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The Galaxy Zoo View of the Hubble Sequence

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ABSTRACT

We use classifications provided by citizen scientists in the Galaxy Zoo project to give a new perspective on the Hubble Morphological Sequence for galaxies. We find that the modern use age of the Hubble spiral classifications (Sa–Sd) is based almost entirely on bulge size, with no reference to spiral arm winding, or "degree of concentration" of the arms, and that furthermore in a volume limited sample of galaxies with both automated and crowdsourced measures of bulge size and spiral arm tightness there is no correlation between the two.

1 INTRODUCTION

The classification of objects into categories is a common technique across many areas of science. Galaxy morphology (*i.e.* the shapes and features seen in images of galaxies) remains the most common starting point for this process in extragalactic astronomy.

Many galaxy classification schemes have been developed (see Buta 2012, and Sandage 2005 for recent reviews, older reviews which will be of particular interest for historical notes include de Vaucouleurs 1959, Sandage 1975, Buta 1992, Buta, Corwin & Odewahan 2007). However, the scheme first presented by Hubble (1926, 1936) remains the basis of the most commonly used classifications (e.g. as used in revised and expanded versions in *The Hubble Atlas* by Sandage (1961); or in the Third Reference Catalogue of Bright Galaxies, RC3 by de Vaucouleur (1991)).

The basic "Hubble sequence" splits galaxies into "spiral" and "elliptical" types, labelling ellipticals by their degree of elongation (from E0 being completely round, to E7 galaxies, with an ellipticity of 0.7). The spiral galaxies or then ordered in a sequence extending away from the ellipticals,, split into two arms by the presence or absence of a galactic bar (see Figure 1). Hubble predicted the existance of an intermediate type (lenticulars, or S0s), but no examples were known at the time (Buta 2012). By analogy with the terminology used for star classification at the time (and explicitly making the point that this was not a comment on evolutionary paths[1]) Hubble dubbed the spiral types (a) "early", (b) "intermediate" and (c) "late"-type spirals. This

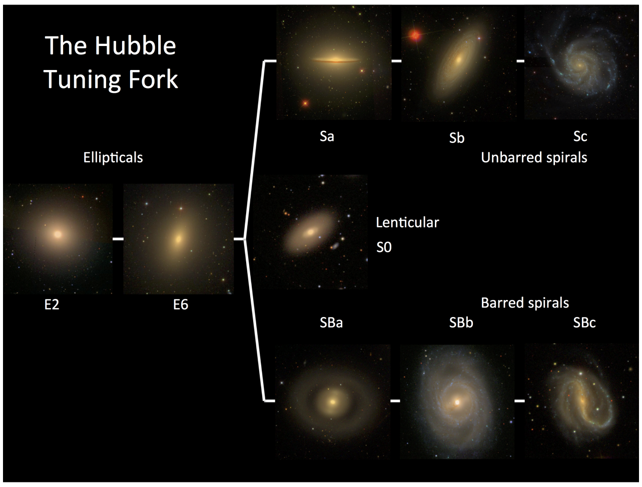

Figure 1. The Hubble Sequence illustrated by the examples suggested by Hubble (1926) with images from the SDSS. The galaxies are: : E0 NGC 3379; E5 NGC 4621; Sa - NGC 4594 ("The Sombrero"); Sb - NGC 2841; Sc - NGC 5447 ("The Pinwheel"); SBa - NGC 2859; SBb - NGC 3351 (or M95); SBc - 7479. We have also included an S0 (NGC 6278), not in Hubbles original scheme as no examples were known at the time.)

[1] see the Footnote I on pg 326 of Hubble (1926)

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appears to be the basis of sometimes confusing terminology which has stuck, with astronomers now more commonly using "early-type galaxies" to refer to ellitptical and lenticular galaxies (and often, but not always, excluding the "early-type" or Sa spirals), while "late-type" is commonly used to refer to spiral galaxies.

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 remarkably well with other physical properties (e.g. Roberts & Haynes 1994). These correlations, long with the ease of automated measurement of colour or spectral type, have resulted in a recent trend for classification on the basis of these properties rather than morphology per se (e.g. some examples). Indeed the strength of the correlation has led some to authors to claim that the correspondance between colour and morphology is so good that they are equivalent (see Faber et al. 2007). Meanwhile the size of modern data sets (e.g. the Main Galaxy Sample of the Sloan Digital Sky Survey, SDSS, Strauss et al. 2002) made the traditional techniques of morphological classification by small numbers of experts implausible. This was solved making use of the technique of crowdsourcing by the Galaxy Zoo project (Lintott et al. 2008, 2011). One of the first results from the Galaxy Zoo morphological classifications was to demonstrate on a firm statistical basis that colour and morphology are not equivalent for all galaxies (Bamford et al. 2009, Schawinski et al. 2009, Masters et al. 2010) and that morphology provides additional information on galaxy populations useful to understand the processes of galaxy evolution.

