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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 themselves are as diverse as the theories proposed to govern their evolution; ranging from the quintessential pair of well-defined arcs of the grand design spiral, to the patchy and 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, 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). However it is recognised that no two methods of spiral formation are mutually exclusive.

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**]] successfully solve this problem through the use of citizen science to provide the starting point for a computational fit.

A common assumption when measuring galaxy pitch angle is that observed spiral arms have a constant pitch angle, these spirals are known as logarithmic spirals and are described by

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

One method used to obtain a pitch angle of a galaxy from identified arm segments is by taking the weighted mean of their pitch angles (as used by SpArcFiRe, Davis & Hayes 2014), where weighting is determined by the length of the

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arc segment, with longer arcs having 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.

One notable drawback of the use of length-weighted arms is the sensitivity of the end result to the number and quality of the spiral arm segments identified [[**...**]]

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*. We test for signs of spiral arm winding using the predictions derived by Pringle & Dobbs 2019 (uniformity of galaxy pitch angle in cot ϕ) and conclude 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 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, and perform clustering and point cleaning as detailed in [[**Lingard et al, in prep.**]], and remove any galaxies for which no arms were identified. This results in a hierarchiacal data structure of 109 galaxies and 250 spiral arms, with 307,861 points in polar coordinates, which are scaled such that the radius of each spiral arm has unit maximum.

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

2.2 Bayesian modelling of spiral arms in *Galaxy Builder*

Assume we can model spiral arms 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, 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:

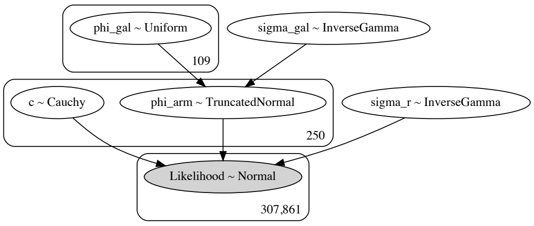

Figure 1. The model used for galaxy pitch angle measurement for the sample.

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

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

$$\phi_{\mathrm{gal}} \sim \mathrm{Uniform}(\mathrm{min}=0, \mathrm{max}=90), \tag{5}$$

$$\sigma_{\mathrm{gal}} \sim \mathrm{InverseGamma}(\alpha=2,\ \beta=20). \tag{6}$$

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), implemented in PYMC3[1], an open source probabilistic programming framework written in python. [[**does PYMC3 have a citation?**]]

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 perform the marginalized Anderson-Darling test on a 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 92% of the possible realizations of galaxy pitch angle. Therefore we cannot unilaterally reject winding of the kind described by Pringle & Dobbs (2019), though .

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

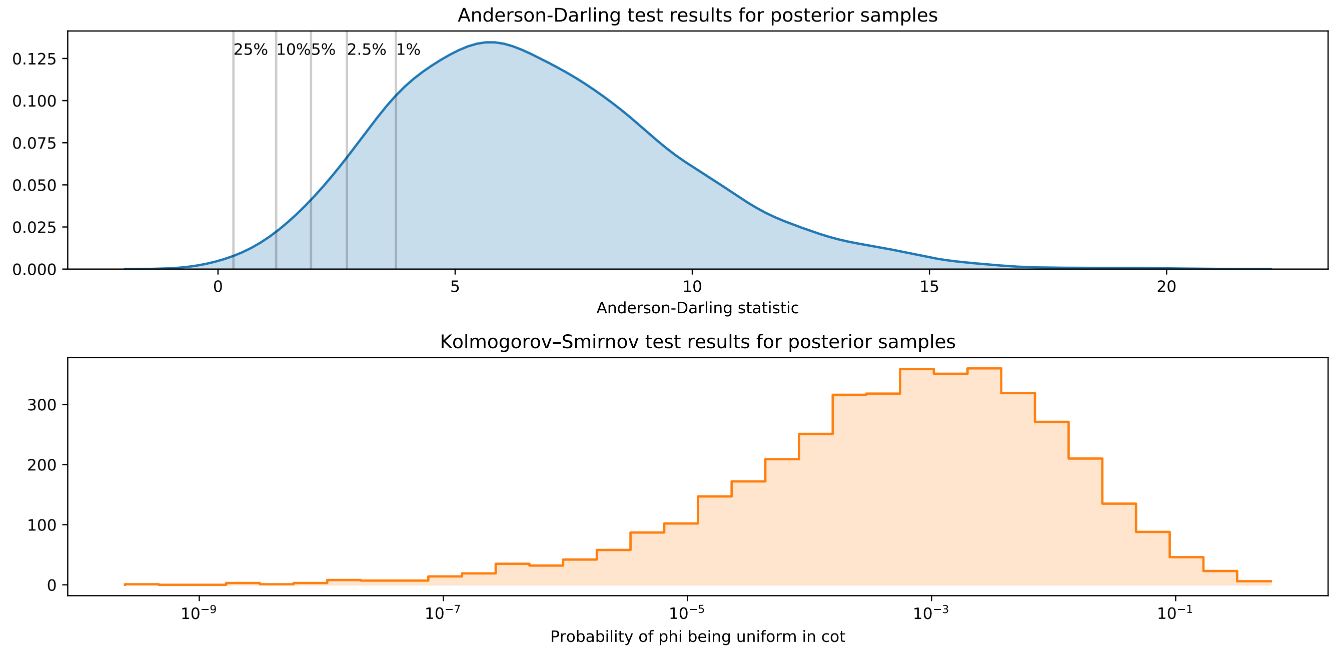

Figure 2. The results of a marginalized Anderson-Darling test (top panel), with confidence intervals shown, and marginalized Kolmogorov-Smirnov test p-values (lower panel).

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 GZ2's *pbulge*, which is widely viewed as a good measure of bulge size.

3.2.2 Pitch angle vs. Bar Strength

We see no correlation between galaxy pitch angle derived from the *hierarchial normal model* and GZ2's *pbar*, which is widely viewed as a good measure of bar strength, and therefore a measure of the torque applied on the disc gas.

A marginalized Anderson-Darling test does not find that the samples were drawn from different distributions (statistic of -0.91).

4 DISCUSSION

Discussion

5 ACKNOWLEDGEMENTS

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Appendix

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