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Galaxy Zoo: Little Correlation Between Spiral Bulge Size and Arm Windiness – Evidence that Most Spirals are Winding Up*

Karen L. Masters[1,2], Chris Lintott[3], Ross E. Hart[4], Sandor J. Kruk[3], Rebecca J. Smethurst[4], Kevin V. Casteels[5], Bill Keel[6], Kyle Willett[7,8]
[1] Haverford College, Department of Physics and Astronomy, 370 Lancaster Avenue, Haverford, Pennsylvania 19041, USA
[2] Institute for Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, UK
[3] Oxford Astrophysics, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
[4] Centre for Astronomy & Particle Theory, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[5] Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada
[6] Department of Physics & Astronomy, 206 Gallalee Hall, 514 University Blvd., University of Alabama, Tuscaloosa, AL 35487-0234, USA
[7] Amazon (?)
[8] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

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E-mail: klmasters@haverford.edu

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ABSTRACT

We use classifications provided by citizen scientists in the Galaxy Zoo project to investigate the correlation between bulge size and arm windiness in spiral galaxies. While the traditional spiral sequence is said to be based on a combination of bulge size and arm winding, and is noted to favour arm winding where disagreement exists, we demonstrate that in the modern useage, the spiral classifications Sa–Sd are based almost entirely on bulge size, with no reference to spiral arm windiness (or "degree of concentration" of the arms). Furthermore in a volume limited sample of galaxies with both automated and crowdsourced measures of bulge size and spiral arm tightness there is no strong correlation between the two traditional measures of spiral galaxy type. Galaxies with small bulges are found to exhibit a wide range of spiral arm winding, while those with large bulges are found only with tightly wound arms. This is interpreted as revealing how the winding speed of spiral arms varies with central concentration; as such it may provide evidence that the majority of spiral arms are not static density waves, but rather wind-up over time. We further find that galaxies with strong bars are likely to both have larger bulges, but also are found with more loosely wound arms for the same bulge size as an unbarred spiral - suggesting that the presence of a bar slows the winding speed of spirals.

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) was the most obvious starting point for this process in extragalactic astronomy. As a result many galaxy classification schemes have been developed (see Buta 2013, and Sandage 2005[1] for recent reviews). The scheme first laid out 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*, or RC3 by de Vaucouleurs et al. 1991).

As a reminder, 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 ellipticals the most "cigar-like"). The spiral galaxies are ordered in a sequence extending away from the ellipticals, split into two arms by the presence or absence of a galactic bar. Hubble correctly predicted the existence of

[1] In which readers may also enjoy instructions for simulating the structures seen in galaxies using cream in coffee or frozen butter sticks in milk.