In this article 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 classifications are described in detail in Willett et al. (2013), and were made public there [2] (as well as being a Value Added Catalogue available in SDSS DR10 (Ahn et al. 2013) onwards). The basic division into spiral–elliptical (or early–late-type) galaxies has been discussed at length (e.g. Willett et al. 2013). In this article we particularly focus on the spiral sequence, and investigate if the traditional criteria for the ordering along the sequence fit in with the picture revealed by Galaxy Zoo morphologies.

The original Hubble sequence of Sa-Sb-Sc spiral galaxies (Hubble 1926; 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 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 the example galaxies given in Hubble (1926; except for the S0 classification which first 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 (2012) explains however, that "in conflicting cases, emphasis is usually placed on the appearance of the arms". Examples of conflicting cases, particularly of galaxies with tightly wound spirals and small bulges are found in the literature (for example - Sandage 1961, Hogg, Roberts & Sandage 1993, Sandage & Bedke (1994), Jore, Broeils & Haynes 1996, see Figure 2). 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.

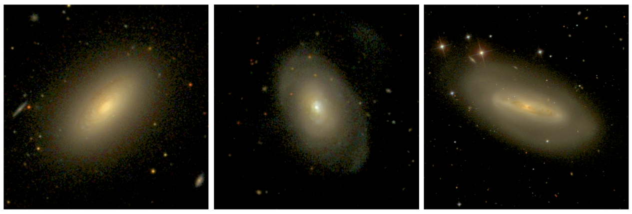

Figure 2. Examples of Sa galaxies with large, intermediate and small bulges from the classifications by Hogg, Roberts & Sandage (1993). The galaxies are (from left to right) large bulge Sa: NGC 2639; intermediate bulge Sa: NGC 3604; small bulge Sa: NGC 4293

However modern automatic galaxy classification has tended to conflate bulge size alone with spiral type (e.g. Laurikainen 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"

Kormendy & Bender (2012) present an update to a parallel lenticular classification scheme S0a-S0b-S0c first presented by van den Bergh (1976) and explicitly based on B/T (since S0s by definition have no spiral arms). They extensively discuss S0c galaxies.

The diversity of spiral arms observed in galaxies is not perfectly captures by the Sa-Sb-Sc descriptions. As discussed at length by Buta (2012), the number of arms (commonly denoted m), "character" of the arms (e.g. "grand-design" or "flocculent") and the sense of the winding of the arms relative to the galaxy rotation are all additional dimensions which can be used for classification. Buta (2012) notes that most low m spirals are grand design, and goes on to discuss how spiral arm "character" is thought to link to typical formation mechanism (with grand design spirals linked to density wave mechanisms, and flocculent spirals suggested to come from sheared self-propogating star formation regions).

Need something about what the pitch angle of spiral arms tells us physically and why we should care if it correlates with bulge size.

From Hart et al 2016 "These properties are weakly related (Kennicutt 1981; Seigar & James 1998): spiral arm

[2] see data.galaxyzoo.org

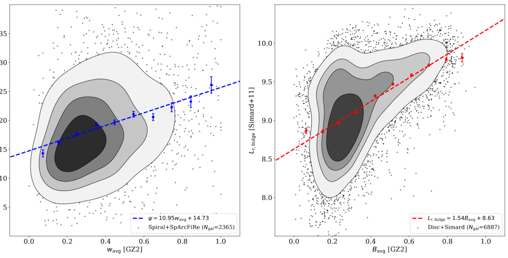

Figure 3. Figure by Ross Hart showing comparison between SpaRCFIRE and Galaxy Zoo.

tightness has been shown to be more strongly correlated with bulge total mass (Seigar et al. 2008; Berrier et al. 2013; Davis et al. 2015), rather than bulge-to-disk ratio." "In particular, the pitch angle of spiral arms is related to both the star-formation rate in spiral galaxies (Seigar 2005), and the central mass concentration of the spiral galaxies (Seigar et al. 2006, 2014)."

From Dobbs & Baba 2015 'Kennicutt (1981) indicates that the pitch angle correlates only in an aver- age sense with galaxy type, and there is quite substan- tial spread.'

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. Also cite Hart et al. papers.

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 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 $p_{\rm features}$ 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 ellitpticals 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 $p_{\rm odd} > 0.42$ and $N_{\rm odd} > 20$ (as recommended in W13), and then by requiring ($p_{\rm irregular} + p_{\rm disturbed} + p_{\rm merger} > 0.6$ (ie. approximately 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 $p_{\rm smooth} > 0.8$ and $p_{\rm features} > 0.8$ 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. 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 $p_{\rm edgeon} > 0.8$. This is consistent with the number of galaxies expected to be found with $i = 100\,\text{deg}$ 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 $p_{\rm notedgeon} > 0.715$ (and $N_{\rm notedgeon} > 20$). We find that 71% of the "featured" galaxies fall into this group ($N = 6858$).

