The Galaxy Zoo View of the Hubble Sequence

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** This publication has been made possible by the participation of more than 200,000 volunteers in the Galaxy Zoo project.
Their contributions are individually acknowledged at* `http://www.galaxyzoo.org/volunteers`.

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12 July 2017

ABSTRACT

We use classifications provided by citizen scientists in the Galaxy Zoo project to consider the current view of the Hubble Morphological Sequence for galaxies.

1 INTRODUCTION

The classification of objects into categories is a common starting point for many areas of science. Galaxy morphology (shapes and types) remains the most obvious starting point for this process in extragalactic astronomy. The morphology of a galaxy encodes information about its formation history and evolution through what it reveals about the orbits of the stars in the galaxy, and is known to correlate well with other physical properties (e.g. Roberts & Haynes 1994). Many galaxy classification schemes have been developed (see Buta 2011, and Sandage 2005 for recent reviews), but the one first presented by Hubble (1926) remains the basis of the most commonly used schemes. The "Hubble sequence" splits galaxies into "spiral" and "elliptical" types, and in addition orders the spiral galaxies in a sequence extending away from the ellipticals. By analogy with the terminology used for star classification at the time (and with no comment on evolutionary paths) Hubble dubbed these "early" and "late"-types, a terminology which has stuck. Here we explore an updated view of the Hubble Sequence obtained from visual classifications provided by 160,000 members of the public on $\sim$ 250,000 galaxies from the Sloan Digital Sky Survey (SDSS) Main Galaxy Sample (MGS; Strauss et al. 2002). These classification were made public as part of the SDSS DR10 (Ahn et al. 2013), and are described in detail in Willett et al. (2013)[1].

The original Hubble sequence of disc galaxies (Hubble 1926) labelled Sa-Sb-Sc (and extended to Sd by de Vaucouleurs 1959) was set up using three distinct criteria. These were based on (1) spiral arm appearance, split into (a) how tightly wound the spiral arms are and (b) how clear, or distinct the arms are, and (2) the prominence of the central
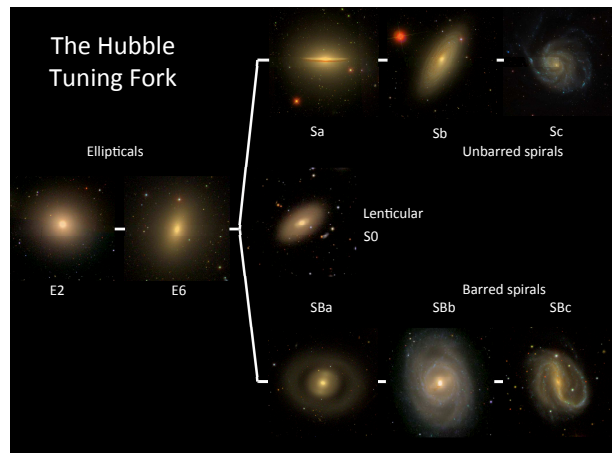

Figure 1. The Hubble Sequence illustrated by the examples suggested by Hubble (1926) with images from the SDSS. The galaxies are: : E0 NGC 3379; E5 NGC 4621; Sa - NGC 4594 ("The Sombrero"); Sb - NGC 2841; Sc - NGC 5447 ("The Pinwheel"); SBa - NGC 2859; SBb - NGC 3351 (or M95); SBc - 7479. We have also included an S0 (NGC 6278), not in Hubbles original scheme.)

bulge. Sa galaxies were described as having large bulges and tight, smooth (very distinct) arms, while in contrast a typical Sc was described as having a very small "inconspicuous" bulge and very loose patchy (indistinct) arms. In Hubble's language "normal" (S) and "barred" (SB) spirals had identical parallel sequences. These types are illustrated by Hubble's own preferred examples (except for the S0 which appeared later) in Figure 1.

