outer ring, outer disc, lens, and outer bar. The blue square represents the MUSE 1 arcmin × 1 arcmin field of view. The right-hand panels show a zoom-in (upper panel) and contour (lower panel) images highlighting the central photometric structures, i.e. inner disc, inner bar, and central bulge. They correspond to the actual field of view observed with MUSE, which is slightly offset with respect to the centre of the galaxy. North is up and East is left.

The corresponding observations of NGC 1291 were performed during ESO Period 97 (2016 April to September) with a typical seeing on the combined data cube of 1.1 arcsec (spaxel size = 0.2 arcsec), mean spectral resolution of 2.65 Å (full width at half-maximum), and spectral coverage from 4750 Å to 9350 Å. NGC 1291, being one of the closest galaxies in the TIMER sample, the MUSE 1 arcmin × 1 arcmin field of view (FoV) corresponds to a (almost) square region of ≈2.5 kpc on a side (i.e. 1 arcsec corresponds to 42 pc).

The MUSE pipeline (version 1.6) was used to reduce the data set (Weilbacher et al. 2012), correcting for bias and applying flat-fielding and illumination corrections, as well as wavelength calibration. The exposures were flux-calibrated through the observation of a spectrophotometric standard star, which was also used to remove telluric features. Dedicated empty-sky exposures and a PCA methodology were employed to remove signatures from the sky background. Finally, the exposures were also finely registered astrometrically, so that the point spread function of the combined cube is similar to that in individual exposures. More details can be found in Gadotti et al. (2018).

3.1 Stellar kinematics

The fully reduced data cube was spatially binned using the Voronoi scheme of Cappellari & Copin (2003) to achieve a signal-to-noise ratio of approximately 40 per pixel on each spatial bin. We used the penalized pixel fitting (PPXF) code developed by Cappellari & Emsellem (2004) to extract the stellar kinematics from the binned spectra, masking emission lines and using the E-MILES model library of single age and single metallicity populations from Vazdekis et al. (2016) as stellar spectral templates. Additionally, a multiplicative low-order Legendre polynomial was included in the fit to account for small differences in the continuum shape between the galaxy and template spectra. We restricted our analysis to the rest-frame wavelength range between 4750 Å and 5500 Å for the minimization, after verifying that including the whole spectral range produces no noticeable differences in the derived kinematics.

The LOSVD was parametrized with the mean stellar velocity (V), stellar velocity dispersion (σ), and the Gauss–Hermite higher order moments h_3 and h_4 (see e.g. van der Marel & Franx 1993). We refer the reader to Paper I for further details. The measured stellar kinematic maps for NGC 1291 are shown in Fig. 2. We also extracted radial profiles of the different moments of the LOSVD along the major axes of both the inner bar and inner disc, corresponding to position angles of 16 and 140 deg (North-East), respectively. The inner disc position angle is obtained as the perpendicular to the zero-velocity line within the FoV. We chose a pseudo-slit width for both profiles of 2 arcsec to account for the MUSE PSF. The errors shown in the radial profiles account for both errors in the individual spaxels and the standard error of the mean within the pseudo-slit.

4 RESULTS AND DISCUSSION

The rightmost panels of Fig. 2 show the h_4 spatial distribution and radial profiles of NGC 1291. Clear, symmetric, double minima in the h_4 are seen along the major axis of the inner bar. These minima are neither observed along the galaxy nor the main bar major axis indicating that they are related to the presence of the inner bar. The double minima occur at a projected distance of ∼4 arcsec, which corresponds to 26 per cent of the inner bar effective radius. Following these minima, the radial profile of h_4 along the major axis of the bar grows until it reaches two maxima at radii comparable to the inner bar radii. These maxima are not part of a positive h_4 ring around the inner bar, as it has been found in numerical simulations (Du et al. 2016), but they nicely correspond to the σ-hollows observed in the velocity dispersion profile. The σ-hollows are a kinematic confirmation for the presence of an inner bar as

