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Galaxy Zoo Builder: Morphological Dependence of Spiral Galaxy pitch angle

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ABSTRACT
Abstract

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1 INTRODUCTION

Spiral structure is present in a majority of massive galaxies (Buta 1989, Lintott et al. 2008) yet the formation mechanisms through which spiral structure originates are still hotly debated. Spirals are as diverse as the theories proposed to govern their evolution; from the quintessential pair of well-defined arcs of the grand design spiral, to the fragmented arm segments of the flocculent spiral, to the disjointed multi-armed spiral. These variatons on structure account for 18%, 50% and 32% of the population respectively (Elmegreen et al. 2011, Buta et al. 2015). Our current understanding of the mechanisms which drive spiral growth and evolution suggest that each of the different forms of spiral galaxy may be triggered primarily by different processes. Grand Design spirals are thought to have undergone a tidal interaction, be driven by a bar (as suggested by Manifold theory, Romero-Gomez et al. 2011), or be obeying quasi-stationary density wave theory (QSDW theory), in which spiral arms are slowly evolving, ever-present structures in the disc (Lin & Shu 1964). Flocculent spirals are thought to be formed through swing amplification (shearing of small gravitational instabilities in the disc), and be transient and reccurent in nature (Julian & Toomre 1966). It is recognised that methods of spiral formation are not mutually exclusive. There is also debate as to the evolution of spiral structure: whether spirals maintain their shape over many rotational periods (assumed by QSDW theory, Lin & Shu 1964), or "wind up" with the differential rotation of the disc (as found by Masters et al. 2019).

Arms of spiral galaxies are the source of the vast majority of star formation in the Universe, and spirals rearrange disc gas and can lead to the formation of disc-like bulges (e.g. Kormendy & Kennicutt 2004). Studies of spiral morphology have found interesting correlations between spiral morphology and other galactic properties, such as a correlation between spiral tightness and central mass concentration (Yu & Ho 2019, Davis 2015, though Hart et al. 2017 found no such relation) and tightness and rotation curve shape (Seigar et al. 2005, with rising rotation curves creating more open spiral structure). These predictions and observations provide compelling reasons for investigating their underlying rules and dynamics, as doing so is essential for understanding the secular evolution of disc galaxies.

1.1 Measuring galaxy pitch angle

Many methodologies have been proposed and implemented to measure spiral arm properties, including visual inspection (Herrera-Endoqui et al. 2015), fourier analysis (i.e. 2DFFT, Davis et al. 2012), texture analysis (i.e. SpArcFiRe, Davis & Hayes 2014), and combinations of automated methods and human classifiers (Hart et al. 2017). One potentially underused method of obtaining measurements of spirals is through photometric fitting of spiral structure, as possible using tools such as GALFIT (Peng et al. 2010) and *Galaxy Builder* (**[[Lingard et al, in prep]]**). These methods attempt to localize light from an image of a galaxy into distinct subcomponents, such as a galaxy disc, bulge, bar and spiral arms, generally finding the optimum solution using computational optimization. This optimization process, however, is often not robust for complex, many-component models and requires significant supervision to converge to a physically meaningful result (Gao & Ho 2017). **[[Lingard et al, in prep]]** propose a solution to this problem through the use of citizen science to provide the starting points for computational fitting.

A common assumption when measuring galaxy pitch angle is that observed spiral arms have a constant pitch angle. Spirals of this kind are known as logarithmic spirals and are described by

$$r = A\, e^{\theta \tan\phi}, \tag{1}$$

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where ϕ is the arm's pitch angle. One method used to obtain a pitch angle of a galaxy is to fit logarithmic spirals to individually identified arm segments and take the weighted mean of their pitch angles (which often vary by upwards of 10°, Davis & Hayes 2014). Weighting is determined by the length of the arc segment, with longer being assigned higher weights, i.e. for a galaxy where we have identified N arm segments, each with length L_i and pitch angle ϕ_i

$$\phi_{\mathrm{gal}} = \left(\sum_{i=1}^{N} L_i\right)^{-1} \sum_{i=1}^{N} L_i \phi_i. \tag{2}$$

The most commonly used measurement of uncertainty of length-weighted pitch angles is the [[**unweighted?**]] sample variance between the arm segments identified.