Among experts in morphology (e.g. Sandage 2005, Buta 2012), there has been a consensus that for most spiral galaxies these three criteria result in consistent classification. Buta explains however, that "in conflicting cases, emphasis is usually placed on the appearance of the arms". Examples,
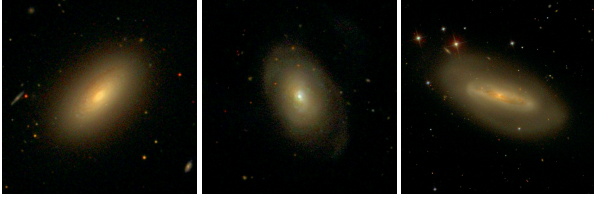
[1] Also see `data.galaxyzoo.org`

Figure 2. Examples of Sa galaxies with large, intermediate and small bulges from the classifications by Hogg, Roberts & Sandage (1993). The galaxies are (from left to right) large bulge Sa: NGC 2639; intermediate bulge Sa: NGC 3604; small bulge Sa: NGC 4293

particularly of Sa galaxies with small bulges are described in the literature (for example - Sandage 1961, Hogg, Roberts & Sandage 1993, Sandage & Bedke (1994), Jore, Broeils & Haynes 1996), and Sandage (2005) notes that the existence of "small bulge Sa galaxies" (as defined by their arm types) had been recognised even in Hubble's time. Buta (2012) also explains that SB galaxies with nuclear rings in small bulges may commonly have tightly wound arms, and therefore be classes as Sa.

However modern automatic galaxy classification has tended to conflate bulge size alone with spiral type (e.g. Lauikainen et al. 2007, Masters et al. 2010a need more), and automatic classification of galaxies into "early-" and "late-" types, referring to their location on the Hubble Sequence and based on B/T or some proxy for this through central concentration (e.g. Sersic index, cite) has become common. Indeed, Sandage (2005) says this is not new, claiming "the Hubble system for disk galaxies had its roots in an arrangement of spirals in a continuous sequence of decreasing bulge size and increasing presence of condensations over the face of the image that had been devised by Reynolds in 1920"

Also see Kormendy & Bender 2011 about the S0a, S0b, S0c sequence based on B/T alone. Elmegreen & Elmegreen 1987 - classes of spirals arms from flocculent to grand design.

Discuss pseudo-bulges versus classical bulges (e.g. Fisher & Drory)? Talk about ATLAS-3D results on early-types?

Obviously not yet a finished intro.

2   SAMPLE AND DATA

Todo: Description of Galaxy Zoo classifications pointing heavily to Willett et al. (2013).

Todo: Cite Davis & Hayes (2013) about the reliability of spiral arm tightness identification. Ask for their sample to make better plot that Figure 3, and also to calibrated A_{Winding} with pitch angle.

We select a low redshift volume limit for the main sample considered in this paper. Of the 243500 galaxies in the main spectroscopic sample of GZ2 (Willett et al. 2013), we selection $N = 22118$ which are found in the redshift range $0.01 < z < 0.035$, and which have an r-band absolute Petrosian magnitude of $M_r < -19.0$. We remove eight of these galaxies which have more than 50% of their classification votes for "star or artefact". Inspecting these objects they are typically genuine galaxies, but with corrupted images (e.g. under a satellite trail, or diffraction spike from a nearby
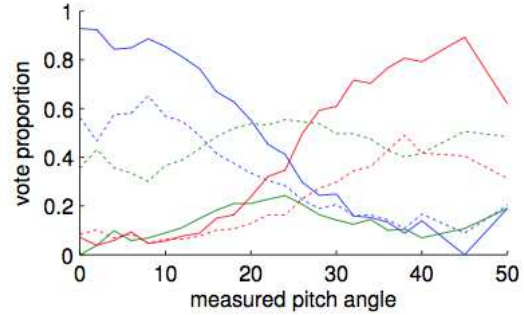

Figure 3. TODO: Figure to be added by Ross Hart.

bright star). However, they do not have useful GZ2 classification since so many people marked them as artefacts.

