Buckling Bars in Nearly Face-on Galaxies Observed with MaNGA

Katherine M. Xiang1,2, David M. Nataf1, E. Athanassoula3, Nadia L. Zakamska1, Kate Rowlands4, Karen Masters5, Amelia Fraser-McKelvie5, Niv Drory7, and Katarina Kraljic3

1 Center for Astrophysical Sciences and Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA; kxiang@g.harvard.edu, katherine.m.xiang@gmail.com, dnataf1@jhu.edu, david.nataf@gmail.com
2 Department of Physics, Harvard University, Cambridge, MA 02138, USA
3 Aix Marseille Université, CNRS, CNES, LAM, Marseille, France
4 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
5 Department of Physics and Astronomy, Haverford College, 370 Lancaster Avenue, Haverford, PA 19041, USA
6 School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
7 McDonald Observatory, University of Texas at Austin, 1 University Station, Austin, TX 78712, USA

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Abstract

Over half of disk galaxies are barred, yet the mechanisms for bar formation and the lifetime of bar buckling remain poorly understood. In simulations, a thin bar undergoes a rapid (<1 Gyr) event called “buckling,” during which the inner part of the bar is asymmetrically bent out of the galaxy plane and eventually thickens, developing a peanut/ X-shaped profile when viewed side-on. Through analyzing stellar kinematics of N-body model snapshots of a galaxy before, during, and after the buckling phase, we confirm a distinct quadrupolar pattern of out-of-plane stellar velocities in nearly face-on galaxies. This kinematic signature of buckling allows us to identify five candidates of currently buckling bars among 434 barred galaxies in the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) Survey, an integral field unit spectroscopic survey that measures the composition and kinematic structure of nearby galaxies. The frequency of buckling events detected is consistent with the 0.5–1 Gyr timescale predicted by simulations. The five candidates we present more than double the total number of candidate buckling bars and are the only ones found using the kinematic signature.

Unified Astronomy Thesaurus concepts: Barred spiral galaxies (136); Galaxy structure (622); Galaxy kinematics (602)

1. Introduction

Galactic bars are elongated, smooth stellar systems in the inner parts of disk galaxies. They can be morphologically approximated as triaxial ellipsoids and sometimes have a superimposed peanut/ X-shaped structure when viewed side-on (Combes & Sanders 1981). Within the local universe, it is estimated that roughly two-thirds of disk galaxies have stellar bars (Mulchaey & Regan 1997; Eskridge et al. 2000; Menéndez-Delmestre et al. 2007; Barazza et al. 2008; Sheth et al. 2008; Aguerri et al. 2009; Lee et al. 2019), though the precise number is uncertain owing to differences in factors such as the classification scheme and the details of the methodology. For example, Mulchaey & Regan (1997) found that 55% of the galaxies classified as “unbarred” in the Revised Shapley-Ames Catalog of Bright Galaxies (Sandage & Tammann 1981) were barred in 2.1 μm data.

The presence and strength of bars are major variables of Hubble’s galaxy sequence (Hubble 1936), still the most commonly used classification scheme for galaxies. It is thus not surprising that an understanding of galaxy evolution requires an understanding of bars, and that the relationships between bars and other galaxy properties have been subject to extensive research. Observationally, the probability of a galaxy hosting a bar is a decreasing function of its specific star formation rate (Masters et al. 2011; Cheung et al. 2013). The bar fraction is minimized for spirals with log(Mstellar/M⊙) ≈ 10.20 and then increases for both lower- and higher-mass spiral galaxies (Nair & Abraham 2010). High-redshift galaxies are less likely to host strong bars: Sheth et al. (2008) find that the barred fraction in a sample of luminous spirals declines from 65% at z = 0 to 20% at z ≈ 0.84, and Melvin et al. (2014) find that the bar fraction in a sample of visually selected disk galaxies decreases from 22% at z = 0.4 to 11% at z = 1.0.

N-body models have yielded numerous, detailed predictions for evolution, kinematics, and photometry of bars in observed galaxies. They demonstrate that bars grow and evolve through their interaction with the stellar and dark matter halos of their host galaxies (Weinberg 1985; Debattista & Sellwood 1998, 2000; Athanassoula 2003a, 2003b; Athanassoula et al. 2013, hereafter AMR13) and with other galaxies (Gerin et al. 1999; Lokas et al. 2014). Thus far, the match between simulation predictions and galactic observations has been strikingly impressive, both for photometric features in field galaxies (Athanassoula et al. 2015; Ciambur & Graham 2016; Laurikainen & Salo 2017; Salo & Laurikainen 2017) and in the Milky Way (Nataf et al. 2015; Athanassoula et al. 2017; Ciambur et al. 2017; Portail et al. 2017; Bovy et al. 2019). Comparisons between observations of the Milky Way bar and N-body simulations can now be used in Galactic archeology and for probing the Galactic merger history and bulge formation (Shen et al. 2010; Ness et al. 2013; Erwin & Debattista 2017; Di Matteo et al. 2019). Bureau & Athanassoula (2005) analyzed N-body simulations of galactic disks from Athanassoula (2003b), viewed them edge-on, and found a number of characteristic kinematic bar features. One such interesting feature is that the mean and skewness of the radial profiles from the line-of-sight velocity distributions are positively correlated over the projected bar length. This was also found by Chung & Bureau (2004) for a sample of 30 field galaxies from the work of Bureau & Freeman (1999), as well as for the metal-rich stars in the Milky Way (Zasowski et al. 2016). Such diagnostics are reviewed by Athanassoula (2013, 2016).
In this paper, we study a prediction from N-body models of a specific phase of bar evolution, that of the buckling of the bar (Combes & Sanders 1981; Combes et al. 1990; Raha et al. 1991). Buckling is one of several dynamical processes that have been discussed in the literature as a means for an in-plane bar to evolve into a boxy/peanut bulge (Petersen et al. 2014; Quillen et al. 2014; Sellwood & Gerhard 2020). The buckling phase is due to a violent dynamical instability, during which an initially thin bar bends asymmetrically out of its host galaxy’s plane over a short period of time and then settles to a vertically thicker symmetric configuration. The bar settles to having a boxy/peanut shape when viewed edge-on. The changes in the bar’s structure can be large: the first buckling event of the galaxy simulation studied by Martinez-Valpuesta et al. (2006) culminates in the height of the bar nearly doubling and the size of the bar’s semimajor axis shrinking by nearly a half.

Despite the near ubiquity of buckling in simulations, few predictions for the buckling phase have been tested with direct observations. If buckling is short-lived, then finding galaxies in the buckling phase may be difficult. Some models predict longer-lived (∼2–3 Gyr) secondary buckling events (Martinez-Valpuesta et al. 2006; Łokas 2019b), though the frequency of these events is lower (Smirnov & Sotnikova 2019) than that of the first buckling. Note that this frequency depends on the strength of the bar (Athanassoula 2008). Only three candidates have been identified so far: Erwin & Debattista (2016), who built on the work of Erwin & Debattista (2013), showed that the surface brightness profiles in the nearby face-on spirals NGC 3227 and NGC 4569 are consistent with predictions for buckling from N-body simulations. One additional candidate has been identified by the same method and is described in Li et al. (2017). Specifically, the central surface brightness isophotes of these bars show 180° symmetry with respect to reflection around the bar’s minor axis, but not the major axis. Another potentially testable model prediction is that the buckling instability is expected to be inhibited in galaxies with a large gas fraction (Debattista et al. 2006; Berentzen et al. 2007; Wozniak & Michel-Dansac 2009; Villa-Vargas et al. 2010; Smirnov & Sotnikova 2019). A large sample of buckling candidates is required to test these predictions.

