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Galaxy Zoo: bars in disc galaxies*

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ABSTRACT

We present first results from Galaxy Zoo 2, the second phase of the highly successful Galaxy Zoo project (www.galaxyzoo.org). Using a volume-limited sample of 13 665 disc galaxies ($0.01 < z < 0.06$ and $M_r < -19.38$), we study the fraction of galaxies with bars as a function of global galaxy properties like colour, luminosity and bulge prominence. Overall, 29.4 ± 0.5 per cent of galaxies in our sample have a bar, in excellent agreement with previous visually classified samples of galaxies (although this overall fraction is lower than that measured by automated bar-finding methods). We see a clear increase in the bar fraction with redder ($g - r$) colours, decreased luminosity and in galaxies with more prominent bulges, to the extent that over half of the red, bulge-dominated disc galaxies in our sample possess a bar. We see evidence for a colour bimodality for our sample of disc galaxies, with a 'red sequence' that is both bulge and bar dominated, and a 'blue cloud' which has little, or no, evidence for a (classical) bulge or bar. These results are consistent with similar trends for barred galaxies seen recently both locally and at higher redshift, and with early studies using the RC3. We discuss these results in the context of internal (secular) galaxy evolution scenarios and the possible links to the formation of bars and bulges in disc galaxies.

Key words: surveys – galaxies: bulges – galaxies: evolution – galaxies: photometry – galaxies: spiral – galaxies: structure.

1 INTRODUCTION

Bars are common in disc galaxies, and are thought to have an important impact on the evolution of galaxies through their ability to transfer angular momentum in both the baryonic and dark matter components of the galaxy (Combes & Sanders 1981; Weinberg 1985; Debattista & Sellwood 2000; Berentzen, Shlosman & Jogee 2006). Bars are efficient at driving gas inwards, perhaps sparking central star formation (e.g. Hawarden et al. 1986; Knapen et al. 1995; Jogee, Scoville & Kenney 2005; Sheth et al. 2005), and thus help to grow a central bulge (e.g. for a review Kormendy & Kennicutt 2004). Bars may also feed a central black hole [as per Shlosman, Frank & Begelman (1989) and Shlosman, Begelman & Frank (1990), and see Jogee (2006) for a recent review], but so far no correlation has been found between active galactic nucleus (AGN) activity and bar fraction in galaxies forming stars (e.g. Ho, Filippenko & Sargent 1997 and as recently discussed by Hao et al. 2009).

Early visual inspection of spiral galaxies in catalogues like the RC3 (de Vaucouleurs et al. 1991) gave an optical bar fraction of $f_{\rm bar} \sim 0.25$–0.3, rising to 60 per cent if weaker bars or oval distortions were included (as discussed in e.g. Sellwood & Wilkinson 1993; Moles, Marquez & Perez 1995; Knapen, Shlosman & Peletier 2000; Sheth et al. 2008).

More recent work on the bar fraction of disc galaxies has relied on automated methods of detecting bars in galaxies including

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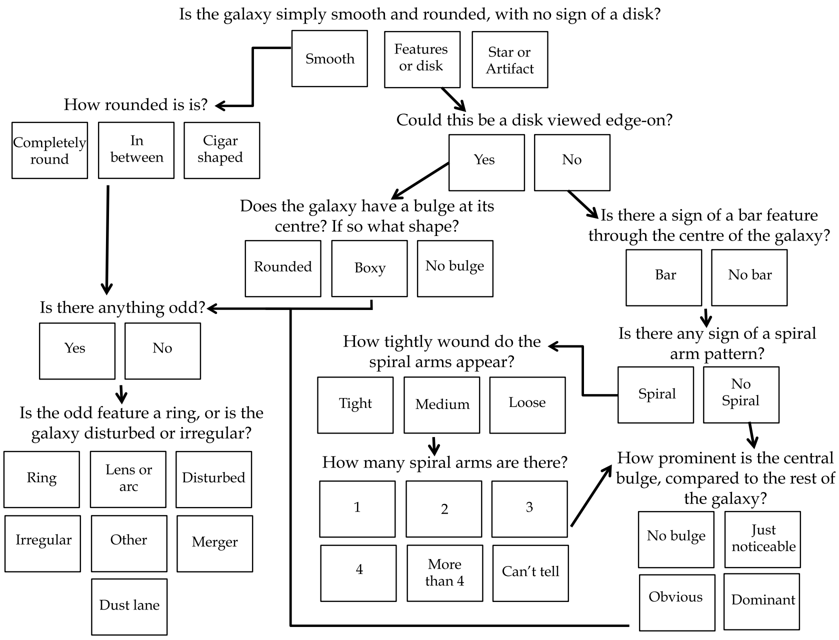