Define other properties considered below. E.g. colours, stellar masses.

3   FREQUENCY OF DIFFERENT GALAXY ZOO MORPHOLOGIES

We show in Figure **??**, the 22110 galaxies in our nearby volume limited sample on plots of p_{features} versus optical colour and magnitude (**TODO: these are not the best way to get colour from SDSS, and also currently using DR7 not DR10**). These plots illustrate the well known tendency for galaxies to have two main morphological classes, in the GZ2 language those with features and those without, which is similar to the classic "early-type" (meaning without spirals arms) and "late-type" (*i.e.* with spiral arms or other features). Note that the locus of "featured" galaxies span the entire colour range of this volume limited sample, while "smooth" galaxies are predominately red (although small samples of blue "smooth" galaxies do exist, like the blue ellitpicals of Schawinski et al. 2009).

"Features" in the Galaxy Zoo classification tree might include disturbed or irregular morphology or mergers. Users could identify these in GZ2 after indicating the that the galaxy showed "odd" features, and then indicating what they thought was odd. All users classifying a galaxy answered this question. We select for these by requiring at $p_{\mathrm{odd}} > 0.42$ and $N_{\mathrm{odd}} > 20$ (as recommended in W13), and then by requiring ($p_{\mathrm{irregular}} + p_{\mathrm{disturbed}} + p_{\mathrm{merger}} > 0.6$ (ie. aproximately 60% or more of the classifiers thought the galaxy was either irregular, disturbed or merging). As users could select only one of these options, using the sum is the most reliable way to identify all such objects. We find that $N = 1362$ (or 6% of the galaxies) meet these criteria, and of these 73 (0.3%) are found to have the largest vote for "merger", 411 (1.9%) for "disturbed" and 848 (3.8%) for "irregular". As these are a small fraction of the sample removing them makes little difference to the results below, never-the-less we remove them in what follows and proceed with $N = 20748$ "normal" galaxies.

Using thresholds of $p_{\mathrm{smooth}} > 0.8$ and $p_{\mathrm{features}} > 0.8$ to identify cleanly classified galaxies we find that 39% of galaxies in the sample are clearly "featured", and 13% are clearly "smooth", (the remaining 48% have only lower consensus

classifications). Relaxing this to find the majority answer for all galaxies in the sample we find 63% of the normal galaxies are best identified as "featured" and 37% as "smooth". Random examples of these two classes at $z = 0.03$ (the median redshift of the sample) and as a function of absolute magnitude are shown in Figure 4. In Willet et al. (2013) we recommend thresholds of $p_{\text{smooth}} > 0.469$ and $p_{\text{features}} > 0.430$, with a minimum classifier count of $N = 20$ to identify samples of galaxies in which classifications from further down the classification tree will be reliable. We find 39% of the sample ($N = 8063$) pass this smooth threshold and 46% ($N = 9610$ pass it for featured), leaving 15% ($N = 3075$ galaxies) with only basic classifications. Table 1 summarises these data, and in addition includes fractions for galaxies in subsets by their absolute magnitude which demonstrates the well known tendency for brighter (or more massive galaxies) to be more likely to be "smooth".

3.1 Visibility of Spiral Arms and Bars

Among the galaxies identified as "featured" and with enough classifications at the next questions, we find 16% ($N = 1498$) have values of $p_{\text{edgeon}} > 0.8$. This is consistent with the number of galaxies expected to be found with $i = 100 \deg$ in a completely randomly orientated sample of objects. The recommended threshold for "oblique" galaxies in which we can reliably identify disc features (e.g. bars, spirals; Willett et al. 2013) is $p_{\text{notedgeon}} > 0.715$ (and $N_{\text{notedgeon}} > 20$). We find that 71% of the "featured" galaxies fall into this group ($N = 6858$).