A notable drawback of length-weighted pitch angle is sensitivity to the number and quality of the spiral arm segments identified; Hart et al. (2017) found that only 15% of the arm segments identified by a leading algorithm (SpArcFiRe) were identified as "good" matches to real spiral arms by citizen science classifiers.

Fourier analysis in one-dimension (as performed by [[**...**]]) and two-dimensions ([[**...**]]) is another widely used method of computationally obtaining galaxy pitch angles. Two-dimensional fourier methods generally decompose a deprojected image of a galaxy into a superpositions of logarithmic spirals between inner and outer annuli (Davis et al. 2012), and reports the pitch angle with the highest amplitude as the galaxy's pitch angle. It is uncertain how the large observed variation between pitch angles of individual arms impacts this measurement.

This paper makes use of the photometric models obtained through the *Galaxy Builder* citizen science project for the 196 spiral galaxies present in [[**Lingard et al, in prep**]]. In this paper we focus on the use of measured spiral tightness (quantified using pitch angle, Binney & Tremaine 1987) as a probe into the dynamical mechanisms governing a spiral galaxy's evolution. We make use of Bayesian hierarchical modelling to measure galaxy pitch angle from the spiral arm clusters producted by *Galaxy Builder*.

Section 3.1 investigates spiral arm winding using the test derived by Pringle & Dobbs 2019 (uniformity of galaxy pitch angle in cot ϕ) and concludes using a marginalized Anderson-Darling test that we [[**cannot unilaterally reject winding of this form at the 1% level**]]. Section 3.2 examines the correlation between pitch angle and bulge size implied by the Hubble sequence and reported by [[**citation**]], and pitch angle and bar strength implied by Manifold theory, and find [[**no significant correlation**]].

2 METHOD

2.1 The Galaxy Sample

The galaxies selected analysed in this paper are the 198 galaxies from [[**Lingard et al, in prep.**]]. We combine classifications of galaxies which were repeated in the *validation subset* with the original classifications. Clustering of drawn spiral arms and cleaning of points was then performed as detailed in [[**Lingard et al, in prep.**]]. We remove any galaxies for which no arms were identified. This results in a hierarchiacal data structure of 109 galaxies, 250 spiral arms and 307,861 points.

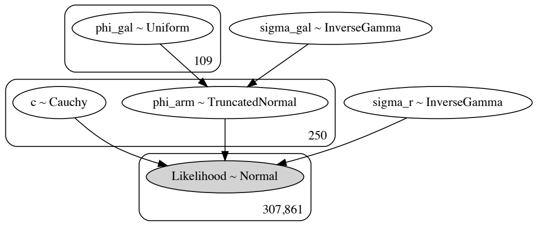

Figure 1. The model used for galaxy pitch angle measurement for the sample.

Spiral arm points are deprojected to a face-on orientation using the position angle PETRO_PHI90 and axis ratio PETRO_BA90 keywords from the NASA-Sloan Atlas [[**citation**]]. We scale the radii to have unit variance (which does not impact log spiral pitch angle due to its scale invariance).

[[**Should I elaborate more on the sample?**]]

2.2 Bayesian modelling of spiral arms in *Galaxy Builder*

We model a spiral arm as a logarithmic spiral, described by

$$r_{\mathrm{arm}} = \exp\left[\theta_{\mathrm{arm}} \tan\phi_{\mathrm{arm}} + c_{\mathrm{arm}}\right]. \tag{3}$$

Assume the pitch angle of a galaxy's spiral arms are drawn from a Normal distribution, truncated between 0 and 90 degrees, centred on some value we will call the galaxy's pitch angle, ϕ_{gal}. This dispersion in arm pitch angle has some measure of spread, σ_{gal}, which we will assume is the same in galaxies:

$$\phi_{\mathrm{arm}} \sim \mathrm{TruncatedNormal}(\phi_{\mathrm{gal}}, \sigma_{\mathrm{gal}}, \min = 0, \max = 90). \tag{4}$$