Figure 1. We present a schematic diagram of the decision tree for GZ2 classifications. We provide the questions asked of the user for each SDSS galaxy image (starting with the top question first). For each question, we provide the possible answers they are allowed. Depending on their answers, the user can navigate down different branches of the tree.

elliptical isophote fitting or the Fourier decomposition of CCD images. Such automated studies find optical bar fractions of ∼50 per cent for nearby disc galaxies (Barazza, Jogee & Marinova 2008; Aguerri, Méndez-Abreu & Corsini 2009), which is consistent with near-infrared (NIR) studies that find that a majority (at least 60 per cent) of disc galaxies appear to have a bar (e.g. Mulchaey & Regan 1997; Marinova & Jogee 2007). These differences are probably due to a combination of selection effects, wavelength dependence, differences in the strength of the bar, and small sample sizes. While studies of bars in galaxies have been collectively moving towards automated classifications (and away from possibly subjective visual classifications) in recent years, concerns have arisen about the reliability of a completely automated approach for detecting bars which struggle to distinguish spiral arms and bars in some cases (see for example the discussion of problems with the Fourier method in Aguerri et al. 2009).

For such reasons, especially to provide a larger sample of visually selected barred galaxies, we started a new phase of the successful Galaxy Zoo project[1] by asking the public to provide more detailed visual classifications of galaxies seen in the Sloan Digital Sky Survey (SDSS). This new project is known as ‘Galaxy Zoo 2’ (GZ2) throughout this paper. The project and data set will be fully described in a future paper (Lintott et al., in preparation).

In this paper, we present the first results on the bar properties of 13 665 visually classified GZ2 disc galaxies. This sample is nearly an order of magnitude larger than previous studies using SDSS data (Barazza et al. 2008; Aguerri et al. 2009) which facilitate a detailed statistical study of the fraction of barred disc galaxies as a function of other galaxy properties like global optical colour, luminosity and estimates of the bulge size, or prominence. Where appropriate, we assume a standard cosmological model of $\Omega_{\rm m} = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$ and all photometric quantities are taken from SDSS.

2 IDENTIFICATION OF BARS AND SAMPLE SELECTION

The first phase of Galaxy Zoo[2] (known as GZ1 hereafter) has now finished collecting data, is described in detail in Lintott et al. (2008) and the data have been made public (Lintott et al. 2010). In the second phase (GZ2), users were asked to provide more detailed classification of galaxies than in the original GZ1 (see Fig. 1). Specifically, after identifying a galaxy as possessing *‘features or a disc’* (see top question in Fig. 1), the users were then asked different questions (depending on their prior answers) as they navigate to the bottom of the decision tree presented in Fig. 1. For example, if the user identified a disc from the first question in the tree, they are then asked if the galaxy could be an edge-on disc, and if the answer to that question is ‘no’, then they are further asked to identify if the galaxy has a bar or not. This identification process is based on the SDSS *gri* composite images as it was in GZ1.