Of these oblique featured galaxies:

• 78% have clear spiral arms ($p_{\text{spiral}} > 0.5$) and just 7% are found to not have spiral arms to a high consensus ($p_{\text{spiral}} < 0.2$).

• 26% have obvious bars ($p_{\text{bar}} > 0.5$). This strong bar fraction is consistent with previous Galaxy Zoo based work (e.g. Masters et al. 2011, Masters et al. 2012), given the differences in sample selection. Weaker bars can be identified by $0.2 < p_{\text{bar}} < 0.5$ (e.g. Willett et al. 2013, Skibba et al. 2011). Another 22% of the oblique spirals have weak bars by this definition, leaving just over 50% of oblique spirals without any clear sign of a bar feature (*i.e.* $p_{\text{nobar}} > 0.8$) at the scales detectable by the SDSS images.

3.2 The Correlation of Bulge Size and Spiral Arm Tightness

The classic Hubble Sequence for spiral galaxies suggests that bulge size and spiral arm winding are highly correlated in most cases. In this section we investigate how tightly correlated bulge size and spiral arm tightness are found to be for galaxies with visible spiral arms in the Galaxy Zoo sample. We define a unique value of bulge size and spiral arm tightness from the GZ2 classifications as:

$$B_{\text{size}} = 0.0 \, p_{\text{nobulge}} + 0.2 p_{\text{just}} + 0.8 p_{\text{obvious}} + 1.0 \, p_{\text{dominant}} \quad (1)$$

and

$$A_{\text{Winding}} = 0.0 \, p_{\text{loose}} + 0.5 p_{\text{medium}} + 1.0 p_{\text{tight}} \quad (2)$$

such that these numbers increase from zero to one for either bulge sizes increasing, or arms getting tighter (note that I
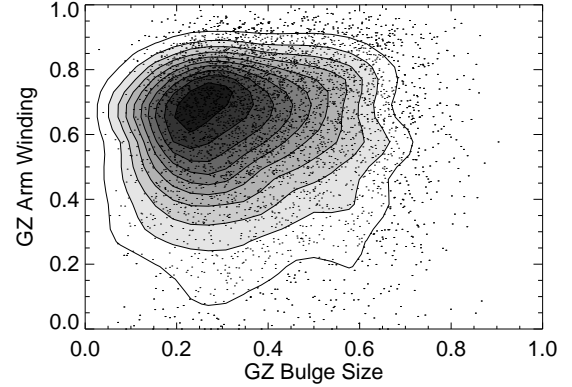
Figure 5. We show here the location of 4471 nearby spiral galaxies on a plot of bulge size versus degree of arm winding as indicated by Galaxy Zoo classifications. The contours indicate regions of high density of points, with points themselves shown at the lowest density.

inverted the arms index from what Casteels et al. in prep. is using in order than a "classic" Sa would have both values of 1.0, and a "classic Sc" would have both values of zero).

We can plot these values only for the subsample of Galaxy Zoo galaxies which have reliable classifications for both - *i.e.*. those galaxies with visible spiral arms. We select this sample (as advised by Willett et al. 2013) using cuts on the classification votes in answers earlier up the GZ2 tree, specifically $p_{\text{features}} > 0.430$, $p_{\text{notedgeon}} > 0.715$, $p_{\text{visiblearms}} > 0.619$, and in addition require the number of people answering the question about spiral arm windiness to be at least 20. This gives a sample of $N = 4471$ spiral galaxies in which we can ask how well bulge size correlates with spiral arm winding angles.

We plot the measure of bulge size versus arm windiness for this sample in Figure 5. In this volume limited ($M_r < -19$) sample of nearby ($z < 0.035$) galaxies we find no strong correlation between bulge size and arm windiness. There is a slight tendency spirals with large bulges to have only tightly wound spirals (*i.e.*. both A_{winding} and B_{size} are large), but for spirals with small bulges all values of spiral arm winding are found. This is consistent with the previous literature, in that Sa galaxies (as defined by arm winding) have been discussed with both large and small bulges, while Sc galaxies (as defined by loose arms) are only ever discussed with small bulges.