We choose hyperpriors on ϕ_{gal} and σ_{gal} of

$$\phi_{\mathrm{gal}} \sim \mathrm{Uniform}(\min = 0, \max = 90), \tag{5}$$
$$\sigma_{\mathrm{gal}} \sim \mathrm{InverseGamma}(\alpha = 2,\ \beta = 20). \tag{6}$$

We also have the offset parameter c, and a measure of radial uncertainty σ_r:

$$c_{\mathrm{arm}} \sim \mathrm{Cauchy}(\alpha = 0,\ \beta = 10), \tag{7}$$
$$\sigma_r \sim \mathrm{HalfCauchy}(\beta = 0.2). \tag{8}$$

To perform inference, we make use of the No-U-Turn-Sampler (NUTS, Hoffman & Gelman 2011), implemented in PYMC3[1], an open source probabilistic programming framework written in python (Salvatier et al. 2016).

[1] `https://docs.pymc.io/`

3 RESULTS

3.1 Spiral Winding

In order to test the possible progenitor distribution of our estimated galaxy pitch angles, we repeatedly perform an Anderson-Darling test over each draw present in the MCMC trace, resulting in a distribution of Anderson-Darling statistics. We will refer to this test as the *marginalized Anderson-Darling test*. We make use of the Kolmogorov-Smirnov test in a similar manner for comparison.

We perform the marginalized Anderson-Darling test for a potential source distribution uniform in $\cot\phi$ between the limits present in Pringle & Dobbs (2019) ($1.00 < \cot\phi < 4.75$, or roughly $11.9° < \phi < 45.0°$). The resulting distribution of Anderson-Darling statistics can be seen in Figure 2. We observe that we reject the null hypothesis at the 1% level for only 86% of the possible realizations of galaxy pitch angle, therefore with our sample and methodology we cannot unilaterally reject winding of the kind described by Pringle & Dobbs (2019).

3.2 Dependence of pitch angle on Galaxy Morphology

3.2.1 Pitch angle vs. Bulge size

We see no correlation between galaxy pitch angle derived from the *hierarchial normal model* and Galaxy Zoo 2's debiased (Willett et al. 2013) *pbulge*, which has been shown to be a good measure of bulge size.

We separate our sample into "disc-dominated galaxies" and "obvious bulge galaxies" using the debiased fractions from Galaxy Zoo 2 following Kruk et al. (2017), defining *no bulge* + *just noticeable* > *obvious* + *dominant* for the former and the converse for the latter. A marginalized two-sample Anderson-Darling test (Scholz & Stephens 1987) does not find strong evidence that the samples were drawn from different distributions; we reject the null hypothesis at the 1% level for only 8% of the samples.

3.2.2 Pitch angle vs. Bar Strength

We see no correlation between galaxy pitch angle derived from the *hierarchial normal model* and Galaxy Zoo 2's debiased *pbar*, which is widely viewed as a good measure of bar strength, and therefore a measure of the torque applied on the disc gas.

Separating the sample based off of $pbar > 0.5$, and restricting to galaxies with more than 10 classifications for *pbar* (as performed by Masters et al. 2011 and Kruk et al. 2017) and performing a marginalized two-sample Anderson-Darling test does not find that the samples were drawn from different distributions. [[**Talk about number of galaxies in each sub-sample?**]]

4 DISCUSSION

This paper presents a new Bayesian approach to estimate galaxy pitch angle, making use of citizen science results to measure spiral arms through photometric modelling. We introduce an adaptation of the Anderson-Darling test to incorporate full Bayesian posterior probabilities and utilize this test to investigate theories governing spiral formation and evolution.

The statistical approach implemented in this paper allows a more thorough examination of pitch angle than simpler methods of logarithmic spiral fitting, and better accounts for inter-arm pitch angle variation than fourier analysis [[**This is a strong statement, how can we quantify it?**]].