At the time of submission of this paper we were still collecting data for the GZ2 project, and these first results are based upon data collected up to 2009 July. Only galaxies for which there were at least 10 answers to the bar question (the question beginning *‘Is there a sign of a bar feature . . .’* in Fig. 1) have been included in the sample, which gives a total superset of 66 835 disc galaxies in which the median number of ‘bar’ classifications is 20. In GZ2 galaxies were presented to the user randomly for classification. However, only galaxies which a user identified as having *‘features or a disc’* (see Fig. 1) progressed to the question about bars, so galaxies possessing 10 answers to this question are likely to be biased towards later types

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[1] www.galaxyzoo.org

[2] http://zoo1.galaxyzoo.org

Figure 2. Top row: examples of GZ2-classified barred disc galaxies. Bottom row: examples of GZ2-classified disc galaxies with no bar. The galaxies on the left are at $z \simeq 0.02$, the galaxies in the middle at $z \simeq 0.04$ and the galaxies on the right are at $z \simeq 0.06$, thus spanning the full redshift range of the volume-limited sample used herein (see Section 2). The images are taken from the SDSS (*gri* composite) and are 1 arcmin^2 in size. (These images differ from those presented to users for classification, which are scaled using the Petrosian radius of the galaxy.)

but can include early-types if any identifiable features (e.g. bars) are present.

For the rest of this paper, we classify a galaxy as being 'barred' if the number of users identifying them as having a bar is equal to, or larger than, the number identifying them as not having a bar, i.e. a majority of users voted they saw a bar. A fraction of the sample has also been visually inspected by us and this choice seems to make sense (see Fig. 2). However, as has been discussed extensively for GZ1 data (e.g. Lintott et al. 2008; Bamford et al. 2009), there are many ways to go from 'clicks to classifications'. This simple choice means that no galaxy is left unclassified, and gives equal weight to all users. Alternative threshold classifications were explored, and were found to make no qualitative difference to the results. Future studies using GZ2 data will no doubt explore this issue further.

We select from the superset of 66 835 disc galaxies a volume-limited subsample of GZ2 disc galaxies with $0.01 < z < 0.06$ and $M_r < -19.38$, where M_r is the SDSS Petrosian r-band magnitude k-corrected to $z = 0$ and with the standard Galactic dust extinction correction (Schlegel, Finkbeiner & Davis 1998). A correction for dust extinction internal to the galaxy, as described in Masters et al. (2010a), is also applied (this corrects for the inclination dependence and is zero for face-on discs). Furthermore, we limit our sample to $\log(a/b) < 0.3$ ($i \sim 60^\circ$) as identifying bars in highly inclined disc galaxies is challenging. This is a comparable cut in inclination to other recent studies of bars in spiral galaxies (e.g. Barazza et al. 2008; Sheth et al. 2008; Aguerri et al. 2009). These constraints provide a final sample of 13 665 disc galaxies used throughout this paper (with median number of 22 answers to the GZ2 'bar' question). Examples of barred and non-barred galaxies in our sample are shown in Fig. 2, over the range of redshifts included in this study. We have cross-matched this sample with the GZ1 (SDSS DR6) sample discussed in Bamford et al. (2009). The distribution of GZ1 spiral likelihood, $p_{\rm sp}$, for the disc galaxies in this sample peaks at $p_{\rm sp} = 1$ with a median value of $p_{\rm sp} = 0.9$, and a long low tail to small spiral likelihoods. Overall 66 per cent of the sample would be classified by GZ1 as spiral ($p_{\rm sp} > 0.8$) with less than 1 per cent GZ1 early-types ($p_{\rm el} > 0.8$). The remaining fraction have uncertain classifications in GZ1 (using the 'clean' sample criteria). This cross-match indicates that what we will call 'disc galaxies' in GZ2 should be interpreted as being mostly classic spiral galaxies, but also consisting of earlier type galaxies in which a 'disc or features' (see the top question of Fig. 1) was discernable to GZ2 users.

The stellar mass range of this volume-limited GZ2 sample of 13 665 disc galaxies is approximately $10^9 < M < 10^{11}\,{\rm M}_\odot$ (using the stellar mass estimates from Baldry et al. 2006) with a colour and luminosity dependence such that the dimmest, bluest objects in our sample have stellar masses of $10^9 < M < 10^{10}\,{\rm M}_\odot$, while the reddest, most luminous, galaxies have higher stellar masses (red galaxies in our sample are only complete to stellar masses of $10^{10}\,{\rm M}_\odot$).