We have checked a closer sample ($0.01 < z < 0.25$), and also a sample of only the brightest spirals ($M_r < -21$) and find no significant difference in the result, except for a tendency for the brighter spirals to have larger bulges, as expected.

We also split the sample based on bar classification, finding that spirals with strong bars ($p_{\text{bar}} > 0.5$) were more likely to have larger bulges and less tightly wound spirals than those with no bars ($p_{\text{bar}} < 0.2$), but there remains no clear correlation in either subgroup (see Figure 6). The correlation between bars and spiral arm tightness is explored more in Casteels et al. in prep.

Table 1. Distribution of basic morphological class

Sample/defintion	$N_{\rm smooth}$	$\%_{\rm smooth}$	$N_{\rm featured}$	$\%_{\rm features}$
All ($N = 22118$)				
$p > 0.8$	2695	13	8053	39
$p > 0.5$	7859	38	13069	63
Majority vote	7751	37	12993	63
W13 criteria	8063	39	9610	46
Majority vote				
Faint $M_r > -20$ ($N = 10483$)	3744	39	5896	61
Mid 1 $-21 < M_r < -20$ ($N = 7609$)	2436	34	4802	66
Mid 2 $-22 < M_r < -21$ ($N = 3553$)	1318	38	2105	62
Bright $M_r < -22$ ($N = 465$)	253	57	190	43
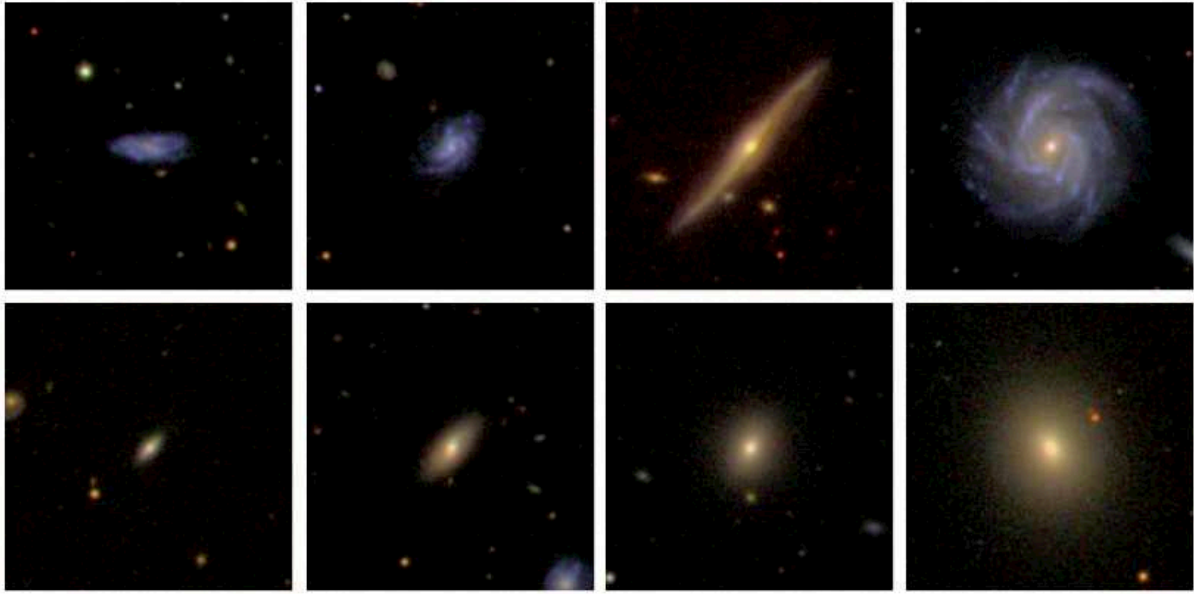
Figure 4. Randomly selected example images of galaxies classified as either "featured" (top row) or "smooth" (bottom row) from Galaxy Zoo as a function of r-band absolute magnitude (brighter to the right). All galaxies have a redshift $z = 0.03$ and are shown at the same angular scale. Images are gri composites from SDSS with a scale of $1.7'$ square. **Add an intermediate or uncertain row**.
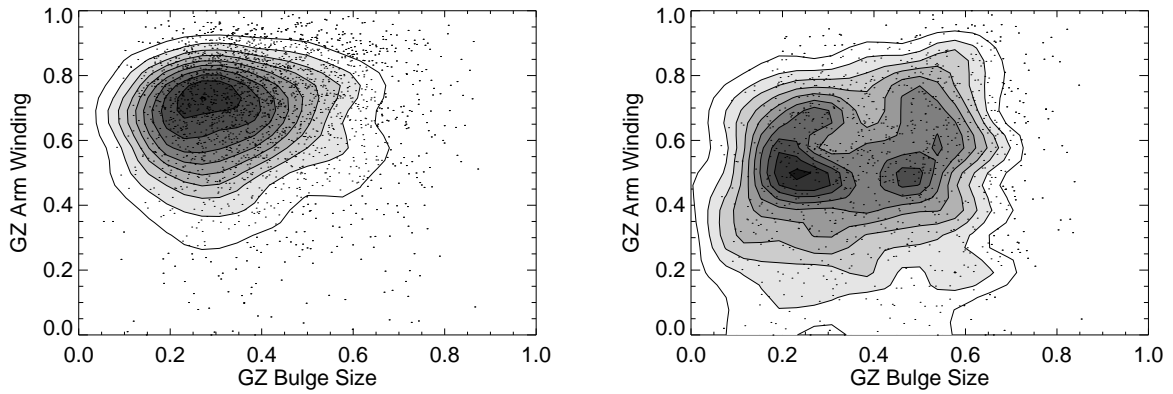
Figure 6. As Figure 5 but for subsamples of the oblique spirals split by bar classification. Left panel: galaxies with $p_{\rm bar} < 0.2$; right panel: galaxies with $p_{\rm bar} > 0.5$
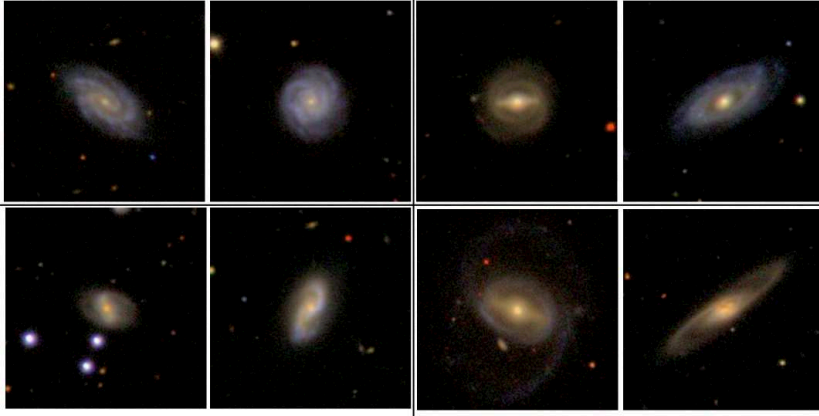
Figure 7. Example images of galaxies at $z = 0.03$ and $M_r \sim -21$ with both loose and tightly would spiral arms (lower and upper rows respectively) and small or large bulges (left and right columns respectively). In each case galaxies are shown with either strong bars, or no bar. Images are gri composites from SDSS with a scale of $1.7'$ square.