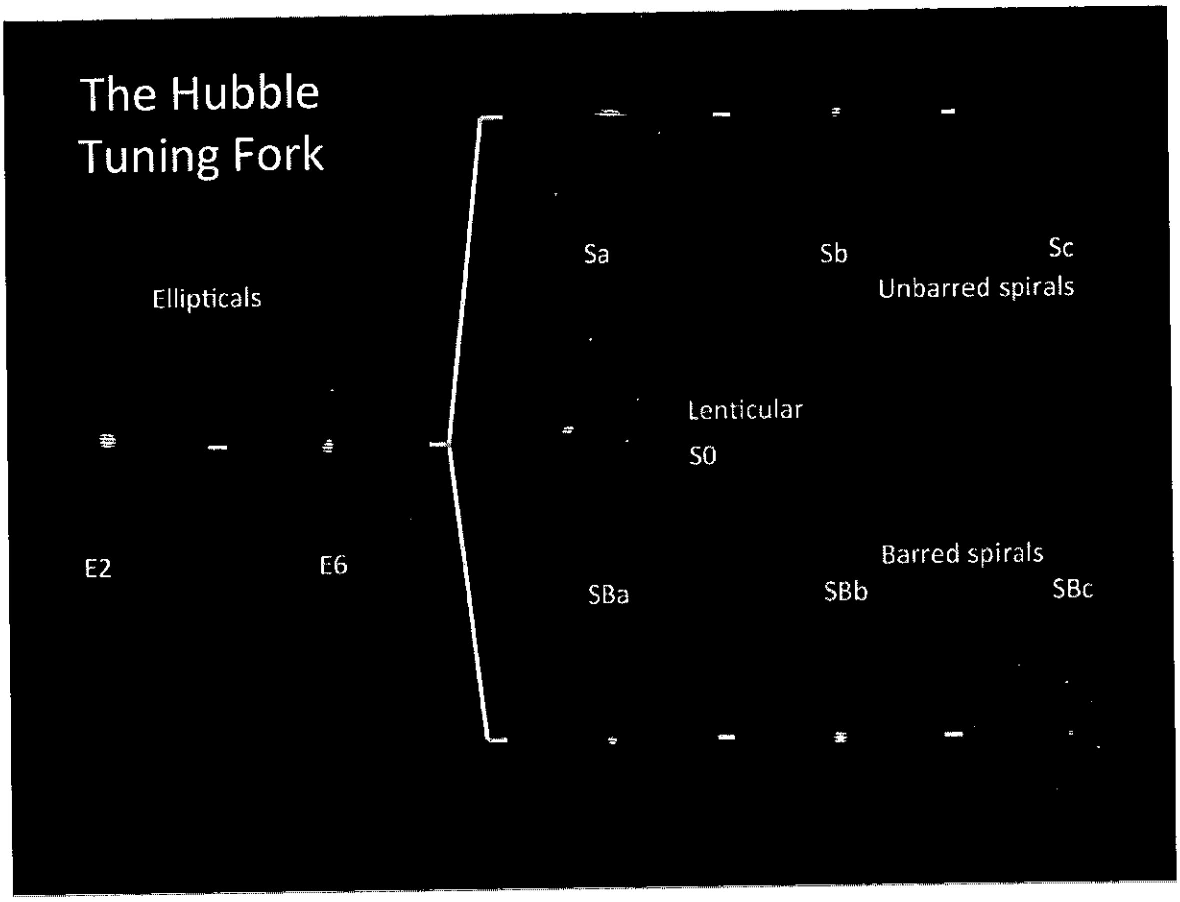

Figure 1. The Hubble Sequence illustrated by the examples suggested by Hubble (1926) with images from the SDSS. The galaxies are: E0 – NGC 3379; E5 – NGC 4621; Sa – NGC 4594 (The Sombrero); Sb – NGC 2841; Sc – NGC 5447 (The Pinwheel); SBa – NGC 2859; SBb – NGC 3351 (or M95); SBc – NCG 7479. We have also included an S0 (NGC 6278); only theorised in Hubble's original scheme as no examples were known at the time.

an intermediate type (lenticulars, or S0s), even through no examples were known at the time (Buta 2013).

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 in Figure 1 by the example galaxies given in Hubble (1926).

By analogy with the terminology used for stellar classification (and explicitly making the point that this was not a comment on evolutionary paths[2]), Hubble dubbed the spiral types (a) "early", (b) "intermediate" and (c) "late"-type. This was the basis of sometimes confusing terminology which has stuck, with astronomers now more commonly using "early-type galaxies" (ETG) to refer to ellitptical and lenticular galaxies (often, but not always, excluding the "early-type" or Sa spirals, e.g. as used by the ATLAS-3D team; Cappellari et al. 2011a,b, and also Stanford et al. (1998); while "late-type" is commonly used to refer to any spiral galaxies (but sometimes excludes Sa spirals, e.g. Strateva et al. 2001).

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; Kennicutt 1998; Strateva et al. 2001). These correlations, along with the ease of automated measurement of colour or spectral type, have resulted in a tendency for astronomers to make use of classification on the basis of these properties rather than morphology per se (e.g. to select just a few examples[3]: Bell et al. 2004; Weinmann et al. 2006; van den Bosch et al. 2008; Cooper et al. 2010; Zehavi et al. 2011). Indeed the strength of the correlation has led some to authors to claim that the correspondence between colour and morphology is so good that that clas-

[2] See the Footnote I on pg 326 of Hubble (1926), and also Baldry (2008)

[3] With thanks to the participants of the Galaxy Zoo Literature Search for finding many of these .

sification by colour alone can be used to replace morphology (e.g. Park & Choi 2005; Faber et al. 2007; Ascasibar & Sánchez Almeida 2011), or to simply conflate the two (e.g. Tal & van Dokkum 2011; but see van den Bergh 2007 for a contrary view). 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 problem 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 (i.e. as first presented in Bamford et al. 2009; Schawinski et al. 2009; Masters et al. 2010), making it clear that morphology provides complementary information to stellar populations (traced by either photometry or spectra) to understand the population of galaxies in our Universe.

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), available to download from `data.galaxyzoo.org` (as well as being included in SkyServer.org as an SDSS Value Added Catalogue from DR10 (Ahn et al. 2014 onwards). The basic division into spiral–elliptical (or featured–smooth in the language of Galaxy Zoo, which corresponds to what many astronomers mean by early- and late-type) galaxies has been discussed at length (Willett et al. 2013, e.g.). In this article we particularly focus on the spiral (or more precisely "featured, but not irregular") sequence, and investigate if the traditional criteria for the ordering of spiral galaxies along this sequence fit in with the picture revealed by Galaxy Zoo morphologies.

Among experts in morphology (Sandage 2005; Buta 2013, e.g.), there has been a consensus that for most spiral galaxies the traditional criteria involving both spiral arm appearance and bulge size result in consistent classification. Buta (2013) 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 (examples are given from Hogg et al. 1993 in Figure 2; also see Sandage 1961; Sandage & Bedke 1994; Jore et al. 1996), and the existence of "small bulge Sa galaxies" (as defined by their arm types) had been recognised even in Hubble's time (according to Sandage 2005. Buta (2013) 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 (Goto et al. 2003; Laurikainen et al. 2007; Masters et al. 2010, e.g.), and automatic classification of galaxies into "early-" and "late-" types, referring to their location on the Hubble Sequence and based on bulge-total luminosity ratio (B/T) or some proxy for this through a measure of central concentration, or light profile shape (e.g. Sersic index, as reviewed by Graham & Driver 2005[4]) has become common (van der Wel et al. 2011, e.g.). 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 (1920)."

use single quotes inside the double quotes

It is clear that early S0 classification also included S0s with bulges of different sizes (S0a-S0c; Spitzer & Baade 1951; van den Bergh 1976, a classification recently promoted by ATLAS-3D in their morphololology "comb" which includes parallel sequences of star forming and passive (or aneamic) spirals, and a ETG fast-rotator bulge size sequence similar to the S0 sequence (Cappellari et al. 2011b), as well as by Kormendy & Bender (2012) in their parallel lenticular classification scheme explicitly based on B/T.

→ no end to parantheses!

It has also been understood for some time that the diversity of spiral arms observed in galaxies is not perfectly captured by the Sa-Sb-Sc spiral arm descriptors. As discussed at length by Buta (2013), 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 (also see Elmegreen & Elmegreen 1987; Ann & Lee 2013). Buta (2013) 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-propagating star formation regions).