To address concerns that the requirement of $n > 10$ answers to the GZ2 bar question might bias the sample we compare the luminosity, colour, axial ratio and redshift distributions compared to GZ1 selected spirals ($p_{\rm sp} > 0.8$) in the same volume limit and find no significant differences in these distributions excepting a slightly larger tail to more luminous, redder and more distant galaxies in the sample studied here – easily explained by the addition of small numbers of early-types. It might initially appear worrisome that early-types may be present in our sample if they possess a bar (since then they make it past the 'features or a disc' question) but not if they are unbarred. However, the contamination appears small enough that we find no differences in the results presented below if the sample is further restricted to include only GZ1 'clean' spirals or if we remove the small fraction of GZ1 'clean' early-types. Therefore we leave the selection as is.

3 RESULTS

First, we compute the overall mean bar fraction of our sample which is 29.4 ± 0.5 per cent (we find 4020 barred disc galaxies in our sample of 13 665 GZ2 disc galaxies). This value is in excellent agreement with the fraction of 25–30 per cent of galaxies having strong bars found by visual inspection of classic optical galaxy samples (e.g. the RC3 and UGC; Nilson 1973; de Vaucouleurs et al. 1991) and also with Marinova et al. (2009) who found a bar fraction of ∼30 per cent for disc galaxies in a dense cluster at $z \sim 0.165$ (in the STAGES survey). However, it is lower than recent bar fractions quoted for nearby disc galaxies using automated ellipse fitting techniques to find bars, e.g. Barazza et al. (2008) find a bar fraction of 50 ± 2 per cent, while Aguerri et al. (2009) find 45 per cent. This difference could depend on the strength of bars included in these analyses as it has been known for sometime that the bar fraction in the RC3 catalogue increases to ∼60 per cent if weak or ovally distorted systems are included (e.g. Sellwood & Wilkinson 1993; Knapen et al. 2000). We return to this issue in Section 3.1 and in future work, but it appears that our GZ2 bars may be consistent with the classic optically identified strong bars (i.e. SB types).

We see no trend of bar fraction with redshift in our sample, and only a mild trend with inclinations (for $i < 60^\circ$) such that bars are slightly less likely to be identified as the galaxies become more inclined. As the inclinations are random with respect to other galaxy properties, we do not expect this trend to have a significant effect on our results. We argue here that the absence of a trend of bar fraction with redshift may also be taken as suggestive that our bar classification using a simple $N_{\rm bar} > N_{\rm nobar}$ from GZ2 clicks picks out only the strongest and largest bars, since smaller bars would not be resolved over the full redshift range considered. We reiterate that all trends of bar fraction we discuss should most likely be considered trends in the fraction of strong or obvious bars. Future work comparing GZ2 bar classifications with other classification methods will test this.

3.1 Bar fraction with colour

In Fig. 3, we present the bar fraction of our GZ2 volume-limited sample as a function of the $(g - r)$ global, *k*-corrected colour of the galaxy.[3] We find a significant trend for redder GZ2 disc galaxies to have larger bar fractions, e.g. over half of the reddest galaxies in our sample possess a bar. This is consistent with the recent results of Masters et al. (2010b) who found that passive red spiral galaxies had a high fraction of bars; these passive spirals would be in the extreme red population in our GZ2 sample. Interestingly, the trend seen in Fig. 3 does not appear to be monotonic, given the Poisson error bars, and we see a slight increase in the bar fraction for the bluest objects [compared to intermediate colours of $(g - r) \sim 0.5$].

