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Galaxy Zoo Builder: Morphological Dependence of Spiral Galaxy pitch angle

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ABSTRACT
Abstract

Key words: galaxies: evolution – galaxies: spiral – galaxies: photometry

INTRO LIT REVIEW (TO BE REMOVED)

Dobbs & Baba (2014) introduction:

- spirals patterns are present in 2/3 of all massive galaxies (GZ2)
- Sites of a majority of a star formation
- understanding spirals is essential for understanding star formation and galaxy evolution
- hubble classification of spirals are divided by tightness and the presence of a bar
- can also include information on bulge size and luminosity, and galaxy gas content
- Elmegreen & Elmegreen proposed another scheme, classifying spirals into 12 types depending on the number and lenght of spiral arms
- This was simplified into *flocculent*, *grand design* and *multi-armed* spirals
- 60% of galaxies exhibit some grand design structure
- the type of spiral is linked to the mechanism which generated them
  - (quasi-stationary) density wave theory ($QSDW$)
  - local instabilities, perturbations or noise which are swing-amplified
  - tidal interactions
  - bars may also play a role in inducing spiral arms
- **these mechanisms are not mutually exclusive**
- flocculent and multi-arm spirals generally thought to arise from local instabilities
- grand designs are thought to have undergone a tidal interaction, have a bar driving arms or be obeying $QSDW$
- we can measure spiral number, pitch angle, amplitude, arm shape and lifetime

Masters et al. (2019) introduction:

- Hubble classification is a common technique
- Hubble spirals are ordered in a sequence extending away from the ellipticals, and separated depending on the presence of a bar
- Extended by de Vaucouleurs to include Sd
  - split by spiral arm appearance (how tightly wound and how distinct the arms were)
  - the prominence of a central bulge
- galaxy morphology encodes information on its dynamical history, including its formation and evolution
- morphology is known to correlate well with other physical properties
- people have taken to using proxies for morphology
- this is not a valid approach
- this paper explores an updated view of the Hubble sequence with the morphological classifications provided by Willett et al. (2013)
- most experts say that classifying based on bulge size vs spiral tightness result in consistent classification
- modern automatic galaxy classification conflates bulge size alone with spiral type
- differences in arm characteristics is linked to different formation mechanisms (floculent to shearing, grand design to density waves)

Díaz-García et al. (2019) introduction:

- Arms are noticeable and pretty and they host intense star formation, H2 regions and dust.
- More prominent in blue, but backbone is comprised of old stars.
- 2/3 massive galaxies are Spirals.
- 3 types of spiral arm (GD, 18%; FL, 50%; MA, 32%; Elmegreen et al, 2011 and Buta et al., 2015).
- GD have two long and well-defined spiral arms, FL have short and fragmented arm sections, MA are a fairly symmetric middle-ground, comprised of central 2-armed section which develops long ramifications in teh outer parts of the optical disc.

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- Spiral formation is a matter of debate - including *density wave theory*, *tidal triggering* and *swing amplification*.
- GD spirals and inner section of MA spirals are seen as density wave driven, whereas FL patterns are seen as swing-amplified regions of local gravitational instability
- Numerical models show that FL patterns are transient and reccurent, whereas GD last longer (~ 1 Gyr).
- pitch angle is a measure of arm tightness. Positive pich angle gives trailing arm, and vice versa.
- pitch angle is not necessarily constant, regardless of the class of the spiral arm.
- It is claimed that pitch angles depend on central mass concentration and atomic gas density (e.g. Kennicutt 1981; Block et al. 1994; Davis et al. 2015; Yu & Ho 2019), galactic shear rate (e.g. Seigar et al. 2006; Grand et al. 2013), or on the steepness of the rotation curves (Seigar et al. 2005, 2014).
- Spiral arms are more open in galaxies with rising rotation curves (larger absolute pitch angle) and tighter in those with falling rotation curves.
- Very tight scaling relation reported by Davis et al. (2017) between supermassive black hole mass and the spiral pitch angle.
- Spirals rearrange gas and lead to the formation of disc-like bulges (e.g. Kormendy & Kennicutt 2004). Making them important agents for the secular evolution of disc galaxies (a process in which bars also play a significant role).
- Spirals could be driven by bars, though this is still debated. Manifold theory suggests a strong coupling between bars and spirals (Romero-Gómez et al. 2006, and many others). Numerical simulations show that material becomes confined to tubes (invariant manifolds) that extend from the two unstable Lagrangian points at the end of the bar (L_1 and L_2). This theory predicts a dependence of the pitch angle on the bar perturbation strength (Athanassoula et al. 2009a).

Pringle & Dobbs (2019) introduction:

- Spirals make up **one-third** (*this is a typo, two-thirds is correct*) of all massive galaxies
- They are the site of a majority of star formation
- Dobbs and Baba argue that in unbarred spirals spiral arms are either transient and recurrent due to self-gravity within steller and / or gaseous discs, or are the result of tidal interactions
- Supported by lack of relation between pitch angle and central galaxy concentration observed in GZ (Hart 2017)
- Shabani et al. (2018) only find evidence of a fixed density wave in a galaxy with a strong bar, however Yu and Ho (2018, 2019) do find correlations between pitch angle and galaxy morphology

TL;DR

Understanding spirals is very useful

Spiral tightness can be used as a measure of useful things

It's difficult to measure spiral tightness at scale

Bars cause predictions of tightness to change measurably

1 INTRODUCTION

Spiral structure is present in a majority of massive galaxies (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.