Of these oblique featured galaxies:

- 78% have clear spiral arms ($p_{\rm spiral} > 0.5$) and just 7% are found to not have spiral arms to a high consensus ($p_{\rm spiral} < 0.2$).
- 26% have obvious bars ($p_{\rm bar} > 0.5$). 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 $0.2 < p_{\rm bar} < 0.5$ (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

Table 1. Distribution of basic morphological class. TODO: update numbers for final sample.

Sample/defintion	$N_{\rm smooth}$	$\%_{\rm smooth}$	$N_{\rm featured}$	$\%_{\rm features}$
All ($N = 22118$)				
$p > 0.8$	2695	13	8053	39
Majority vote	7751	37	12993	63
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

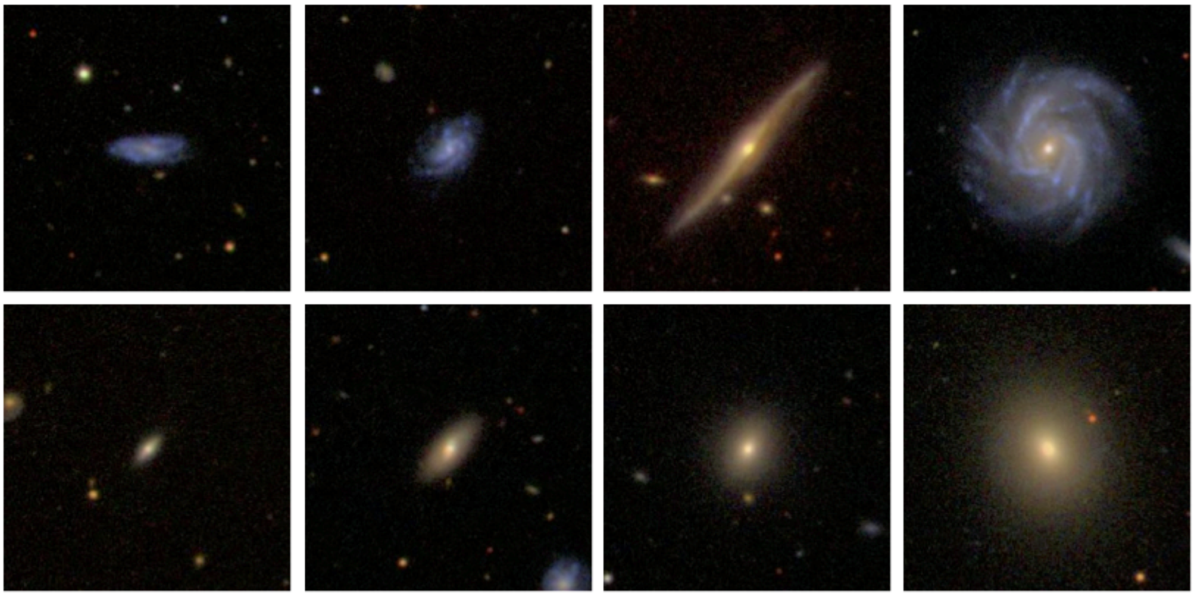

Figure 4. Randomly selected example images of galaxies classified as either "featured" (top row) or "smooth" (bottom row) from Galaxy Zoo as a function of r-band absolute magnitude (brighter to the right). All galaxies have a redshift $z = 0.03$ and are shown at the same angular scale. Images are gri composites from SDSS with a scale of $1.7'$square.

without any clear sign of a bar feature (*i.e.* $p_{\rm nobar} > 0.8$) 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:

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

and

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

such that these numbers increase from zero to one for either bulge sizes increasing, or arms getting tighter (note that I 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 $p_{\rm features} > 0.430$, $p_{\rm notedgeon} > 0.715$, $p_{\rm visiblearms} > 0.619$, 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 $A_{\rm winding}$ and $B_{\rm size}$ 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

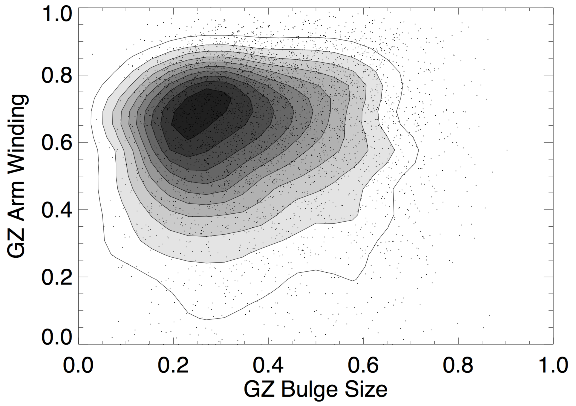

Figure 5. We show here the location of 4471 nearby spiral galaxies on a plot of bulge size versus degree of arm winding as indicated by Galaxy Zoo classifications. The contours indicate regions of high density of points, with points themselves shown at the lowest density.

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 ($p_{\rm bar} > 0.5$) were more likely to have larger bulges and less tightly wound spirals than those with no bars ($p_{\rm bar} < 0.2$), 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.

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

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

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

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.

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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.

Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

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