Our method and results do not completely reject spiral winding of the form described by Pringle & Dobbs (2019), however this result is highly sensitive to the boundaries used; using limits of $10.0° < \phi < 40.0°$ results in us rejecting the null hypothesis at the 1% level for every MCMC draw. As no physical justification was provided for the limits present in Pringle & Dobbs (2019), this is a far from ideal test of arm winding.

We we do not find a relationship between bar strength and pitch angle, as would have been predicted by Manifold theory, and do not find evidence for the relationship between central mass concentration and pitch angle predicted by the Hubble sequence.

This work is primarily limited by the sample used; due to time constraints the *Galaxy Builder* galaxies used are not guaranteed to be representative. A larger and more complete sample is needed to be completely confident in our results. However, we believe that the methodlogy proposed here is a scalable solution to the problems facing investigation of spiral morphology.

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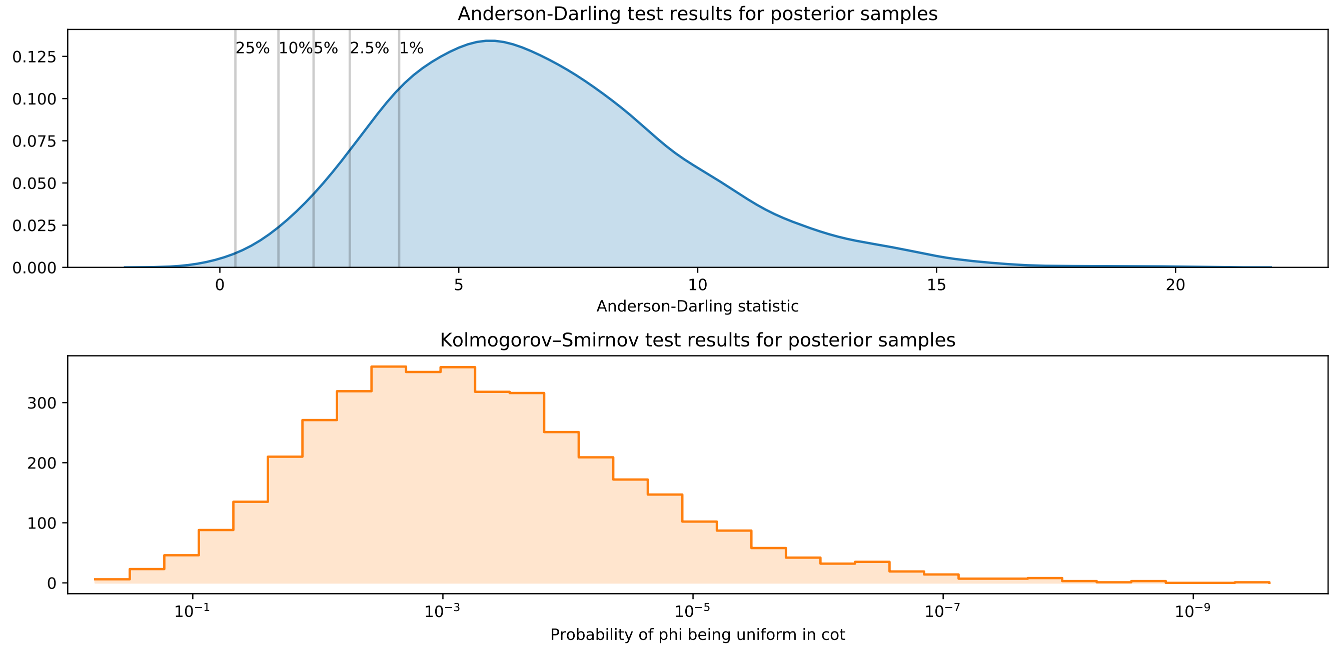

Figure 2. The results of a marginalized Anderson-Darling test (top panel), with values corresponding to various confidence intervals shown, and marginalized Kolmogorov-Smirnov test p-values (lower panel). Moving rightwards on the x-axis implies greater confidence in rejecting the null hypothesis.