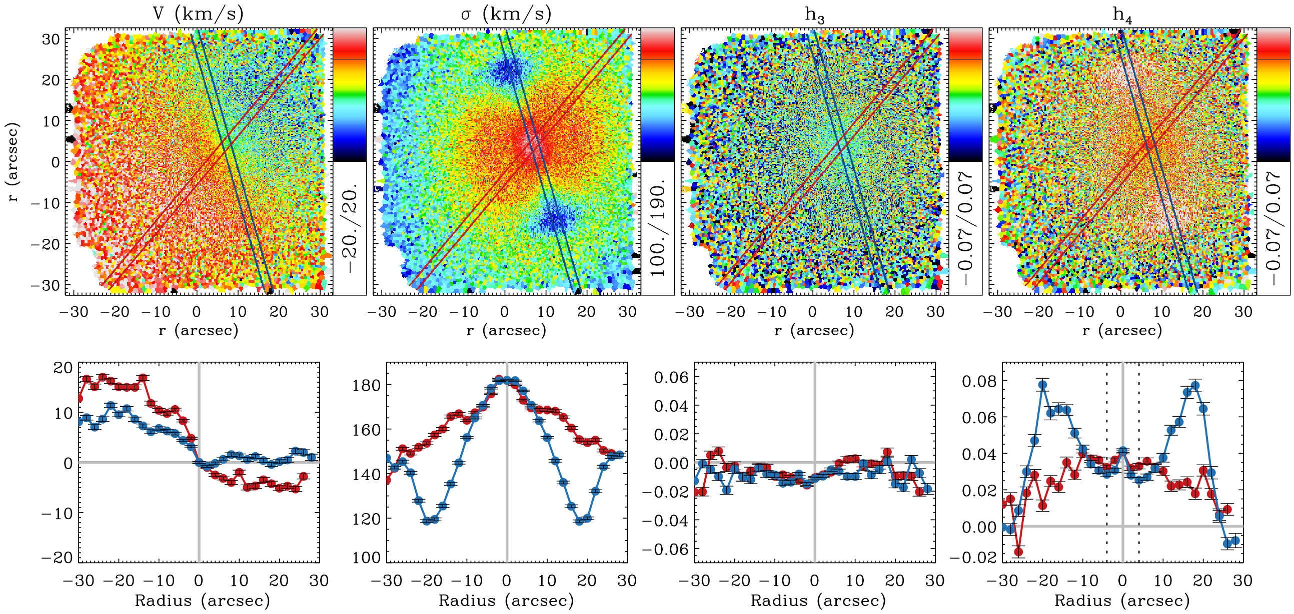

Figure 2. Stellar kinematic maps (top rows) and radial profiles (bottom rows) obtained from the MUSE TIMER observations of NGC 1291. From left to right: velocity, velocity dispersion, h_3, and h_4 moments. The radial profiles in the bottom panels were extracted along 2 arcsec width pseudo-slits (shown in the maps) for both the inner bar major axis (blue) and the galaxy major axis (red). The positions of the h_4 minima are shown with dashed lines in the bottom right-hand panel. North is up and East is left.

demonstrated by de Lorenzo-Cáceres et al. (2008), and are also not observed along the major axis of the galaxy.

As demonstrated by numerical simulations of single-barred galaxies (Debattista et al. 2005; Iannuzzi & Athanassoula 2015), bi-symmetric minima in the h_4 profile along the bar major axis indicate the presence of a vertically extended B/P structure in the bar. This kinematic criterion to detect B/P in face-on galaxies has been previously confirmed in main bars (Méndez-Abreu et al. 2008b, 2014), but this is the first time a B/P is detected in a face-on inner bar. Hints of multiple B/P in edge-on galaxies have also been discussed in Ciambur & Graham (2016). Remarkably, these results strongly suggest that inner and outer bars in double-barred galaxies are analogous systems, governed by the same physical processes.

A closer look at Fig. 2 reveals that the h_4 minima do not occur at negative values of h_4, as predicted in some simulations (Debattista et al. 2005), but they happen at $h_4 \sim 0.03$. This is not surprising since the inner bar is embedded in a more complex dynamical environment than the outer (single) bars which are usually simulated. Numerical simulations have also demonstrated that the presence of a central dispersion-dominated system tend to smooth the h_4 radial profile (see figure 14 in Debattista et al. 2005). We indeed found photometric ($n = 2.9$) and kinematic (velocity dispersion gradient) evidence for a classical bulge (i.e. a dispersion-dominated system) in NGC 1291. In addition, more recent numerical simulations including the effect of gas dissipation have shown that symmetric double minima in the h_4 profile, even if not negative, are a clear signature for the presence of a B/P structure (bottom right-hand panel of figure 24 in Iannuzzi & Athanassoula 2015).

An alternative configuration able to mimic the observed h_4 and σ maps would invoke the presence of a counterrotating disc instead of the inner bar. Nevertheless, if the disc lied in the same equilibrium plane of the galaxy, we would expect a ring-like maximum/minimum in the h_4/σ maps, which is not observed. On the other hand, if the disc was settled perpendicular to the line of sight (LOS) and aligned to the inner bar major axis, then its higher LOS velocities would stand out in the velocity map, which is not observed either. Therefore, we consider unlikely these two possibilities, reinforcing the conclusion of a B/P associated to the inner bar.