Furthermore, one could argue that the trend seen in Fig. 3 is consistent with a difference in bar fraction which is correlated with the well-established colour bimodality relationship of galaxies (illustrated in the lower panel of Fig. 3). Discs in the 'blue cloud' [e.g. with $(g - r) < 0.6$] have a constant bar fraction (with colour) of ≃20 per cent, while disc galaxies in the 'red sequence' [e.g. $(g - r) > 0.7$] have a clear increase in bar fraction with colour. The split between 'normal' and 'red' passive spiral galaxies discussed by Masters et al. (2010b) falls approximately at the dip of the colour distribution of our GZ2 disc galaxies [the colour cut applied by Masters et al. (2010b) was $(g - r) = 0.63 - 0.02(M_r + 20)$ while the median magnitude of our GZ2 sample used here is $M_r = -20.9$, but note that Masters et al. (2010b) also removed spiral galaxies with any sign of a bulge, something which has not been done here].

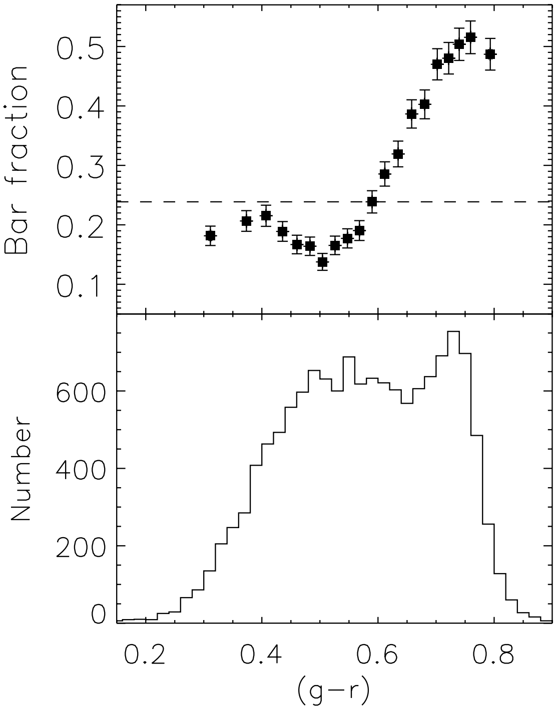

Figure 3. Top panel: the bar fraction as a function of global galaxy $(g - r)$ colour. The dashed line shows the median bar fraction for the entire volume-limited sample of GZ2 disc galaxies. Poisson error bars are shown. Lower panel: the distribution of $(g - r)$ colours for GZ2 disc galaxies used in this study.

We should consider if the trend of bar fraction with colour could be an artefact of the visual identification of bars in the SDSS composite *gri* images. It does seem feasible that the bluer GZ2 discs might have stellar bars hidden under the ongoing star formation which would dominate the SDSS *g* band, while in the redder discs, the light would be dominated by the *i* band, and thus lead to an increased bar fraction. It has been argued in the literature that bar fraction increases when moving from the optical into the NIR (e.g. Eskridge et al. 2000; Marinova & Jogee 2007), with more bars being revealed in the NIR (e.g. Keel, Byrd & Klaric 1996; Mulchaey, Regan & Kundu 1997). However, more recently it has been quite clearly shown that overall the bar fraction does not change between optical (*B* band) and the NIR (e.g. Eskridge et al. 2002; Menéndez-Delmestre et al. 2007). In particular we highlight the findings of Sheth et al. (2008) who show for a sample of 139 local SDSS galaxies that bar fraction (both from visual inspection and ellipse fitting) is constant over the SDSS *griz* passbands, and only drops significantly in the *u* band. Furthermore, we highlight the fact that the bar fraction for our bluest GZ2 disc galaxies [$(g - r) < 0.5$]

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[3] Standard Galactic extinction corrections are also applied, but no correction for internal extinction – this last corrections would be at most 0.04 mag because of the inclination limit $\log{(a/b)} < 0.3$.