Finally we note that bulges have also been revealed to have diversity – with a distinction needing to be made between "classical" bulges (those with an $R^{1/4}$ profile, or Sersic $n = 4$) and "pseudo" or "discy" bulges (having an exponential profile). It is observed that the stellar populations of these two types of bulges are noticeably different (Fisher & Drory 2008), and it is generally assumed that the former is formed in galaxy merging, while the latter could be grown via secular evolution driving radial flows.

In this paper we will make use of Galaxy Zoo classifications, which provide a quantitative visual description of structures seen in local galaxies, capturing the typical range of descriptions used to construct the traditional Hubble sequence, but are not tied to any specific classification scheme (e.g. a spiral galaxy might easilly be described has having tightly wound spiral arms and a large bulge, if this is how it looks). We'll review these classifications in Section 2, give basic demographics of the local sample in Section 3, and discuss how to use them to construct a traditional Hubble sequence, along with the implications of trends of various visible structures in Section 4. We conclude with a Summary section. Where distances are needed a value of $H_0 = 70$km/s/Mpc is used **Sandor, Becky, Ross - is this true in the plots you made?.**

→ plots I made didn't incorporate H_0 !

[4] It is noted in Sandage (2005) that this effort to classify galaxies on the basis of the concentration of their light alone was first begun by Shapley (1927).

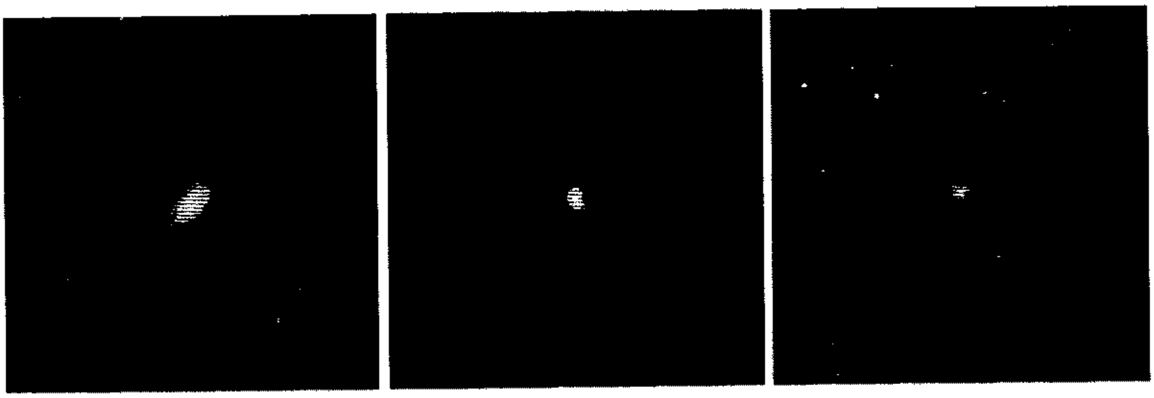

Figure 2. Examples of Sa galaxies with large, intermediate and small bulges from the classifications by Hogg et al. (1993). The galaxies are (from left to right) large bulge Sa: NGC 2639; intermediate bulge Sa: **Can't Find in paper: check NGC 3604**; small bulge Sa: NGC 4293

2 SAMPLE AND DATA

The first two phases of Galaxy Zoo (which ran from July 2007-April 2010[5]) were entirely based on imaging from the Legacy Survey of the Sloan Digital Sky Survey (SDSS; York et al. 2000). In this paper we make use exclusively of classifications from the second phase of Galaxy Zoo (or GZ2; Willett et al. 2013) In total, almost 300,000 images of galaxies were shown in GZ2, selected to represent the largest and brightest galaxies observed by SDSS. For full details of the sample selection see (Willett et al. 2013), but in brief GZ2 made use of the SDSS DR7 imaging reduction (Abazajian et al. 2009) and selected galaxies with $m_r < 17.0$, $r_r > 3''$ and $0.0005 < z < 0.25$ (or with no measured redshift). Image cutouts were generated as gri colour composites centred on each galaxy with a size $8.48r_{90}'' \times 8.48r_{90}''$, where r_{90} is the radius containing 90% of the r-band Petrosian aperture flux).

Visual classifications for GZ2 were collected via a web interface, which presented volunteers with the colour cutout, and a selection of simple questions about the object shown. Following Willett et al. (2013, hereafter W13) we define a *classification* as the sum of all information collected about a galaxy by a single user. These *classifications* are made up of answers to a series of *tasks* presented in a decision tree. A flow chart of this tree is presented as Figure 1 in W13, and for the convenience of the reader we reproduce Table 2 of W13 which summarizes all possible *tasks* and answers in our Table 1.

W13 describes the process by which user responses are weighted and combined to provide vote fractions for each answer to each task for each galaxy in GZ2. We will refer to vote fractions as $p_{\rm xxx}$, where "xxx" will describe the answer of interest. For example $p_{\rm features}$ will refer to the fraction of users answering *task* 01 by indicating they could see "features or a disc" in the galaxy. W13 also describes a process of correcting for classification bias, caused primarilly by galaxies at larger redshift appearing dimmer and at coarser physical resolution than if viewed at lower redshift. Hart et al. (2016, hereafter H16) investigate this classification bias further, especially with regard to the visibility of spiral arms in GZ2, and update the redshift debiasing method to provide an updated set of debiased classifications from GZ2. In this paper we make use of the debiased classifications from H16, and when we use the terminology $p_{\rm xxx}$ we specifically refer to the debiased vote fraction using the H16 debiasing.