Here we develop a different set of buckling metrics, focused on kinematics rather than surface brightness, by inspection of a −body simulations. One additional candidate is expected so far: Erwin & Debattista (2016), who built on the work of Erwin & Debattista (2013), showed that the surface brightness profiles in the nearby face-on spirals NGC 3227 and NGC 4569 are consistent with predictions for buckling from N-body simulations. One additional candidate has been identified by the same method and is described in Li et al. (2017). Specifically, the central surface brightness isophotes of these bars show 180° symmetry with respect to reflection around the bar’s minor axis, but not the major axis. Another potentially testable model prediction is that the buckling instability is expected to be inhibited in galaxies with a large gas fraction (Debattista et al. 2006; Berentzen et al. 2007; Wozniak & Michel-Dansac 2009; Villa-Vargas et al. 2010; Smirnov & Sotnikova 2019). A large sample of buckling candidates is required to test these predictions.

We then proceed to identify and evaluate buckling candidates from the MaNGA survey on which we test these predictions. We then proceed to identify and evaluate buckling candidates from this sample. We present a discussion of our findings in Section 4 and conclude in Section 5. In this study, we use $H_0 = 100$ (km s$^{-1}$) Mpc$^{-1}$.

2. Models

2.1. N-body Model

The three simulation snapshots studied here are part of a larger suite of simulations run by AMR13. These simulations include a live halo (i.e., a halo where the dark matter particles can exchange energy and angular momentum with the baryons), a realistic prescription for gas physics, and a suite of initial conditions with varying gas fractions and halo shape. We chose the simulation producing the strongest bar and peanut, in order to have the clearest example of the buckling signature with which to compare to observations; thus, the initial conditions had a spherical halo and no gas. Bar strength was determined by considering the $m=2$ Fourier component of the face-on mass distribution (Athanassoula 2003b). The simulation used in this work is referred to as run 101 and GTR-101 in AMR13 and Iannuzzi & Athanassoula (2015), respectively, and these two studies describe the physics, initial conditions, and numerical methods in greater detail.

Briefly, the initial conditions of the simulations were constructed using the iterative method (Rodionov et al. 2009) and were run using a version of GADGET-3 (Springel et al. 2001; Springel & Hernquist 2002; Springel 2005). The dark matter and the stars are followed by N-body particles, and gravity is calculated with a TREE code. The models have a 50 pc linear resolution and a $2.5 \times 10^5 M_\odot$ mass resolution for the stars. There are 200,000 particles representing the stars. Two thousand output files are saved for this run, corresponding to different snapshots in time.

The stars are initially distributed as a disk, whose azimuthally distributed average spatial distribution is given by

$$\rho_d(R,z) = \frac{M_d}{4\pi h^2 \sigma_z} \exp\left(-\frac{R}{h}\right) \sech^2\left(\frac{z}{\sigma_z}\right),$$

(1)

where $R$ is the cylindrical radius, $z$ is the vertical coordinate, $M_d = 5 \times 10^{10} M_\odot$ is the disk mass, $h = 3$ kpc is the disk radial scale length, and $\sigma_z = 0.6$ kpc is the disk vertical scale thickness. The radial velocity dispersion of the particles is initialized to

$$\sigma_R(R) = 100 \exp(-R/3h) \text{km s}^{-1}.$$

(2)

The halo has been built so as to have an initial distribution function that is spherical, with a radial density profile distributed as

$$\rho_h(R) = \frac{M_h}{2\pi r_c^3/2} \frac{\alpha}{r_c} \exp\left(-\frac{r^2}{r_c^2}\right) \frac{r_c^2}{r^2 + \gamma^2},$$

(3)

where $r$ is the spherical radius, $M_h = 2.5 \times 10^{11} M_\odot$ is the mass of the halo, and $\gamma = 1.5$ kpc and $r_c = 30$ kpc are the halo core and cutoff radii, respectively. The parameter $\alpha$ is a normalization constant.

2.2. Snapshots from N-body Simulation

We select three snapshots for our present investigation, at 2.00, 3.53, and 4.50 Gyr. We choose these particular snapshots so as to study the bar of the galaxy in its pre-buckling state, during the buckling, and in its post-buckling state, respectively. Figures 4 and 5 of AMR13 show further snapshots at 6 and 10 Gyr, i.e., well after the buckling. Snapshots from the earlier times, more relevant to this work, will be given in our analysis in the following sections. Figures 7 and 8 of AMR13 also show the time evolution of the bar strength $A_2$. Here the buckling epoch can be easily identified from the sharp drop in the bar strength parameter in the top left panels of both of these figures. The time evolution of the bar strength is also plotted in Figure 1 of Iannuzzi & Athanassoula (2015). These figures demonstrate that buckling corresponds to a short-lived sharp decrease of the
bar strength. This starts after \( \sim 3 \) Gyr, and by \( 4.8 \) Gyr it has recovered to its peak pre-buckling value.

We investigate the mean line-of-sight velocity of disk particles in each snapshot. We bin the 200,000 particles using equal spatial intervals (0.4 by 0.4 kpc square bins in Figure 1), and we plot the average line-of-sight velocity of particles in each bin. We generate maps for all three snapshots from a variety of viewing and inclination angles in an effort to observe a signal of bar buckling based on the simulated stellar velocities.

In Figure 1, we show the face-on maps of the mean stellar line-of-sight velocities, as well as the particle distributions and stellar density profiles for three different orientations, for each of the three snapshots. For a smoothly rotating disk viewed face-on, one would expect little to no line-of-sight component of velocity, as seen in the pre-buckling and post-buckling snapshots. However, at the time of buckling, we observe a significant out-of-plane velocity signature, resembling a quadrupole in stellar velocities with a diameter of approximately 18 kpc along the bar major axis, as seen in the middle panel of the top row of Figure 1. The velocity signal is most distinct when viewed directly face-on, which we define to be \( i = 0^\circ \), i.e., when viewing the galaxy with a line of sight parallel to the galaxy’s angular momentum vector. (We elaborate on the coordinate system in Section 2.3.) For this model, the peak velocity amplitude of the buckling signal is \( \sim 75 \) km s\(^{-1}\) (measured from a face-on view), which is approximately one-third of that of the galaxy’s rotation signal (measured from an edge-on view).