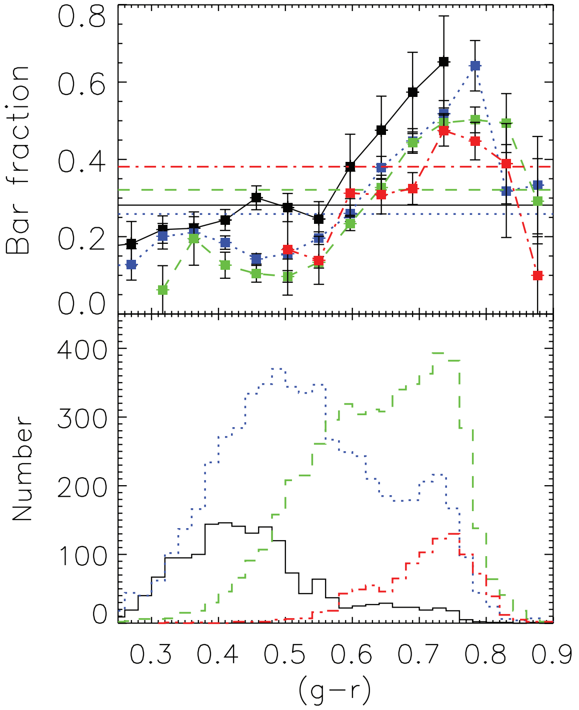

Figure 4. Similar to Fig. 3, but with the sample split into four bins of absolute magnitude: $M_r > -20$ (black solid), $-20 < M_r < -21$ (blue dotted), $-21 < M_r < -22$ (green dashed) and $M_r < -22$ (red dot–dashed). Bins are only plotted if they have at least 10 galaxies.

is greater than at intermediate colours (as discussed above) and is consistent with a constant bar fraction for all colours bluer than $(g - r) < 0.6$. These results argue against a significant colour bias in identifying bars in our composite *gri* images but further studies may be necessary to discover any subtle biases with colour.

3.1.1 Bar fraction, colour and luminosity

The trend observed in Fig. 3, and in particular the upturn in bar fraction at the bluest colours, suggests that colour may not be the only variable of importance for the bar fraction. We therefore split the sample into four subsamples of absolute magnitude and show the results in Fig. 4 (we avoid using stellar mass estimates which introduce completeness effects dependent on colour). This figure shows that at a fixed $(g - r)$ colour, there is a residual trend of bar fraction with luminosity such that bars are more common in lower luminosity disc galaxies (since this is at fixed colour this corresponds to lower stellar mass). However, the trend with luminosity is still subdominant compared to the correlation of bar fraction with colour.

Fig. 4 highlights a maximum bar fraction of ∼70 per cent (for our optical GZ2 sample) for low-luminosity disc galaxies with colours in the range of $0.7 < (g - r) < 0.8$, and a drop in bar fraction for the most massive, red discs in this sample (if these are identified with S0s this drop in bar fraction has been observed before, e.g. Laurikainen et al. 2009). Interestingly the overall trend is for an increase in bar fraction with galaxy luminosity, but this is obviously driven by the trend of bar fraction with colour and the fact that more luminous disc galaxies tend to be redder.

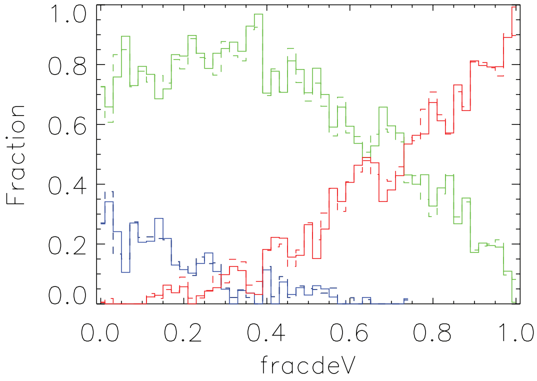

Figure 5. The distribution of values of fracdeV for GZ2 disc galaxies classified by their visual bulge size into 'no bulge' (blue), 'just noticeable' (green) and 'obvious' (orange). We have not plotted 'dominant' bulges as they are few in this category and a vast majority have fracdeV = 1. Histograms for barred galaxies are shown by the dashed lines, unbarred by the solid lines.