Many methodologies have been proposed and implemented to measure spiral arm properties, including visual inspection (i.e. Herrera-Endoqui et al. 2015), fourier analysis (i.e. Díaz-García et al. 2019), more complex automated identification (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 paper makes use of the photometric models obtained through the *Galaxy Builder* citizen science project [[**(Lingard et al, in prep)**]] which measure spiral brightness, thickness and tightness. 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 multilevel modelling to test for signs of spiral arm winding using the predictions derived by Pringle & Dobbs 2019 (uniformity of galaxy pitch angle in $\cot\ \phi$) and conclude that our sample of galaxies do not show winding of this form. We model galaxy pitch angle as a truncated normal distribution make use of the resulting pitch angles to examine the correlation between pitch angle and bulge size, implied by the Hubble sequence, and bar strength, implied by Manifold theory.

2 METHOD

2.1 Length-weighted spiral arms

A common method used to obtain a pitch angle of a galaxy is by identifying all

2.2 Bayesian modelling of spiral arms in *Galaxy Builder*

We fit a number of models, including various priors on the global pitch angle distribution. We make use of PYMC3[1], an open source probabilistic programming framework written in python.

2.2.1 Spiral arms from Galaxy Builder

Clustered, cleaned points in polar coordinates

$$r_{\rm arm} = \exp\left[\theta\tan(\phi_{\rm arm}) + c_{\rm arm}\right] + \sigma_r.$$

2.2.2 Cot-Uniform model

Assume the pitch angle of a galaxy's spiral arms are drawn from a Normal distribution, truncated between 0 and 90, centred on the galaxy's "pitch angle", $\phi_{\rm gal}$ with some measure of spread, $\sigma_{\rm gal}$, common to all galaxies:

$$\phi_{\rm arm} \sim \mathrm{TruncatedNormal}(\phi_{\rm gal}, \sigma_{\rm gal}, \min = 0, \max = 90). \quad (1)$$

We choose a prior on $\phi_{\rm gal}$ such that

$$\cot\left(\phi_{\rm gal}\right) \sim \mathrm{Uniform}(\min = 1, \max = 4), \quad (2)$$

and $\sigma_{\rm gal}$ of

$$\sigma_{\rm gal} \sim \mathrm{InverseGamma}(\alpha = 2,\ \beta = 20). \quad (3)$$

We model point

$$c_{\rm arm} \sim \mathrm{Cauchy}(\alpha = 0,\ \beta = 10). \quad (4)$$

$$\sigma_r \sim \mathrm{HalfCauchy}(\beta = 0.2) \quad (5)$$

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

2.2.3 Hierarchial Normal Model

Instead of the above model, assume

$$\phi_{\rm gal} \sim \mathrm{TruncatedNormal}(\mu_{\rm global}, \sigma_{\rm global}, \min = 0, \max = 90), \quad (6)$$

Hyperpriors used are as follows:

$$\mu_\phi \sim \mathrm{Uniform}(0, 90) \quad (7)$$

$$\sigma_{\rm global} \sim \mathrm{InverseGamma}(\alpha = 1,\ \beta = 10) \quad (8)$$

3 RESULTS

Results

4 SUMMARY AND CONCLUSIONS

Conclusions

5 ACKNOWLEDGEMENTS

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References

Binney J., Tremaine S., 1987, Galactic dynamics
Buta R. J., et al., 2015, VizieR Online Data Catalog, p. J/ApJS/217/32
Davis B., 2015, PhD thesis, University of Arkansas
Davis D. R., Hayes W. B., 2014, ApJ, 790, 87
Díaz-García S., Salo H., Knapen J. H., Herrera-Endoqui M., 2019, arXiv e-prints, p. arXiv:1908.04246
Dobbs C., Baba J., 2014, Publ. Astron. Soc. Australia, 31, e035
Elmegreen D. M., et al., 2011, ApJ, 737, 32
Hart R. E., et al., 2017, MNRAS, 472, 2263
Herrera-Endoqui M., Díaz-García S., Laurikainen E., Salo H., 2015, A&A, 582, A86
Julian W. H., Toomre A., 1966, ApJ, 146, 810
Kormendy J., Kennicutt Robert C. J., 2004, ARA&A, 42, 603
Lin C. C., Shu F. H., 1964, ApJ, 140, 646
Lintott C. J., et al., 2008, MNRAS, 389, 1179
Masters K. L., et al., 2019, MNRAS, 487, 1808
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, AJ, 139, 2097
Pringle J. E., Dobbs C. L., 2019, arXiv e-prints, p. arXiv:1909.10291

Romero-Gomez M., Athanassoula E., Antoja T., Figueras F., 2011, in Zapatero Osorio M. R., Gorgas J., Maíz Apellániz J., Pardo J. R., Gil de Paz A., eds, Highlights of Spanish Astrophysics VI. pp 548–548
Seigar M. S., Block D. L., Puerari I., Chorney N. E., James P. A., 2005, MNRAS, 359, 1065
Yu S.-Y., Ho L. C., 2019, ApJ, 871, 194
Appendix

This paper has been typeset from a TEX/LATEX file prepared by the author.