We select a low redshift volume limited sample, which is similar to the sample selection of (Hart et al. 2016, 2017a). This is motivated by the desire to have galaxies with sufficient angular resolution that spiral arm features can be clearly identified and limit the impact of redshift debiasing. Of the 239,695 galaxies in GZ2 which have spectroscopic redshifts in DR7 (Abazajian et al. 2009; Strauss et al. 2002), we select $N = 22,045$ galaxies 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 six 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.

"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 $N = 1785$ (or 8% of the galaxies) meet these criteria, and of these 445 (2%) are found to have the largest vote for "merger", 137 (0.6%) for "disturbed" and 1203 (5.4%) 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 $N = 20,254$ "normal" (or not "odd") galaxies.

We make use of Petrosian aperture photometry from

[5] GZ1 is archived at `http://zoo1.galaxyzoo.org`, and GZ2 at `http://zoo2.galaxyzoo.org`

Table 1. The GZ2 decision tree, comprising 11 tasks and 37 responses. The 'Task' number is an abbreviation only and does *not* necessarily represent the order of the task within the decision tree. The text in 'Question' and 'Responses' are displayed to volunteers during classification. 'Next' gives the subsequent task for the chosen response.

Task	Question	Responses	Next
01	*Is the galaxy simply smooth and rounded, with no sign of a disk?*	smooth	07
		features or disk	02
		star or artifact	**end**
02	*Could this be a disk viewed edge-on?*	yes	09
		no	03
03	*Is there a sign of a bar feature through the centre of the galaxy?*	yes	04
		no	04
04	*Is there any sign of a spiral arm pattern?*	yes	10
		no	05
05	*How prominent is the central bulge, compared with the rest of the galaxy?*	no bulge	06
		just noticeable	06
		obvious	06
		dominant	06
06	*Is there anything odd?*	yes	08
		no	**end**
07	*How rounded is it?*	completely round	06
		in between	06
		cigar-shaped	06
08	*Is the odd feature a ring, or is the galaxy disturbed or irregular?*	ring	**end**
		lens or arc	**end**
		disturbed	**end**
		irregular	**end**
		other	**end**
		merger	**end**
		dust lane	**end**
09	*Does the galaxy have a bulge at its centre? If so, what shape?*	rounded	06
		boxy	06
		no bulge	06
10	*How tightly wound do the spiral arms appear?*	tight	11
		medium	11
		loose	11
11	*How many spiral arms are there?*	1	05
		2	05
		3	05
		4	05
		more than four	05
		can't tell	05

SDSS in the *urgriz* bands. These are k-corrected as described in Bamford et al. (2009). Stellar masses are estimated from the colour-dependent mass-light ratio calibration presented by Baldry et al. (2008). Where a value for H_0 is required we use ? **CHECK THIS!!!!.**

3 MORPHOLOGY OF LOCAL GALAXIES

Many published works with Galaxy Zoo classifications use thresholds of $p_{\rm smooth} > 0.8$ and $p_{\rm features} > 0.8$ to identify cleanly classified galaxies. With these cuts, we find that 28% of galaxies in the sample are clearly "featured", and 24% are clearly "smooth", (the remaining 48% have only lower consensus classifications; this can include genuinely intermediate type galaxies, but also any galaxy where volunteers did not have clear consensus on morphology for reasons to do with the imaging rather than the galaxy itself). While galaxies with $p_{\rm smooth}$ and $p_{\rm features} < 0.8$ are sometimes described as "uncertain" and removed from studies (Schawinski et al. 2014, e.g.), information is contained in the lower agreement classifications. Relaxing the thresholds to use the majority answer for all galaxies in the sample allows every galaxy to be put into some category, although with increased uncertainty near the threshold. With this cut (which is similar, but not identical to $p_{\rm smooth} > 0.5$ or $p_{\rm features} > 0.5$, as well as the thresholds for classification recommended in W13) we find 50% of the normal galaxies in our volume limited sample to $z < 0.035$ are best identified as "featured" and 50% 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 3. Table 2 summarises these data, and in addition includes fractions for galaxies in subsets separated by their absolute magnitude.

3.1 Spiral Arms and Bars

It is only possible to identify spiral arms, bars and other disc features in disc galaxies which are sufficiently face-on for these to be visible. Among the galaxies identified as "featured" in our "normal" galaxy sample, we find 17% ($N = 1699$) have values of $p_{\rm edgeon} > 0.8$. This is the number of galaxies expected to be found with $i \simeq 90$ deg in a randomly orientated sample of objects[6]. W13 publish a recommended threshold for "oblique" galaxies in which we can reliably identify disc features (e.g. bars, spirals) of $p_{\rm notedgeon} > 0.715$ (and $N_{\rm notedgeon} > 20$). In the sample discussed in this article, we find that 66% of the "featured" galaxies fall into this group ($N = 6614$).

Of these oblique featured galaxies:

• 86% have clear spiral arms ($p_{\rm spiral} > 0.5$); just 5% are found to not have spiral arms to a high consensus (i.e. have $p_{\rm spiral} < 0.2$).

• 31% have obvious bars ($p_{\rm bar} > 0.5$). This strong bar fraction is consistent with previous Galaxy Zoo based work (Masters et al. 2011, 2012, e.g.). Weaker bars can be identified by $0.2 < p_{\rm bar} < 0.5$ (Willett et al. 2013; Skibba et al. 2012, e.g.). Another 25% of the oblique spirals have weak bars by this definition, leaving just over 44% of oblique spirals without any clear sign of a bar feature (*i.e.* $p_{\rm nobar} > 0.8$) at the scales detectable by the SDSS images.