This kinematic signature has also been found by Łokas (2019b) through analysis of an isolated disk galaxy model; the middle panel of Figure 6 depicts a similar quadrupolar pattern in stellar velocities. The same signal has also been found and discussed in Fragkoudi et al. (2020), which uses magnetohydrodynamical Milky Way−mass galaxy simulations (the Auriga suite; Grand et al. 2018, 2019). The quadrupolar signal is displayed and discussed in their Figures 10 and B1. Thus, the quadrupolar kinematic signature of buckling is a robust feature of the buckling phase and is independent of simulation specifics.

At the end of the buckling phase (Figure 1, right column), a slight quadrupolar pattern indicates that vestiges of the buckling signal are still present nearly a full billion years after peak buckling. Therefore, we seek a metric to quantify the strength of buckling and isolate the buckling phase. To this end, we consider the quadrupole moment of the map, \( q \):

\[
q = \sum_{n=0}^{N} V_{\text{los},n} \cos(2(\alpha_n - \alpha_0)),
\]

where we sum over all model particles up to the radius of the bar, and \( V_{\text{los}} \) is the line-of-sight velocity of each model particle. \( \alpha_0 \) and \( \alpha \) are, respectively, the bar angle and the position angle of each model particle in the image plane, both measured counterclockwise from east. Values of \( q \) are plotted for a variety of inclinations and for all three simulation snapshots in Figure 2. We also plot \( q/d \), the quadrupole moment normalized by the dipole moment, which takes into account the signal strength compared to the in-plane stellar velocities. We obtain qualitatively similar results. In summary, our primary observable is the quadrupole moment of the velocity field.

We note that in this simulation the bar exhibits a strong in-plane bending as well (shown in the isodensities in Figure 1), and it is not known whether this in-plane bending of the bar is typical of buckling. However, the quadrupolar signature is not unique to the bar that is present in this model. Estimates of \( q \) from different simulation snapshots in the literature (e.g., Łokas 2019b; Fragkoudi et al. 2020) are similar to that in our simulation.
2.3. Coordinate System

For comparison to observational data, we determine the appearance of the buckling signal from various viewing angles. The position of the observer is specified by two angles: a polar angle and an azimuthal angle. The polar angle is specified by $\theta$ and ranges from 0° to 180°. Both $\theta = 0°$ and $\theta = 180°$ correspond to an inclination of $i = 0°$, for comparison for astronomical data. The azimuthal angle $\varphi$ also ranges from 0° to 180°. A final angle $\gamma$ corresponds to rotations in the image plane. A face-on galaxy with a horizontal bar corresponds to $(\theta = 0°, \varphi = 0°, \gamma = 0°)$, as in the top row of Figure 1, or $(\theta = 180°, \varphi = 0°, \gamma = 0°)$, which corresponds to the other side of the disk.

We transform the coordinates of particles in the $N$-body model and obtain average line-of-sight velocities for each bin. To determine the transformed projected bar angle, we define a unit vector of the bar (1,0,0) and transform it using the same rotation matrices. Then, we project this vector into the plane of the image for comparison of the projected bar angle to observational data. We take the magnitude to obtain the projected simulation bar length.

Figure 3 demonstrates the buckling signal for an inclined view of the model, with the mean stellar line-of-sight velocity plotted in each bin. We find that the buckling signal is detectable through the kinematic signal, by eye, from any $\varphi$ as long as the inclination is fairly low ($i \lesssim 50°$). This effect can be also observed in Figure 2 through the quadrupole moment. Buckling is also detectable through a C-shaped signal, when the bar is viewed end-on. This signal, however, is less useful when comparing to observational data since an end-on bar is difficult to identify through photometry.

2.4. Buckling Signal Amplification with Unsharp Masking

We use digital unsharp masking to amplify the buckling signal. Unsharp masking is a linear image processing technique developed initially for photography, but it is often utilized in astronomical image processing (e.g., Bureau et al. 2006) and in simulation image processing (Athanassoula 2005, Figure 6 therein).

For each pixel $p$ in the map, we take the average value (with 5σ outliers removed) of the velocity signal of all other pixels within a circular aperture of specified radius from $p$. We exclude pixels that are partially inside the aperture. Then, we subtract this average value from the value at the central pixel $p$. Unsharp masking enhances local extrema: using smaller radii for averaging enhances finer detail, and using larger radii can enhance larger features, such as spiral arms. The results from filtering with larger radii are more visually similar to the original map. Subtracting the median instead of the mean generates similar results. The results are also similar to other techniques, such as fitting the velocity within the aperture as a linear function of position ($V_r = V_{r,0} + m(x - x_0) + n(y - y_0)$) and then replacing the central pixel value with the fit residual at that point.

The effects of unsharp masking on a simulated stellar velocity map are displayed in Figure 4, illustrating that this technique helps visually enhance the buckling signal. For this model, an unsharp-masking radius of 6 pixels works best. Given our binning of 0.4 kpc pixel$^{-1}$, this length corresponds to 2.4 kpc.

3. Data and Analysis

3.1. Sample Selection

We now proceed to comparing our simulated buckling signal to observational data. Our parent sample is a large sample of barred galaxies from the MaNGA survey (Bundy et al. 2015). MaNGA is part of the fourth-generation Sloan Digital Sky Survey (SDSS-IV; Blanton et al. 2017) with data taken at the SDSS 2.5 m telescope located at the Apache Point Observatory in New Mexico (Gunn et al. 2006). MaNGA is an ongoing project to map 10,000 galaxies with an integral field unit (IFU) system (Drory et al. 2015) that feeds into a multioject spectrograph (Smee et al. 2013). As a large IFU survey of galaxies, it is particularly well suited to our purposes of identifying and testing kinematic signatures of bar buckling.

The MaNGA survey design is described by Yan et al. (2016a), with the target selection for the survey presented by Wake et al. (2017) and with the observing strategy detailed by Law et al. (2015). The data reduction pipeline and the spectrophotometric calibration are outlined by Law et al. (2016) and Yan et al. (2016b). To access MaNGA data, we used Marvin (Cherinka et al. 2019), a web interface and an application programming interface that allow for analysis of IFU data. Here we make use of products from the MaNGA Product Release 8 (MPL-8).

We use a barred subset of the sample, with bar lengths and angles as measured by Fraser-McKelvie et al. (2020), relying on the method detailed in Krajic et al. (2012). Bar classifications are obtained from Galaxy Zoo 2 (GZ2; Willett et al. 2013). Galaxies in this sample satisfy a debiased bar likelihood $p_{\text{bar-weighted}} > 0.5$ and $p_{\text{not-edgeon}} > 0.5$ in GZ2 and a $b/a$—optical minor-to-major-axis ratio of the outer disk—of greater than 0.6, which roughly corresponds to inclinations of less than 55°. We use $b/a$ for elliptical apertures, obtained by taking the axis ratio using Stokes parameters at 90% light radius, in the NASA-Sloan Atlas (NSA; Blanton et al. 2011), a catalog of images and parameters of local galaxies from SDSS imaging. In this study, we use the version available for MaNGA, v1_0_1.
The sample contains 434 galaxies with measured bar lengths and angles.