3.2 Bar fraction and bulge prominence

As part of GZ2, users were also asked to identify the size, or prominence, of the bulges in disc galaxies (excluding edge-on discs), and were given the four options of 'no bulge', 'just noticeable', 'obvious' and 'dominant' (see Fig. 1 for details). Similar to our treatment of the bar question, we uniquely place all of our GZ2 disc galaxies into one of these four categories based on majority voting. We find that most galaxies are placed into the middle two categories, with only a small number of discs having dominant or no bulge classification. In Masters et al. (2010a), the use of the SDSS parameter fracdeV[4] was used as a proxy for bulge size in GZ1 spirals. In bright spirals, fracdeV is dominated by the inner light profile and should be increased in the presence of a large bulge component.

In Fig. 5, we show the fracdeV distribution of GZ2 disc galaxies separated into the four GZ2 bulge categories. We find that most GZ2 discs with low values of fracdeV are categorized as having 'just noticeable' bulges by the GZ2 users (the green line in Fig. 5), while most GZ2 disc galaxies with large values of fracdeV are categorized as having an 'obvious' bulge (orange line). While the number of galaxies in the 'no bulge' (blue line) and 'dominant' bulge categories are small, there is still a clear trend with fracdeV in the expected direction. These results are reassuring as they demonstrate that both fracdeV and the GZ2 bulge classifications are meaningful and do provide a measure of the bulge prominence in disc galaxies. We further split the sample into barred and non-barred discs using the GZ2 classifications to check that the presence of a bar does not have a significant effect on fracdeV. The resulting histograms (dashed and solid lines in Fig. 5) are identical thus proving there is no impact on fracdeV from the presence of a bar.

In Fig. 6, we show the fraction of GZ2 disc galaxies in our sample as a function of fracdeV. We have chosen to use this SDSS-measured quantity, instead of the GZ2 bulge classification, to follow the work of Masters et al. (2010a) and because it is a continuous variable. Fig. 6 shows a clear monotonic increase of bar fraction with fracdeV, i.e. half of the bulge-dominated disc galaxies in our sample have bars.

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[4] The fraction of the best-fitting light profile which comes from a de Vaucouleurs fit as opposed to an exponential fit.

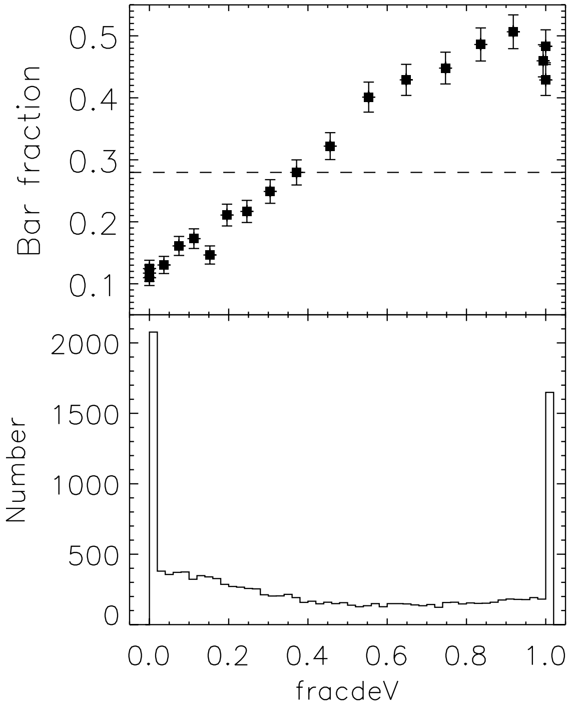

Figure 6. Top panel: the bar fraction as a function of fracdeV. The dashed line shows the median bar fraction for the entire volume-limited sample of GZ2 discs. Poisson error bars are shown. Lower panel: the distribution of fracdeV values of GZ2 discs used in this study. Most galaxies have either fracdeV = 0 or fracdeV = 1.