Bars in GZ2 have been studied in many papers (Masters et al. 2011, 2012; Skibba et al. 2012; Cheung et al. 2013, 2015; Galloway et al. 2015; Kruk et al. 2017, 2018, e.g.), and the number of spiral arms have been investigated by (Willett et al. 2015; Hart et al. 2016, 2017a). Hart et al. (2017b, 2018) make use of automated pitch angle measures along

[6] In a randomly oriented sample of discs, basic probability shows that you expect to find 17% of galaxies within 10 deg of perfectly edge-on.

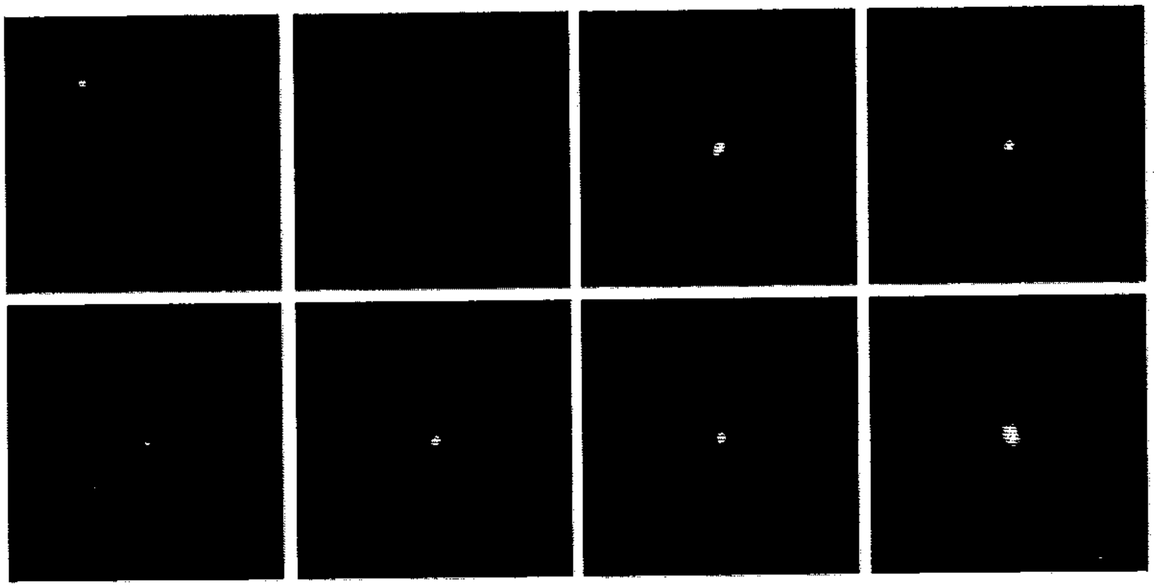

Figure 3. Randomly selected example images of galaxies classified as either "featured" (top row) or "smooth" (bottom row) from Galaxy Zoo as a function of r-band absolute magnitude (brighter to the right). All galaxies in this image are selected to have a redshift $z = 0.03$, so are shown at the same physical resolution. Images are *gri* composites from SDSS with a scale of $1.7'$square.

Table 2. Distribution of basic morphological class. **TODO: update numbers for final sample, or delete?**

Sample/defintion	$N_{\rm smooth}$	$\%_{\rm smooth}$	$N_{\rm featured}$	$\%_{\rm features}$
All ($N = 20254$)				
$p > 0.8$	4860	24	5694	28
Majority vote	10209	50	10045	50
Majority vote				
Faint: $M_r > -20$ ($N = 9302$)	5655	61	3647	39
Mid 1: $-21 < M_r < -20$ ($N = 7103$)	2946	41	4157	58
Mid 2: $-22 < M_r < -21$ ($N = 3408$)	1349	40	2059	60
Bright: $M_r < -22$ ($N = 441$)	259	59	182	41

with spiral arm numbers from Galaxy Zoo to investigate spiral arm formation mechanisms. This is the first paper to attempt to make use of the crowdsourced arm winding measures directly, so we will start by comparing them with the automated measures.

We define an arm winding score from Galaxy Zoo classifications as

$$w_{\rm avg} = 0.0\ p_{\rm loose} + 0.5 p_{\rm medium} + 1.0 p_{\rm tight}. \quad (1)$$

This has the advantage of providing a single number measuring the tightness of the spiral arms as seen by Galaxy Zoo users, and will be $w_{\rm avg} = 1.0$ where the arms are most tightly wound and $w_{\rm avg} = 0.0$ where they are very loose. We compare these identifications with pitch angles measured by the SpArcFiRe method (Davis & Hayes 2014) in Figure 4 (see Hart et al. 2017b for more details). This demonstrates how well arm winding as identified by Galaxy Zoo users correlates with pitch angle for those galaxies where pitch angle can be measured. The best fit trend gives

$$\Psi = 10.95 w_{\rm avg} + 14.73, \quad (2)$$

where Ψ is the pitch angle in degrees, thus providing a way to estimate numerical pitch angles from the GZ2 visual descriptions.