### 3.2. Quadrupole Moment Analysis

We use stellar velocity maps that are Voronoi binned to a signal-to-noise ratio of 10 for all galaxies, along with unsharp filtered images using radii of 4, 6, and 8 pixels. Then, we calculate $q$ for the unsharp filtered maps by using the stellar velocity per bin. We use the lowest $q$ across the three unsharp filtered maps to rank galaxies based on a consistently high quadrupole moment.

After visually inspecting the top 100 galaxies, we identify 16 preliminary high quadrupole moment galaxies with velocity maps resembling a buckling signal: a central disturbance in the stellar line-of-sight velocities, resembling a quadrupole or a bent C-shaped asymmetry, such as in Figure 3. The distribution of quadrupole moments and their dependence on mass and $b/a$ is displayed in Figure 5.

We also considered normalizing the quadrupole moment by the dipole moment (as in Figure 2, inset) and used the metric $q/d = \sum_{n=0}^{N}[V_{los,n} \cos(2(\alpha_n - \alpha_0))] / \sum_{n=0}^{N}[V_{los,n} \cos(\alpha_n - \phi)]$, where $\phi$ is varied from 0° to 180°. We then normalize by the largest dipole moment. Using $q/d$ as a metric yields the same 16 initial buckling candidates, as well as qualitatively similar results.

### 3.3. Buckling Verification and Orientation Fitting

As a consistency check for buckling candidate identification, we directly compare the observational stellar velocity maps to the model. We select 16 preliminary buckling candidates identified from their large $q$ values. One additional candidate is chosen by visual inspection from the remaining galaxies in MPL-8 that are not in Fraser-McKelvie et al. (2020).

We rotate the simulated galaxy and generate stellar velocity maps that match observed maps, optimizing the viewing parameters. A correlation coefficient between stellar velocities at each pixel was obtained for each simulated—observed pair, and we minimize this value. For pixels that are binned together to satisfy a signal-to-noise ratio of 10, we only take into account 1 pixel in each bin. The mask for the observational...
map is then identically applied to the simulation map. Since the calculation is computationally expensive, we select just 26 additional barred galaxies with $b/a > 0.6$ at random as a control sample for comparison.

We fit the stellar velocity maps of the 16 candidates (and of the 26 galaxies in the control sample) to both the buckling and post-buckling simulation snapshots. We choose to fit to the post-buckling snapshot instead of the pre-buckling snapshot, since the observed galaxies were selected on the basis of possessing a strong bar. Therefore, if the observed galaxy in question is not buckling, it is more likely in the longer-lasting secular evolution stage (see Athanassoula 2013, for a review) and thus has already buckled.

We first use a brute-force minimization algorithm (scipy.optimize.brute), which computes a cost function for a multidimensional grid of parameters, detailed in Table 1. The parameters include the viewing angles, size scale, and velocity scale of the simulation snapshot. The cost function is the median of the pixel-wise absolute difference (MAD) between the maps, and we seek to minimize this value. The centers of the observed and simulated maps are aligned and fixed based on the center of mass of the $r$-band flux and the center of the map, respectively. The mask for each observed map is also applied to each generated simulation snapshot map for all iterations.

To minimize the cost function, we vary five parameters: the three angles associated with the galaxy’s orientation ($i, \phi, \gamma$), as well as scale factors for the bar length and the stellar velocity amplitude. This method allows us to find the general location of the global minimum in the parameter space and to reduce degeneracies. The set of parameters that provides the lowest value is recorded. The bar length parameter is fixed based on our initial guess, though we find that the final fit parameters are robust to as much as a 50% difference in the bar length guess.

After brute-force optimization, we take the best result and rescale the simulation velocity amplitude. The default simulation velocity amplitude is roughly 200 km s$^{-1}$. We check scale values from 0.4 to 2.5, in increments of 0.05, and then record the parameters that yield the lowest MAD. We then use a downhill Nelder-Mead simplex algorithm (Nelder & Mead 1965; Gao & Han 2012) to polish the result, with an initial guess given by the brute-force optimization result. Each iteration takes the MAD between the simulated and observed maps (with additional soft constraints) as a cost function and seeks to minimize this value. In the minimization process, a simplex of $(n + 1)$ vertices is generated for $n$ parameters, and the cost function is evaluated at each vertex. Each vertex slightly varies one parameter, and the values of the cost function are compared between all vertices. The vertex with the highest value (i.e., the worst fit) is removed, and a new vertex replaces it. Thus, the simplex contracts toward the final minimum and adapts to the local landscape. We run the optimization for 100 iterations before stopping at the parameters that yield the lowest MAD.

The entire fitting procedure is performed for each observed galaxy twice: once to the buckling snapshot, and once to the post-buckling snapshot. Both steps of fitting are performed with soft constraints to ensure that the orientation and radial extent of the simulation do not differ significantly from those of the observational data.

### 3.4. Constraints

Fitting stellar velocities places a primary constraint on the galaxy orientation, but we require the inclination and bar angle of the model view and the observed galaxy to be consistent as well. Our three priors are inclination, bar position angle, and bar length and are described below. Below we elaborate on our soft constraints.

**Inclination.**—Inclination of each observed target is informed through the axial ratio $b/a$. A ratio of $b/a = 1$ indicates that a galaxy is near face-on, and $b/a$ decreases as the inclination increases toward an edge-on view. To obtain the inclination, we use the relation given by Masters et al. (2010):

$$\cos^2(i) = \frac{(b/a)^2 - p^2}{1 - p^2},$$

where $b/a$ is obtained from the NSA (BA_90, or in MaNGA, elpetro_ba), and $p$ is the intrinsic axial ratio. We use the
Table 1  

| Parameter                          | Range                  | Step |
|------------------------------------|------------------------|------|
| $i$ (deg)                          | Init. guess ± 20       | 10   |
| $\varphi$ (deg)                    | $[-180, 180]$          | 10   |
| $\gamma$ (deg)                     | $[-180, 180]$          | 10   |
| Spatial resolution scale (pixels)  | Init. guess            | ...  |
| Velocity amplitude scale           | $[0.5, 2.0]$           | 0.5  |

Note. The rightmost column details the step size in the parameter range. Velocity amplitude is rescaled before fine-tuning. The spatial resolution scale is fixed for the brute-force optimization and allowed to vary slightly when fine-tuning.

\( b/a \) from an elliptical Petrosian fit; the Petrosian radius is defined here to be the radius at which the \( r \)-band surface brightness in a local annulus is 20% of the mean \( r \)-band surface brightness within that radius. Further details are available on the SDSS web page.\(^9\) To account for the nonzero thickness of the disk, we use \( p = 0.12 + 0.10 f_{\text{oV}} \) (Masters et al. 2010), where \( f_{\text{oV}} \) is the fraction of light that can be fit by a de Vaucouleurs profile. We use the \( r \)-band \( f_{\text{oV}} \) from SDSS since it has the highest signal-to-noise ratio. A linearly increasing penalty is given for a simulation inclination angle that deviates from the observed inclination angle by more than 15°.