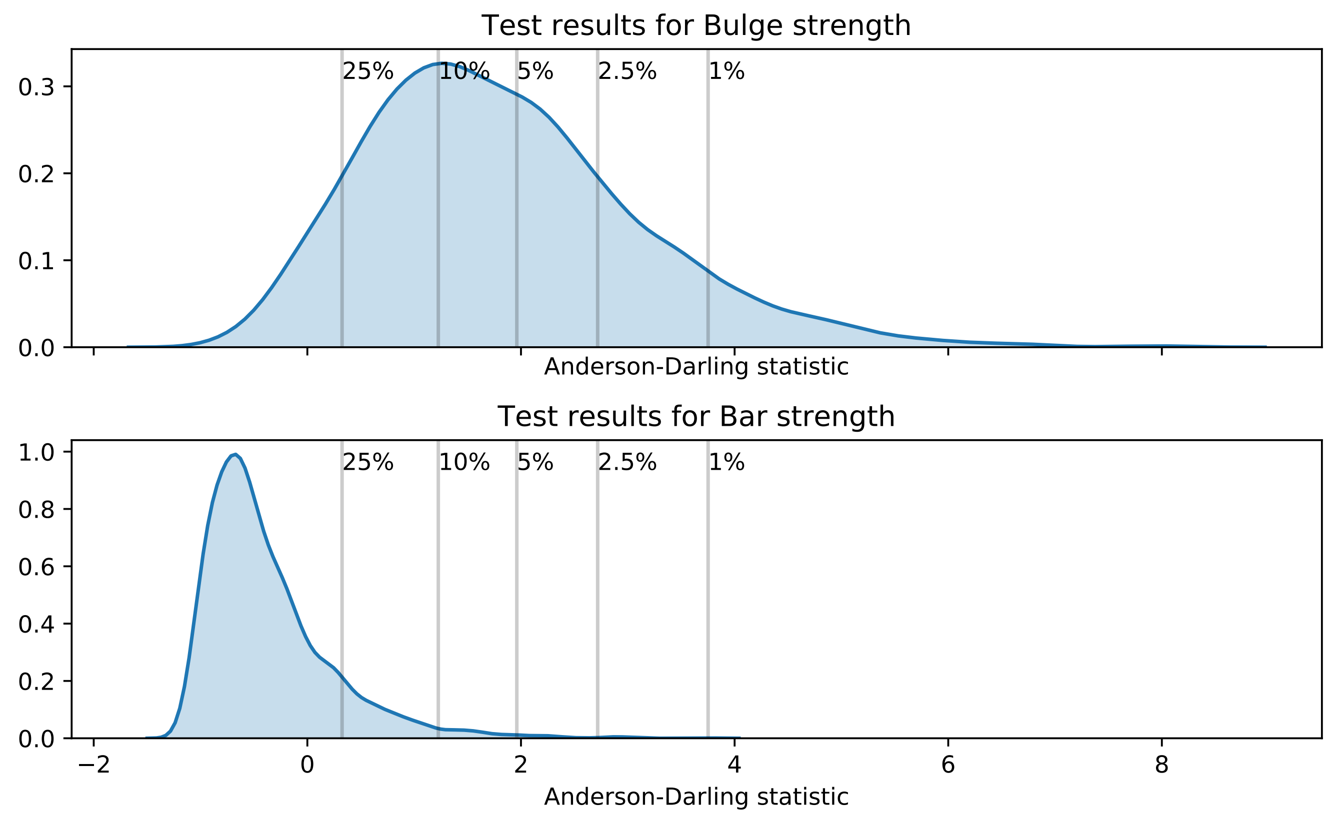

Figure 3. The results of marginalized two-sample Anderson-Darling tests examining whether pitch angles for Bulge-dominated and Disc-dominated galaxies are drawn from the same distribution (top panel), and the results of the same test for strongly-barred vs unbarred galaxies (bottom panel).

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Appendix

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