We also plot on the right hand side of Figure 4, a measure of bulge size from GZ2 against the SDSS r-band luminosity of bulges as measured by Simard et al. (2011). The bulge prominence from GZ2 is defined as

$$B_{\rm avg} = 0.0\ p_{\rm nobulge} + 0.2 p_{\rm just} + 0.8 p_{\rm obvious} + 1.0\ p_{\rm dominant}, \quad (3)$$

again providing a single number, which ranges from $B_{\rm avg} = 0.0$ for galaxies with no bulge component, to $B_{\rm avg} = 1.0$ for spiral galaxies with completely dominant bulges. As can be see in Figure 4 these two measures of bulge size correlate well, with a best fit of

$$L_{r,\rm bulge} = 1.54 B_{\rm avg} + 8.63. \quad (4)$$

3.2 The Correlation of Bulge Size and Spiral Arm Tightness

The classic Hubble Sequence for spiral galaxies implies that bulge size and spiral arm winding are highly correlated in most cases (although it has been noted for some time that this correlation is not perfect, e.g. Freeman 1970; Kennicutt

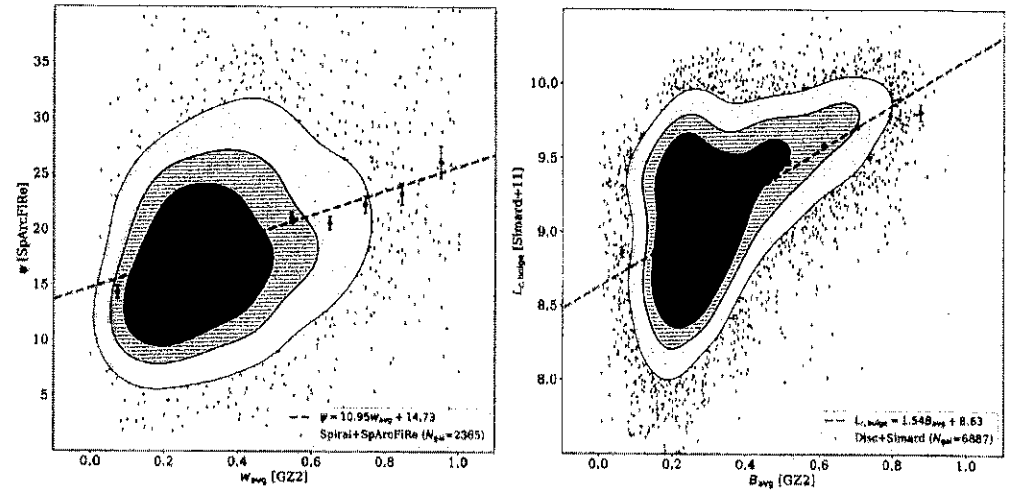

Figure 4. (a) Galaxy Zoo winding score from Eq. 1 vs. measured pitch angles from SpArcFiRe for all spirals with at least one reliably identified arc (see Davis & Hayes 2014 and Hart et al. 2017a). (b) Galaxy Zoo bulge prominence from Eq. 3 vs. SDSS r-band bulge luminosity as measured from Simard et al. (2011). The grey contours indicate where 20, 40, 60 and 80% of the galaxies lie in each plot and the dashed lines show the best fit straight line for each plot.

1981) and it has been recently noted in Davis et al. (2015); Hart et al. (2017b, 2018) **(one to add here from Rings conference; Hererra-G???? (2015))**. 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 making use of the unique value of bulge size and spiral arm tightness from the GZ2 classifications as defined in Equations 1 and 3. These numbers increase from zero to one for either bulge sizes increasing, or arms getting tighter, in order than a "classic" Sa should have both values of 1.0, and a "classic Sc" would have both values of zero.

We plot the measure of bulge size versus arm windiness for the oblique spiral 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 of 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 discussed with both large and small bulges, while Sc galaxies (as defined by loose arms) are only ever discussed with small bulges.

Given the traditional Hubble tuning fork is split by bar classification, and also that the presence of a bar might confuse both automated and crowdsourced measures of bulge size and spiral pitch angle, we also split the sample based on the presence or absence of a strong bar as shown in Figure 6. We find 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 ($p_{\rm bar} < 0.2$), and for a given bulge size, barred spirals will have looser arms than unbarred spirals, but there remains no clear correlation between bulge size and spiral arm pitch angle in either subgroup ~~(see Figure 6)~~.

We show examples of galaxies at $z = 0.03$ from the four quadrants of Figure 5 (ie. class Sas and Scs, but also spirals with a small bulge and tightly wound arms, and those with large bulges and loosly wound arms) with either strong bars ($p_{\rm bar} > 0.5$) or no bar ($p_{\rm bar} < 0.2$) in Figure 7.

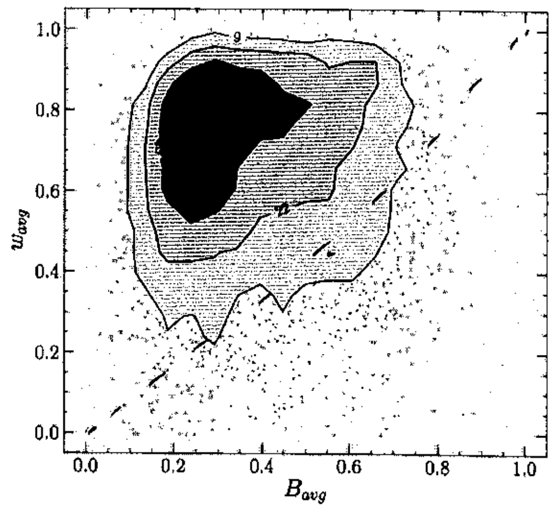

Figure 5. We show here the location of 4830 nearby spiral galaxies on a plot of bulge size versus degree of arm winding as indicated by Galaxy Zoo classifications. The contours indicate regions of high density, with the numbers showing the contour level value and points shown at the lowest density. The classic spiral sequence is a diagonal line in this plot with Sas at the upper right and Scs at lower left. This plot does not display that behaviour.