Bar angle.—For observational target 8947-1901 and a number of the control galaxies, the bar position angle is estimated by using an average of angles generated from ellipse fits of isophotes using astropy Photutils (Bradley et al. 2019). We use the mean \( r \)-band flux per pixel and define bar angle counterclockwise from east; a horizontal bar has a bar position angle of 0°. For the remaining targets, we use the bar angles measured by Fraser-Mckelvie et al. (2020). Elsewhere, uncertainty in bar position angle measurement is one of the key uncertainties in determining other galaxy properties such as bar pattern speed (Debattista 2003; Guo et al. 2019). Hence, a linearly increasing penalty is given if the fit bar angle for the observational map and the calculated bar angle of the simulation map differ by more than 10°.

\(^9\) https://www.sdss.org/dr16/manga/manga-target-selection/nsa

Figure 5. Left: lowest quadrupole moment \( q \) across \( r = 4, r = 6, \) and \( r = 8 \) unsharp filtering, plotted against log stellar mass, for observed galaxy stellar velocity maps. The color bar corresponds to axial ratio \( b/a \). Buckling candidates are indicated with open squares. Right: histogram of all 434 galaxies binned by minimum \( q \).

Bar length.—We use the length of the bar as a parameter for aligning the spatial resolution scale of the observational and simulation maps. MaNGA stellar velocity map bins are \( 0.15 \) pixel\(^{-1} \); we alter the bin size for the simulated galaxy to ensure that the measured length of the bar in the observed map matches the projected length of the bar in the simulated map, in pixels. The bin size parameter is first fixed in the brute-force optimization and then allowed to vary slightly when fine-tuning parameters. A linearly increasing penalty is given if the bar length deviates by more than 4 pixels from the initial guess, which places a strict constraint on bar length. Observed bar lengths are obtained from Fraser-McKelvie et al. (2020) and Hoyle et al. (2011) and averaged when available in both samples. We remake bars with length guesses that appear to be incorrect by significantly more than 4 pixels, to ensure closer fit results.

3.5. Results

In this section, we present the results of the comparison between observations and simulations. The displayed buckling candidates possess a high quadrupole moment consistent with simulation buckling and are shown alongside the simulated stellar velocity maps.

Buckling candidates.—Out of the 16 initial buckling candidates, we select 5 final candidates with low buckling fit median absolute deviation and well-aligned stellar velocity maps. The stellar velocity maps and the fits of the five buckling candidates are displayed in Figures 6 and 7. The fitting procedure mitigates the effect of false positives: 11 candidates from the original buckling sample of 16 are removed. Although these 11 galaxies possess a quadrupolar signal near the center of the line-of-sight stellar velocity maps, the shape and size of the signal are inconsistent with bar angle and size constraints. Therefore, we reject these candidates from the initial buckling sample. Additionally, we find that one of these high quadrupole moment galaxies (MaNGA plate-IFU 8722-3702) has been mistakenly identified as having a bar. The GZ2 redshift-debiased sample generally identifies bars accurately, but in this case, the high redshift (\( z \approx 0.11 \)) resulted in a high \( p_{\text{bar debiased}} = 1 \). However, the original bar likelihood from volunteer identifications was low (\( p_{\text{bar weighted}} = 0.33 \)). Thus, we have excluded 8722-3702 from the barred sample.
Furthermore, we recall that the $N$-body model we used exhibited a significant in-plane bending of the bar. We note that a number of the buckling candidates display this effect as well; this can be observed from the isodensities in Figures 6 and 7. One bar is strongly asymmetric (8947-1901), three are less so (8081-6103, 8337-1902, 8451-12703), and only one is definitely not (8657-19020). As our analysis only involved comparing kinematics and bar angle, it is promising that the in-plane bending, a predominantly photometric feature, appears to be consistent between simulations and observations as well.

The candidates found through our analysis bring the total number of buckling candidates characterized to eight; two were discovered in Erwin & Debattista (2016), and one more probable buckling candidate was characterized in Li et al. (2017). Details for all eight candidates are collected in Table 2.

**Nonbuckling comparison galaxies.**—We provide a sample of galaxies that we believe are not buckling, for comparison.

Figure 6. Stellar velocity maps for three of the five buckling candidates. In each panel, the first and second columns correspond to buckling and post-buckling simulation snapshots, respectively. The third column corresponds to the observed galaxy. The first row depicts stellar velocity maps, and the second row depicts the unsharp filtered stellar velocity maps, with an aperture of radius 6 pixels. Logarithmically spaced isodensity contours are overplotted and are estimated from the particle count in each bin and the mean $r$-band flux, for the simulated and observed galaxies, respectively. Simulated stellar velocity maps are generated using the best-fit parameters (see Table 3) and the optimization algorithm detailed in Section 3.3.
We again fit both the 4.5 Gyr post-buckling model and the 3.53 Gyr buckling model to the observed stellar velocity maps. Three sample nonbuckling comparison galaxies are shown in Figure 8. The optical images for all of the galaxies plotted are shown in Figure 9. Final fit information for each parameter is shown in Table 3. Priors and details are shown in Table 4. For many of these candidates, the nonbuckling MAD is yet lower than the buckling fit MAD. We believe that this result is due to the difference in intensity of buckling signal—these observed galaxies may be in a different stage of buckling from the simulation snapshot.

Figure 10 provides a comparison of the buckling best-fit MAD and the nonbuckling best-fit MAD, along with the 26 control galaxies. Galaxies labeled as "unlikely buckling" are less likely to be buckling owing to a lower quadrupole moment; regardless, we cannot exclude the possibility. Galaxies that are visually identified as nonbuckling are also labeled.

3.6. Gas Masses

$N$-body simulations predict that buckling should be affected by the gas fraction. To test these predictions, we obtain H I...
masses from the Arecibo Legacy Fast Arecibo L-band Feed Array (ALFALFA) survey (Haynes et al. 2011, 2018), as well as from H I-MaNGA follow-up observations at the Robert C. Byrd Green Bank Telescope (Masters et al. 2019).

H I mass data are matched to the MPL-8 barred sample and yield a total of 124 galaxies (10 galaxies are removed from the sample because they are edge-on). We correct for self-absorption using the optical axial ratio, with \( M_{\text{HI},c} = cM_{\text{HI}} \), where \( c = (b/a)^{-0.12} \) (Giovanelli et al. 1994). Stellar masses are obtained from the NSA, via a K-correction fit for elliptical Petrosian fluxes.

\[ M_{\text{HI}}/M_\odot = 2.356 \times 10^3 \left( \frac{D}{\text{Mpc}} \right) \left( \frac{F_{\text{HI}}}{\text{Jy km s}^{-1}} \right). \]

(6)

\( F_{\text{HI}} \) is the H I flux, and we assume that \( D = czH_0 \), where \( z \) is the optical redshift of each MaNGA galaxy in the NSA. The error for H I masses is propagated via the error on the H I flux:

\[ F_{\text{HI, error}} = \text{rms} \sqrt{\Delta v W}, \]

(7)
Observationally, Erwin & Debattista 2008; Saha et al. 2013; Athanassoula 2016; higher-redshift galaxy. We approximate as 1.2

Figure 9. Optical images of the galaxies described in Figures 6–8. The objects to the lower right of 8947-1901 and to the upper left of 8337-1902 are foreground stars; the object to the upper right of 8600-3703 is a noninteracting higher-redshift galaxy.

where rms is the root mean square noise; Δν is the channel resolution, 10 km s⁻¹; and W is the width of the profile, which we approximate as 1.2W₂₀. W₂₀ is the width of the H I line measured at 20% of the peak of the H I line. Typical errors are around δ(M_HI/M_☉)/(M_HI/M_☉) = 0.08. We plot log(M_HI/M_☉) against log(M_stellar/M_☉) for 124 barred galaxies for which gas masses are available, in Figure 11. Buckling and nonbuckling galaxies are indicated, and we overplot the fit line from Huang et al. (2012). The two buckling galaxies in the plot are MaNGA Plate-IFUs 8081-6103 and 8451-12703. Nondetections and galaxies for which upper limits are calculated have not been included in Figure 11.