The presence of a B/P structure in the inner bar of NGC 1291 imposes key constraints on the origin and evolution of double-barred galaxies. First, the evidence that inner bars can also develop vertical structures such as B/P, and therefore they also suffer from vertical instabilities, suggests they are more similar to outer (main) bars than previously thought. Our results indicate that inner bars might mimic the evolution of outer bars with one (or perhaps more) buckling phases that must be reproduced by numerical simulations. To our best knowledge there is no simulation of double-barred galaxies showing that inner bars undergo a buckling phase, but former orbital analysis have found vertically extended periodic orbit families in the innermost parts of bars (Patsis, Skokos & Athanassoula 2002; Skokos, Patsis & Athanassoula 2002). Secondly, the presence of a B/P introduces a timing constraint on the inner bar formation.

Although the formation time-scales of both bars and B/Ps depend on the specific characteristics of the numerical simulations such as gas fraction, halo shape, and bulge dominance, the general timeline includes the formation of the bar itself (∼1 Gyr) and the consequent formation of the B/P, after the bar is formed, due to the first buckling phase (∼1 Gyr). Under the assumption that the evolutionary time-scales of both the inner and outer bars are similar, we speculate that the inner bar of NGC 1291 should have an age of at least ∼2 Gyr, which is longer than the lifetime expected for inner bars in some numerical simulations (Friedli & Martinet 1993). However, further simulations of double-barred galaxies (showing the B/P formation) are necessary to better understand their time evolution. In particular, it is possible that inner bars might form in much shorter times than outer bars (∼150 Myr; Debattista & Shen 2007, but other authors show more similar time-scales ∼0.5–1 Gyrs; Du et al. 2015; Wozniak 2015). Notwithstanding the previous caveats, we found independent support to our conclusion that inner bars are long-lived through the typical age of the stellar populations present in the central parts of NGC 1291, which turns out to be ∼6–7 Gyr (discussed in de Lorenzo-Caceres et al. 2018, submitted).

5 CONCLUSIONS

We used the superb quality of the MUSE TIMER data to identify, for the first time, a B/P structure in the inner bar of a double-barred galaxy, NGC 1291. At the location of the B/P, the vertical density distribution of stars becomes broader and numerical simulations have demonstrated that this effect can be observationally traced as symmetric double minima in the radial profile of the fourth-order Gauss–Hermite moment (h_4) of the LOSVD along the bar major axis. This kinematic diagnostic was confirmed in the single bar of NGC 98 (Méndez-Abreu et al. 2008b) and in this paper we show that inner bars can also buckle, as we detect the same kinematic feature in the inner bar of NGC 1291.

The presence of B/P structures in the inner bars of double-barred galaxies suggests that they follow the same evolutionary path as outer bars, which have been extensively studied in the literature. Therefore, inner bars should grow both radially and vertically depending on the interaction with the outer bar and the amount of angular momentum exchanged by the latter with other baryonic and dark matter components, following buckling phases as those predicted for single-barred galaxies. In addition, we claim that the presence of a B/P in the inner bar, combined with the ages of the stellar populations (presented in de Lorenzo-Caceres et al. 2018, in preparation), suggests that inner bars can be long-lived structures lasting several Gyrs. Our results rule out inner bar formation scenarios where they are short-lived structures, like those invoking an inner gaseous bar as the progenitor of the inner stellar bar.

Additional detections of B/P structures in inner bars, as those reported in this letter, for a sample of double-barred galaxies would allow to further constrain their formation models. This is now feasible with integral-field spectrographs such as MUSE.