4 DISCUSSION

We have previously discussed (in W13) how best to assign T-types to Galaxy Zoo galaxies from the classification votes in GZ2. As is conventional, both the votes for tightness of

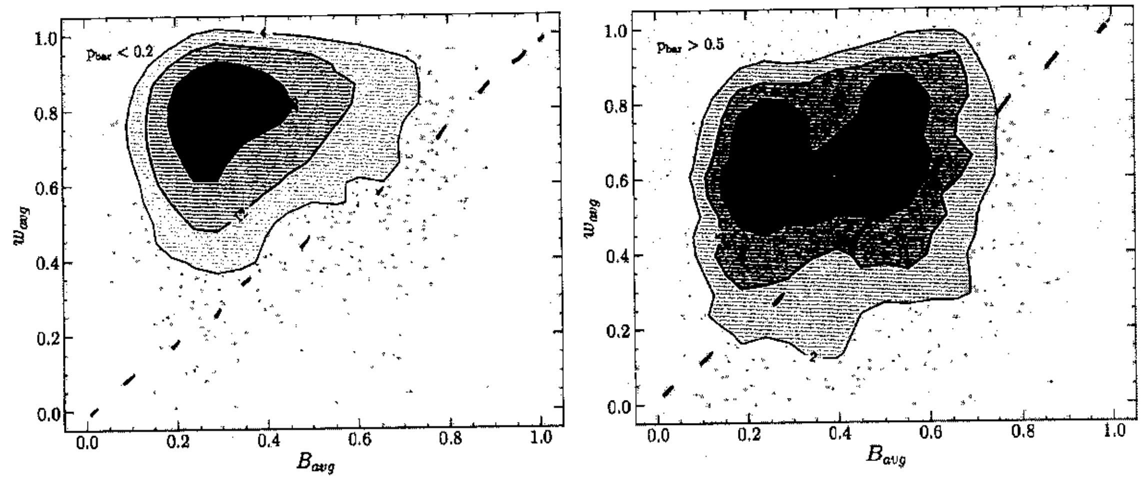

Figure 6. As Figure 5 but for subsamples of the oblique spirals split by bar classification. Left panel: galaxies with $p_{\rm bar} < 0.2$; right panel: galaxies with $p_{\rm bar} > 0.5$, In neither sample is the class spiral sequence trend of correlation between bulge size and arm winding clearly observed.

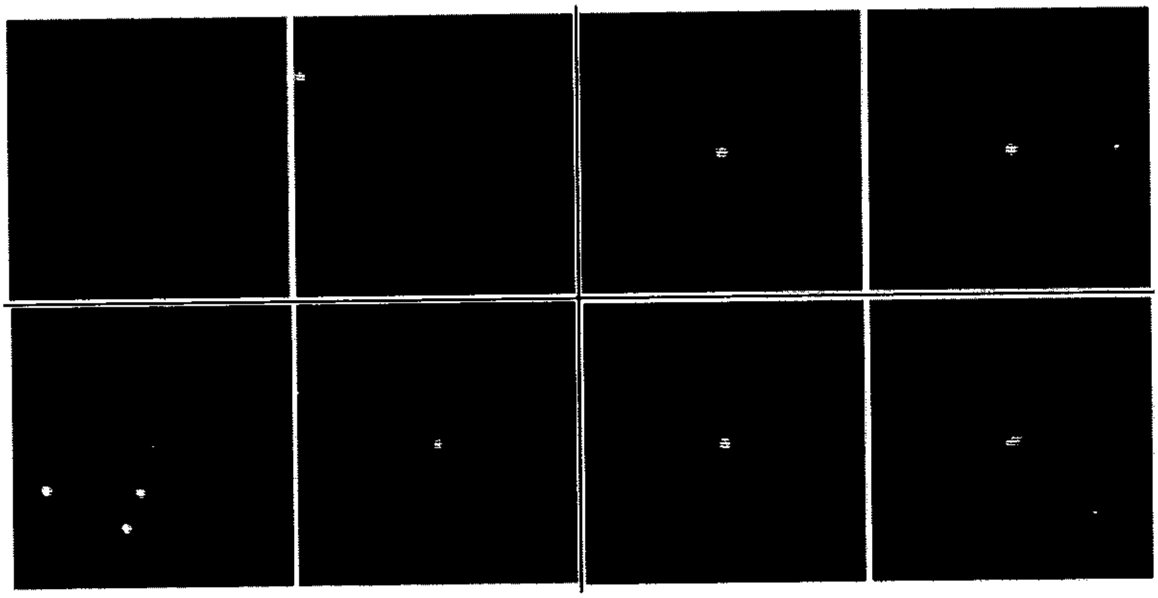

Figure 7. Example images of galaxies at $z = 0.03$ and $M_r \sim -21$ with both loose and tightly would spiral arms (upper and lower rows respectively) and small or large bulges (left and right columns respectively). In each case galaxies are shown with either strong bars ($p_{\rm bar} > 0.5$) or no bar ($p_{\rm bar} < 0.2$). Images are *gri* composites from SDSS with a scale of 1.7′ square. . **TODO: check details of this plot**

spiral arms, and bulge size were considered. In that work however we concluded that modern expert visual classification of spiral Hubble types (based on comparison with both Nair & Abraham (2010, hereafter NA10) and Baillard et al. 2011) was primarily driven by bulge size, regardless of the tightness of spiral arms, with the best fitting relation (based on symbolic regression) being found to be

$$T = 4.63 + 4.17\ p_{\rm nobulge} - 2.27\ p_{\rm obvious} - 8.38\ p_{\rm dominant}. \quad (5)$$

We point the interested reader to the lower panel of Figure 19 from W13 (reproduced for convenience in Figure 8) which compares the predicted T-types from the above equation to the T-types assigned by NA10. As was pointed out in W13, this, and other comparisons with recent expert visual classifications (e.g. the EFIGI sample of Baillard et al. 2011) demonstrate clearly that the modern spiral Hubble sequence is defined by bulge size alone, with little reference to spiral arm tightness.