4. Discussion

4.1. The Fraction of Galaxies with Bars in the Buckling Phase

Theoretically, the buckling phase is consistently predicted by several different investigations to have a duration of ~0.5–1.00 Gyr (O’Neill & Dubinski 2003; Martinez-Valpuesta & Shlosman 2004; Martinez-Valpuesta et al. 2006; Athanassoula 2008; Saha et al. 2013; Athanassoula 2016; Łokas 2019b). Observationally, Erwin & Debattista (2016) have identified two disk galaxies whose bars appear to be buckling. These were identified from observations of a sample of 44 barred galaxies with log(M/M_☉) ≥ 10.4 (Erwin & Debattista 2017), a sample for which 80% of the barred galaxies have boxy/peanut bars. They thus measure a frequency of observed buckling in local, high-mass barred galaxies that is 5.4% for these two galaxies, which may correspond to a period during which the amplitude of the quadrupole in line-of-sight velocities is approximately constant. The finer details of timing, duration, and variation between models are left to future investigations.

This toy model assumes that all bars evolve from being inplane bars to being boxy/peanut bulges via the buckling instability. However, there are at least two other mechanisms for this evolution that have been proposed (Quillen et al. 2014; Sellwood & Gerhard 2020), for example, a gradually increasing fraction of bar orbits getting trapped into a 2:1 resonance. The bar frame of these other mechanisms are common in field galaxies, for example, if they account for half of the boxy/peanut bulges, then our lower bound of 130 Myr would increase to 160 Myr.

This timescale relies on the fact that we identified 5 buckling candidates out of 434 near face-on galaxies, of which no more than ~75% have been observed with sufficient signal-to-noise ratio and resolution to identify buckling. It should thus be considered as a limiting value.

We assume that bars are not destroyed, which is supported by a number of high-resolution simulations (see AMR13 for a discussion). Assuming that bars are in general long-lived may indeed be reasonable for noninteracting galaxies, but it might not be in cases of strong interactions or of minor mergers (Pfenniger 1991; Athanassoula 1999; Berentzen et al. 2003). Furthermore, interactions can themselves drive bar evolution, including the buckling instability (Łokas 2019a). Our model does not include the effects of such interactions. The predictions of the bar model, with a comparison to the observational data, are plotted in Figure 12.

We find τ_bar ≈ 9.5 Gyr, τ_peanut ≈ 4.0 Gyr, and τ_buckling ≈ 130 Myr. The timescale of 130 Myr is a lower bound on the duration of buckling, because the duration of buckling is necessarily longer than its observability, and some galaxies may form peanuts without buckling (Berentzen et al. 2007; Quillen et al. 2014). Given these numbers, the mean age of bars that have already formed is approximately 6 Gyr. Our conversion between cosmological redshifts and look-back times was done using Ned Wright’s cosmology calculator (Wright 2006). Given the assumptions of this model, the mean age of bars that exist today is ~5.9 Gyr, with a mean age of bars that have a peanut/X-shape of ~6.7 Gyr and a mean age of bars that have not yet buckled of ~1.4 Gyr. After a few Gyr, the mean time since buckling is ~4.4 Gyr.

The amplitude of the quadrupole in the line-of-sight velocities need not stay constant over the duration of the buckling event. An increase or decrease in amplitude would alter the signal-to-noise ratio estimate. As an order-of-magnitude limit, we note that the derivative of the bar strength parameter A₂ is minimized and remains constant for a duration of ~250 Myr (Figures 7 and 8 of AMR13), which may correspond to a range during which the amplitude of the quadrupole in line-of-sight velocities is approximately constant. The finer details of timing, duration, and variation between models are left to future investigations.
### Table 3
Fit Results for Preliminary Buckling Candidates and Control Sample