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REFERENCES

Athanassoula E., 2003, MNRAS, 341, 1179
Athanassoula E., Bienayme O., Martinet L., Pfenniger D., 1983, A&A, 127, 349
Athanassoula E., Laurikainen E., Salo H., Bosma A., 2015, MNRAS, 454, 3843
Bournaud F., Combes F., Semelin B., 2005, MNRAS, 364, L18
Buta R. J. et al., 2015, ApJS, 217, 32
Cappellari M., Copin Y., 2003, MNRAS, 342, 345
Cappellari M., Emsellem E., 2004, PASP, 116, 138
Ciambur B. C., Graham A. W., 2016, MNRAS, 459, 1276
Combes F., Sanders R. H., 1981, A&A, 96, 164
Combes F., Debbasch F., Friedli D., Pfenniger D., 1990, A&A, 233, 82
de Lorenzo-Cáceres A., Falcón-Barroso J., Vazdekis A., Martínez-Valpuesta I., 2008, ApJ, 684, L83
de Lorenzo-Cáceres A., Vazdekis A., Aguerri J. A. L., Corsini E. M., Debattista V. P., 2012, MNRAS, 420, 1092
de Lorenzo-Cáceres A., Falcón-Barroso J., Vazdekis A., 2013, MNRAS, 431, 2397
de Vaucouleurs G., 1975, ApJS, 29, 193
Debattista V. P., Sellwood J. A., 2000, ApJ, 543, 704
Debattista V. P., Shen J., 2007, ApJ, 654, L127
Debattista V. P., Carollo C. M., Mayer L., Moore B., 2005, ApJ, 628, 678
Du M., Shen J., Debattista V. P., 2015, ApJ, 804, 139
Du M., Debattista V. P., Shen J., Cappellari M., 2016, ApJ, 828, 14
Englmaier P., Shlosman I., 2004, ApJ, 617, L115
Erwin P., 2004, A&A, 415, 941
Erwin P., 2011, Memorie della Societa Astronomica Italiana Supplementi, 18, 145
Erwin P., Debattista V. P., 2013, MNRAS, 431, 3060
Erwin P., Debattista V. P., 2017, MNRAS, 468, 2058
Friedli D., Martinet L., 1993, A&A, 277, 27
Gadotti D. A., Seidel M. K., Sánchez-Blázquez P., Falcón-Barroso J., Husemann B., Coelho P., Pérez I., 2015, A&A, 584, A90
Gadotti D. A. et al., 2018, MNRAS, 482, 506, (Paper I)
Heller C., Shlosman I., Englmaier P., 2001, ApJ, 553, 661
Herrera-Endoqui M., Díaz-García S., Laurikainen E., Salo H., 2015, A&A, 582, A86
Iannuzzi F., Athanassoula E., 2015, MNRAS, 450, 2514
Kraljic K., Bournaud F., Martig M., 2012, ApJ, 757, 60
Laurikainen E., Salo H., 2017, A&A, 598, A10
Laurikainen E., Salo H., Buta R., Knapen J. H., 2011, MNRAS, 418, 1452
Lütticke R., Dettmar R.-J., Pohlen M., 2000, A&AS, 145, 405
Maciejewski W., Teuben P. J., Sparke L. S., Stone J. M., 2002, MNRAS, 329, 502
Martinez-Valpuesta I., Shlosman I., Heller C., 2006, ApJ, 637, 214
Méndez-Abreu J., Aguerri J. A. L., Corsini E. M., Simonneau E., 2008a, A&A, 478, 353
Méndez-Abreu J., Corsini E. M., Debattista V. P., De Rijcke S., Aguerri J. A. L., Pizzella A., 2008b, ApJ, 679, L73
Méndez-Abreu J., Debattista V. P., Corsini E. M., Aguerri J. A. L., 2014, A&A, 572, A25
Méndez-Abreu J. et al., 2017, A&A, 598, A32
Méndez-Abreu J. et al., 2018, MNRAS, 474, 1307
Michel-Dansac L., Wozniak H., 2006, A&A, 452, 97
Patsis P. A., Skokos C., Athanassoula E., 2002, MNRAS, 337, 578
Rautiainen P., Salo H., 1999, A&A, 348, 737
Rautiainen P., Salo H., Laurikainen E., 2002, MNRAS, 337, 1233
Saha K., Maciejewski W., 2013, MNRAS, 433, L44
Salo H. et al., 2015, ApJS, 219, 4
Sellwood J. A., 2014, Rev. Mod. Phys., 86, 1
Shen J., Debattista V. P., 2009, ApJ, 690, 758
Sheth K. et al., 2010, PASP, 122, 1397
Shlosman I., Heller C. H., 2002, ApJ, 565, 921
Shlosman I., Begelman M. C., Frank J., 1990, Nature, 345, 679
Skokos C., Patsis P. A., Athanassoula E., 2002, MNRAS, 333, 847
van der Marel R. P., Franx M., 1993, ApJ, 407, 525
Vazdekis A., Koleva M., Ricciardelli E., Röck B., Falcón-Barroso J., 2016, MNRAS, 463, 3409
Weilbacher P. M., Streicher O., Urrutia T., Jarno A., Pécontal-Rousset A., Bacon R., Böhm P., 2012, in Radziwill N. M., Chiozzi G., eds, Proc. SPIE Conf. Ser. Vol. 8451, Software and Cyberinfrastructure for Astronomy II. SPIE, Bellingham, p. 84510B
Wozniak H., 2015, A&A, 575, A7
Yoshino A., Yamauchi C., 2015, MNRAS, 446, 3749

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