In fact, regardless of the traditional spiral sequence classification, models of spiral arm formation (see Dobbs & Baba 2014 for a recent and comprehensive review) do not generally predict that spiral arm pitch angle should correlate with bulge size. For example, in swing amplification models, pitch angle should correlate best with spiral arm amplitude,

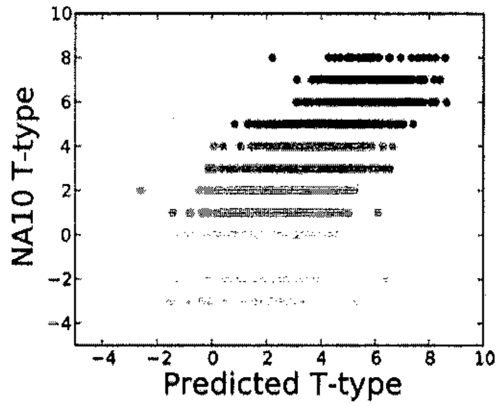

Figure 8. Predicted T-type classifications as fit by Willett et al. (2013) for GZ2 galaxies shown versus their T-types from Nair & Abraham 2010. Galaxies are colour coded by their morphologies as identified by NA10 (as indicated on the y-axis). Galaxies shown are only those with sufficient answers to characterize the arms winding and arms number GZ2 tasks, which selects heavily for late-type galaxies. This explains the lack of ellipticals in the plot, but highlights the fact that S0 galaxies (Type 0) do not agree well with the linear sequence. Reproduced from Willett et al. (2013).

while in density wave models it should correlate best with the local shear in the disc (related mostly strongly to total galaxy mass). Tidally induced spirals should have pitch angles which correlate with the strength of the interaction (e.g see Kendall et al. 2011).

Our result, in Figure 5, shows only a loose correlation between the two parameters of the spiral sequence. Galaxy Zoo classifications of spiral arms have previously been studied by Hart et al. (2017b), who also found a weak correlation between pitch angle and bulge size, in common with previous work which found that the tightness of the spiral arms are more strongly correlated with bulge total mass (Seigar et al. 2008; Berrier et al. 2013; Davis et al. 2015) rather than the ratio of bulge to disk masses.

The spiral density wave model Lin & Shu (1964) was orginially concieved to solve the "spiral winding problem". Interestingly, in recent years there is a growing consensus that spiral arms must in fact wind over time (D'Onghia et al. 2013). Recently Pettitt & Wadsley (2018) investigate the dependence of pattern speeds and wind-up rates on morphology in a sample of 5 model galaxies (designed to mimic M31, NGC4414, M33, M81 and the Milky Way). They were interested in particular at changing bar and disk properties, however, bulge mass also varies between their models, and there is a definite suggestion in their results that the wind-up rate may be affected by bulge mass. Their model of M33, which has a bulge-to-disk mass ratio almost an order of magnitude lower than the other systems, has the slowest wind-up rate of all of their simulations. Unfortunately the number of galaxies was too small to see independently the impact of the bar, but their slowest winding model also hosted a strong bar.

If the rate of winding is dependent on the mass of the central concentration, then there is a natural explanation for the observation we present here. Systems with large bulges would, quickly (formally, compared to the dynamical time), develop tighter spiral arms, leading to the absence of systems with large bulges and loose arms that we observe. We would, in this model, expect systems with smaller bulges to have a range of spiral arm types, just as observed. We therefore suggest that this observation is support for the idea that the majority of spiral arm structure observed in the Universe is transient and winding, rather than the static grand design density waves. The fact that galaxies with strong bars have looser arms for the same bulge size, suggests that the bar also acts to slow down arm winding, perhaps by driving the $m = 2$ mode.

5 SUMMARY

We present the morphological demographics 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 92% of these galaxies show the "normal" morphologies found on the classic Hubble sequence, with 8% 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 31% have strong bars, and 44% have no bars. The majority have clearly identified spirals (86%), with only 5% with a clear consensus for lacking spiral arms. These are likely S0 types with rings or bars.

?

We use this sample to hi-light 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 (this was previously noted by Willett et al. 2013). Authors who make use of morphologies, particularly those drawn from different classifications, should take care that they understand well what is driving these classifications; our results suggest that the traditional morphological classifications do not map well onto current classifications.

do we say this elsewhere in the text as well? Perhaps add para to disc?

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 discuss how this favours winding models of spiral arms, with the winding rate dependent on the bulge size, and winding also slowed down by the presence of a strong bar.

New higher resolution and deeper imaging of significant fractions of the sky will provide significantly more galaxies with well resolved internal structure in the near future. This makes galaxy morphology as relevant today to our understanding of galaxy formation and evolution as it was in 1926.

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[8] `www.galaxyzooforum.org/index.php?topic=280028.0`

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