| Plate-IFU | MAD (km s\(^{-1}\)) | Fit Type | \(\theta\) (deg) | \(\varphi\) (deg) | \(\gamma\) (deg) | Bar Length (pixels) | Velocity Scale |
|----------|---------------------|----------|-----------------|-----------------|-----------------|-------------------|---------------|
| 8947-1901\(^\dagger\) | 8.65 | (buckling sim.) | 36.4 | 138.9 | 49.8 | 18 | 0.50 |
| | 4.10 | (post-buckling sim.) | 35.8 | -40.4 | 48.8 | 20 | 0.64 |
| 8081-6103\(^\dagger\) | 6.91 | (buckling sim.) | 45.8 | 20.1 | 160.0 | 14 | 0.40 |
| | 4.97 | (post-buckling sim.) | 140.9 | -19.7 | 165.8 | 15 | 0.62 |
| 8337-1902\(^\dagger\) | 8.14 | (buckling sim.) | 18.7 | -99.9 | 115.7 | 22 | 0.41 |
| | 5.51 | (post-buckling sim.) | 160.2 | 80.0 | 130.0 | 22 | 0.50 |
| 8657-1902\(^\dagger\) | 10.12 | (buckling sim.) | 48.3 | 108.6 | 40.9 | 38 | 0.63 |
| | 8.61 | (post-buckling sim.) | 38.2 | 40.0 | -50.0 | 38 | 0.80 |
| 8451-12703\(^\dagger\) | 11.26 | (buckling sim.) | 129.0 | -30.5 | 147.0 | 32 | 0.42 |
| | 7.60 | (post-buckling sim.) | 139.6 | -40.1 | 170.2 | 34 | 0.80 |
| 8941-1901 | 7.86 | (buckling sim.) | 128.2 | -29.7 | -111.2 | 21 | 0.51 |
| | 5.37 | (post-buckling sim.) | 59.6 | -160.2 | -119.8 | 21 | 0.65 |
| 8319-3702\(^*\) | 13.99 | (buckling sim.) | 143.1 | -71.4 | -152.5 | 17 | 0.51 |
| | 7.43 | (post-buckling sim.) | 149.2 | -50.8 | -177.3 | 19 | 0.76 |
| 8950-1902\(^*\) | 9.62 | (buckling sim.) | 41.1 | -9.9 | -149.4 | 16 | 0.75 |
| | 6.78 | (post-buckling sim.) | 135.0 | 0.0 | -128.1 | 16 | 1.00 |
| 9025-1902 | 10.78 | (buckling sim.) | 25.4 | -67.9 | 10.2 | 15 | 0.57 |
| | 7.93 | (post-buckling sim.) | 150.8 | 39.6 | 29.2 | 16 | 0.50 |
| 8082-6102\(^*\) | 11.53 | (buckling sim.) | 26.8 | -103.8 | -10.1 | 20 | 1.21 |
| | 12.46 | (post-buckling sim.) | 25.8 | -90.0 | 10.0 | 22 | 0.97 |
| 8600-3703\(^*\) | 15.18 | (buckling sim.) | 148.2 | 99.3 | 120.5 | 19 | 0.96 |
| | 9.25 | (post-buckling sim.) | 150.0 | -89.7 | 140.1 | 21 | 1.05 |
| 8602-12705 | 9.37 | (buckling sim.) | 54.1 | -158.0 | 105.7 | 69 | 0.49 |
| | 10.70 | (post-buckling sim.) | 132.0 | -20.0 | 110.0 | 65 | 0.90 |
| 9883-9102\(^*\) | 22.48 | (buckling sim.) | 38.4 | -169.3 | 129.5 | 21 | 1.20 |
| | 33.60 | (post-buckling sim.) | 130.0 | 0.0 | 112.8 | 21 | 1.05 |
| 9487-3704 | 12.49 | (buckling sim.) | 39.7 | 161.3 | 138.5 | 13 | 0.40 |
| | 11.43 | (post-buckling sim.) | 141.5 | 20.1 | 133.1 | 13 | 0.45 |
| 9863-3704\(^*\) | 17.18 | (buckling sim.) | 33.8 | -81.3 | -108.5 | 23 | 0.71 |
| | 8.48 | (post-buckling sim.) | 34.2 | -38.6 | -59.9 | 22 | 0.95 |
| 8456-12701 | 6.51 | (buckling sim.) | 159.9 | 118.7 | -129.9 | 34 | 0.37 |
| | 4.62 | (post-buckling sim.) | 20.0 | 51.9 | -139.4 | 32 | 0.40 |
| 8252-3702 | 9.25 | (buckling sim.) | 33.9 | 127.0 | 118.4 | 20 | 0.40 |
| | 7.79 | (post-buckling sim.) | 147.7 | 30.3 | 140.3 | 21 | 0.71 |
| 8486-6101\(^*\) | 14.39 | (buckling sim.) | 36.3 | 162.0 | -19.7 | 18 | 0.97 |
| | 5.93 | (post-buckling sim.) | 123.1 | 10.9 | -10.1 | 19 | 1.00 |
| 8942-12702\(^*\) | 13.72 | (buckling sim.) | 48.4 | -161.8 | 50.3 | 43 | 0.85 |
| | 13.40 | (post-buckling sim.) | 46.0 | 9.9 | 40.2 | 40 | 1.12 |
| 9035-3704 | 7.91 | (buckling sim.) | 130.1 | -21.1 | 119.6 | 33 | 0.55 |
| | 5.43 | (post-buckling sim.) | 136.2 | -21.1 | 115.8 | 34 | 0.92 |
| 9026-9102 | 7.72 | (buckling sim.) | 36.1 | -141.2 | -143.5 | 35 | 0.30 |
| | 4.55 | (post-buckling sim.) | 151.7 | -59.2 | -114.8 | 39 | 0.40 |
| 8592-6102\(^*\) | 12.56 | (buckling sim.) | 55.6 | -146.1 | 158.1 | 36 | 0.61 |
| | 7.89 | (post-buckling sim.) | 139.9 | -50.0 | -170.0 | 39 | 0.86 |
| 9506-9101 | 22.11 | (buckling sim.) | 133.9 | 158.8 | 29.6 | 23 | 1.31 |
| | 14.51 | (post-buckling sim.) | 35.7 | -160.4 | 31.5 | 22 | 1.72 |
| 9490-12702 | 13.57 | (buckling sim.) | 42.1 | 102.9 | -117.5 | 22 | 0.41 |
| | 12.19 | (post-buckling sim.) | 141.1 | 79.7 | -120.0 | 23 | 0.40 |
Notes. Galaxies deemed buckling and nonbuckling are annotated with † and *, respectively. Additional parameters and initial conditions for inclination and bar position angle are shown in Table 4.

### 4.2. Gas Mass

Prior theoretical investigations of buckling in the literature have agreed that buckling should be suppressed in relatively gas-rich galaxies (Debattista et al. 2006; Berentzen et al. 2007; Wozniak & Michel-Dansac 2009; Villa-Vargas et al. 2010; AMR13). Stronger bars are preferentially found in galaxies with lower specific star formation rates (Cheung et al. 2013; Rosas-Guevara et al. 2020), with observations showing that longer bars are preferentially found in galaxies with a lower specific star formation rate (Fraser-McKelvie et al. 2020). Masters et al. (2012) show that more bars are present in galaxies with lower H I gas fraction. Furthermore, in low-mass \((\log M_{\text{gal}}/M_\odot \leq 10.3)\) galaxies, the probability of observing a bar is a decreasing function of the central mass concentration (Nair & Abraham 2010).

Therefore, we expect that the buckling instability would be most likely observed in relatively gas-poor galaxies. This expectation is weakly consistent with our results, as shown in Figure 11, but the buckling galaxies appear to follow the same general trend as the rest of the barred galaxies in the sample. Since only two of our identified buckling galaxies have HI mass measurements, we cannot definitively conclude whether or not bar buckling is suppressed in gas-rich galaxies. The predicted trend is