Figure 7 shows examples of galaxies at $z = 0.03$ from the four quadrants of Figure 5 with strong bars ($p_{\mathrm{bar}} > 0.5$) or no bar ($p_{\mathrm{bar}} < 0.2$)

4 CONSTRUCTING A HUBBLE SEQUENCE FROM GALAXY ZOO

In W13 we discussed how best to assigned T-types to Galaxy Zoo galaxies from the classification votes in GZ2. Both the votes for tightness of spirals arms, and bulge size were considered. In that work we concluded that modern expert visual classification of spiral Hubble types (based on comparison with either Nair & Abraham 2010, or Baillard et al. 2013) was primarily based on bulge size, regardless of the tightness of spiral arms, with the best fitting relation (based on symbolic regression) being found to be

$$T = 4.63 + 4.17\, p_{\mathrm{nobulge}} - 2.27\, p_{\mathrm{obvious}} - 8.38\, p_{\mathrm{dominant}} \quad (3)$$

We point the interested reader to the lower panel of Figure 19 from W13 which compares the predicted T-types from the above equation to the T-types assigned by Nair & Abraham (2010). As was point out in W13, this, and other comparisons with recent expert visual classifications (e.g. the EFIGI sample of Baillard et al. 2011) demonstrates that the modern spiral Hubble sequence is defined by bulge size alone, with little reference to spiral arm tightness.

5 SUMMARY

We present the morphological make-up of a sample of bright ($M_r < -19$), nearby ($0.01 < z < 0.035$) galaxies with classifications from the Galaxy Zoo project. We find that 94% of these galaxies show the "normal" morphologies found on the classic Hubble sequence, with 6% classified as irregular, disturbed or merging.

Among the "normal" galaxies we find the typical correlation between magnitude, colour and morphology, such that "smooth" (or "early-type") galaxies are more common in the luminous red part of the diagram, where they make up 50% of the galaxies. Galaxies showing "features" (or

"late-types") are found at all colours and magnitudes, and especially dominate the less luminous, bluer parts of the sample where they make up to two-third of the galaxies.

We find that the fraction of edge-on spirals is as expected for a sample of randomly orientated discs, and define a sample of "oblique" spirals which are face-on enough for disc features to be identified. Among these 26% have strong bars, and 50% have no bars. The majority have clearly identified spirals (78%), with only 7% with a clear consensus for lacking spiral arms. These are likely S0 types with rings or bars.

Among the spiral galaxies, we find little or no correlation between spiral arm winding tightness and bulge size. Although spirals with large bulges are found to typically have tightly wound arms, those with small bulges are found with a much wider range of spiral arm pitch angle. We find that the presence of a strong bar tends to correspond to more loosely wound arms and larger bulges.

We demonstrate that modern expert visual classification has moved away from the classic "Hubble sequence" which prioritised spiral arm angles over bulge size (leading to discussion of small bulged Sa galaxies) and is now predominately an ordered on central bulge size. Something about how this makes sense for a sequence on star formation since bulge size correlates so well with star formation in discs...?

Some interpretation of what the degree of arm winding actually means.

REFERENCES

Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2013, arXiv:1307.7735

Baillard, A., Bertin, E., de Lapparent, V., et al. 2011, A&A, 532, A74

Buta, R. J., Corwin, H. G., & Odewahn, S. C. 2007, The de Vaucouleurs Altlas of Galaxies, edited by Ronald J. Buta, Harold G. Corwin and Stephen C. Odewahn. ISBN-13 978-521-82048-6 (HB). Published by Cambridge University Press, Cambridge, UK, 2007.

Hubble, E., 1926, ApJ, 64, 321

Nair, P. B., & Abraham, R. G. 2010a, ApJS, 186, 427 (NA10)

Sandage, A., 2005,ARA&A, 43, 581

Strateva, I., et al. 2001, AJ, 122, 1861

Strauss, M. A., Weinberg, D. H., Lupton, R. H., et al. 2002, AJ, 124, 1810

de Vaucouleurs, G. 1959, Handbuch der Physik, 53, 275

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies, Springer, New York, NY (USA).