| Plate-IFU | MAD (km s\(^{-1}\)) | Fit Type | \(\theta\) (deg) | \(\varphi\) (deg) | \(\gamma\) (deg) | Bar Length (pixels) | Velocity Scale |
|-----------|----------------------|----------|-----------------|------------------|-------------------|---------------------|-----------------|
| 850-12705 | 21.43                | (buckling sim.) | 54.6            | 156.4            | -9.9             | 45                  | 1.23            |
|           | 14.33                | (post-buckling sim.) | 57.9            | 163.4            | 0.0              | 45                  | 1.69            |
| 9505-12704| 8.91                 | (buckling sim.) | 150.7           | -39.7            | -74.8            | 19                  | 0.33            |
|           | 4.38                 | (post-buckling sim.) | 153.5           | -50.8            | -54.3            | 19                  | 0.37            |
| 9041-6104 | 9.19                 | (buckling sim.) | 31.8            | -66.2            | -20.1            | 12                  | 0.71            |
|           | 6.62                 | (post-buckling sim.) | 30.6            | 129.9            | 10.5             | 12                  | 0.71            |
| 8978-12702| 25.23                | (buckling sim.) | 154.7           | 149.2            | -29.2            | 9                   | 2.12            |
|           | 63.40                | (post-buckling sim.) | 27.7            | 21.7             | -30.5            | 9                   | 2.17            |
| 9185-12705| 25.28                | (buckling sim.) | 30.5            | 128.2            | -162.1           | 14                  | 0.46            |
|           | 22.11                | (post-buckling sim.) | 152.2           | -140.4           | -147.9           | 14                  | 0.40            |
| 8985-3702 | 9.00                 | (buckling sim.) | 21.2            | -110.2           | 20.0             | 17                  | 0.40            |
|           | 4.77                 | (post-buckling sim.) | 162.1           | -92.3            | 59.7             | 17                  | 0.44            |
| 8141-3703*| 13.17                | (buckling sim.) | 47.3            | -161.9           | 129.1            | 28                  | 0.96            |
|           | 8.00                 | (post-buckling sim.) | 132.1           | -10.9            | 112.5            | 27                  | 1.20            |
| 8983-9101 | 17.53                | (buckling sim.) | 56.7            | -140.9           | 127.7            | 17                  | 0.86            |
|           | 14.36                | (post-buckling sim.) | 36.9            | -142.5           | 133.2            | 17                  | 1.31            |
| 8992-3702 | 10.27                | (buckling sim.) | 46.1            | 172.5            | -117.9           | 12                  | 0.41            |
|           | 11.42                | (post-buckling sim.) | 149.9           | 30.5             | -143.7           | 12                  | 0.40            |
| 8722-3702 | 8.68                 | (buckling sim.) | 25.6            | -160.9           | 29.3             | 36                  | 0.46            |
|           | 13.94                | (post-buckling sim.) | 25.9            | -19.6            | -179.2           | 35                  | 0.76            |
| 8259-6103 | 9.47                 | (buckling sim.) | 133.7           | 30.9             | 64.7             | 8                   | 0.39            |
|           | 8.83                 | (post-buckling sim.) | 54.5            | -30.5            | 65.5             | 8                   | 0.35            |
| 9038-12703| 7.49                 | (buckling sim.) | 125.4           | -10.3            | 93.5             | 15                  | 0.69            |
|           | 5.67                 | (post-buckling sim.) | 120.0           | -9.8             | 89.7             | 14                  | 0.73            |
| 9879-12704| 11.93                | (buckling sim.) | 147.8           | -40.2            | -90.9            | 15                  | 0.70            |
|           | 8.34                 | (post-buckling sim.) | 138.4           | -38.7            | -93.7            | 14                  | 0.61            |
| 8983-3704 | 22.44                | (buckling sim.) | 46.2            | -70.0            | 98.9             | 15                  | 0.75            |
|           | 18.53                | (post-buckling sim.) | 141.1           | 68.6             | 82.1             | 15                  | 0.70            |
| 9042-12702| 10.00                | (buckling sim.) | 122.3           | -176.9           | -31.6            | 6                   | 0.98            |
|           | 10.53                | (post-buckling sim.) | 38.8            | 172.0            | -40.4            | 6                   | 1.15            |
| 8459-3703 | 9.18                 | (buckling sim.) | 31.7            | 59.5             | 104.9            | 23                  | 0.41            |
|           | 10.89                | (post-buckling sim.) | 144.4           | -89.5            | 143.1            | 23                  | 0.41            |
| 10519-12705| 11.02               | (buckling sim.) | 143.3           | -42.3            | 174.5            | 22                  | 0.74            |
|           | 10.32                | (post-buckling sim.) | 37.5            | -129.7           | -169.3           | 25                  | 0.77            |
| 8335-6101 | 20.72                | (buckling sim.) | 156.9           | -67.1            | 21.1             | 29                  | 0.41            |
|           | 27.06                | (post-buckling sim.) | 30.0            | 30.0             | -19.9            | 29                  | 0.40            |
also absent in the results of Erwin & Debattista (2017). It can be seen, in their Figure 10, that the buckling galaxies have comparable gas masses to the other barred galaxies of that stellar mass. Model predictions of the effects of gas mass on buckling will only be testable once a sufficiently large number of buckling galaxy candidates are identified.

5. Conclusion

In this paper, we present kinematic diagnostics of the bar buckling instability in both simulations and data. The main results of the theoretical work are illustrated by Figure 1, where we present our method for kinematic identification of the buckling phase. The main results of the observational work are illustrated by Figures 6 and 7, where we present our newly identified buckling candidates.

By using N-body snapshots of a galaxy undergoing dynamical evolution, we identify a stellar velocity signal out of the plane of the disk. The signal resembles a quadrupole in shape and amplitude, and has roughly the width of the bar. We seek the buckling signal in observational data, due to its theoretically large scale: in terms of both its amplitude in stellar line-of-sight velocity and the range in kpc over which it is detectable. To amplify the signal visually, we use unsharp masking with a circular aperture. We selected from the MANGA survey 434 galaxies that are barred and are closer to face-on than 55°. We then visually identify buckling candidates based on quadrupolar disturbances of high velocity amplitude near the center of the bar.
Buckling candidates are further characterized by a median absolute deviation $f_i$ fit to the simulated stellar velocity maps. We fit two free parameters—the azimuthal angle and rotation angle in the viewing plane—and numerous constrained parameters (inclination, bar angle, stellar velocity amplitude, and bar length). The optimization confirms that the visually identified quadrupolar signal is consistent with parameter constraints. We identify five galaxies as buckling candidates and present examples of nonbuckling galaxies for comparison. Our results suggest a lower bound for the duration of buckling to be 130 Myr, which is consistent with simulation timescales.

We investigate the relationship between the $\text{H}I$ mass fraction and stellar mass as an initial test of the hypothesis that central gas inhibits bar buckling, but we were not able to reach a conclusion. Possible explanations for the lack of correlation include small sample size, lack of central gas mass estimates, and inadequate treatment of gas effects by the models. Furthermore, the relationship between gas mass and stellar mass may not necessarily be fully captured by models where stellar mass is fixed. At this time, the data are not substantive enough to form a definitive conclusion.

Our results increase the number of buckling candidates discovered to date by over twofold, and we have developed a new approach for buckling identification reliant on both photometry and kinematics. Moving forward, there are multiple avenues for impactful follow-up: reapplying the existing methodology to MaNGA or to other similar surveys as the survey sample increases; obtaining higher-resolution, higher signal-to-noise ratio IFU observations of the buckling candidates; fitting these observations to simulated stellar velocities for more models and at more time points to better estimate the timescales involved in buckling; studying the overlap between the method developed here and that of Erwin & Debattista (2016), which works best for moderately inclined ($40^\circ \lesssim i \lesssim 70^\circ$) galaxies; or applying the methodology to upcoming IFU observations of disk galaxies at higher redshift, for which the NIRSpec instrument aboard the James Webb Space Telescope (Bagnasco et al. 2007; Dorner et al. 2016) will be uniquely suitable. Such future work would help determine the buckling rate across cosmic time and thus enable a completely new diagnostic of galaxy evolution.

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ORCID iDs

Katherine M. Xiang https://orcid.org/0000-0001-5805-8959
David M. Nataf https://orcid.org/0000-0001-5825-4431
E. Athanassoula https://orcid.org/0000-0001-6079-1332
Nadia L. Zakamska https://orcid.org/0000-0001-6100-6869
Kate Rowlands https://orcid.org/0000-0001-7883-8434
Karen Masters https://orcid.org/0000-0003-0846-9578
Niv Drory https://orcid.org/0000-0002-7339-3170
Katarina Kraljic https://orcid.org/0000-0001-6180-0245

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