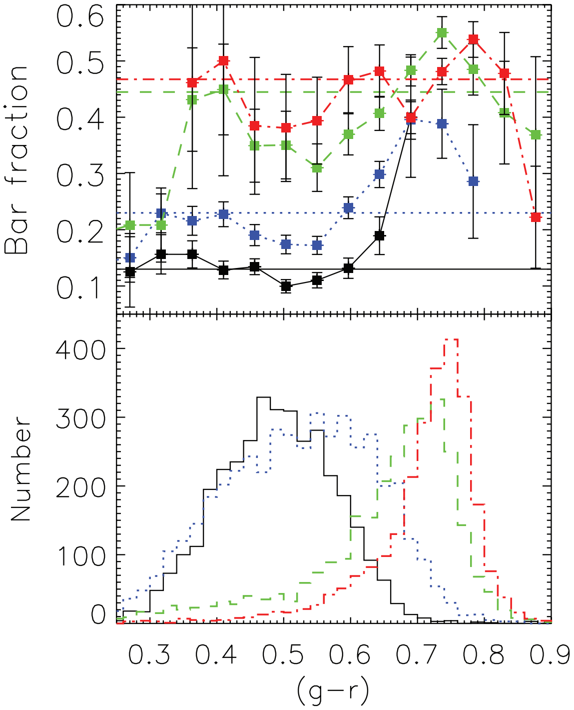

Figure 7. Similar to Fig. 3 but split into four bins of fracdeV: fracdeV < 0.1 (no bulge; black solid lines), 0.1 < fracdeV < 0.5 (small bulge; blue dotted lines), 0.5 < fracdeV < 0.9 (large bulge; green dashed lines) and fracdeV > 0.9 (dominant bulge; red dot–dashed lines). Bins are only plotted if they have at least 10 galaxies.

As is well known, and recently shown for GZ1 spirals by Masters et al. 2010a, early-type spiral galaxies with large bulges tend to be redder than late-type spirals, so the observed trend in Fig. 6 could be due to a correlation between colour and bulge size. To explore this, we split the trend of bar fraction with colour (seen in Fig. 3) into four broad disc galaxy types of

(i) no bulge present with fracdeV < 0.1,
(ii) small bulge with 0.1 < fracdeV < 0.5,
(iii) large bulge with 0.5 < fracdeV < 0.9 and
(iv) dominant bulge of fracdeV > 0.9.

The results of this division are shown in Fig. 7, which shows that late-type disc galaxies (with low fracdeV) have a low bar fraction (except the very reddest as also seen in Masters et al. 2010b) while early-type discs have a high bar fraction. This shows that the bar fraction correlation with colour is primarily driven by bulge prominence.

At this point, it is important to recognize the different types of bulges that are observed to be present in disc galaxies (Athanassoula 2005). In particular, there is a distinction in the literature between *classical* bulges and *pseudo*-bulges. The former appear to resemble a classic elliptical galaxy which just happens to be within a disc (and are often assumed to be formed by merger events) while the latter are disc-like bulges more consistent with being formed by the redistribution of material within the disc. These *pseudo*-bulges as they are called have almost exponential profiles (Kormendy & Kennicutt 2004), while classical bulges more closely follow a de Vaucouleur profile; however (as is seen in elliptical galaxies themselves), a range of profile shapes is observed in bulges which vary with the luminosity of the bulge (Graham & Worley 2008, and references therein), and since dEs can also form with almost exponential profiles, pseudo-bulges may not necessarily be formed by secular evolution (Graham & Worley 2008).

Our use of fracdeV as a proxy for bulge size is likely to be most effective in selecting classical bulges (although any central excess over the disc's exponential profile would favour a larger fracdeV). In the bottom panel of Fig. 7, we see that most of our GZ2 disc galaxies with large fracdeV values have red $(g-r)$ colours (also as discussed in Masters et al. 2010a). It is well known that pseudo-bulges are more common in bluer later type spirals while redder early-type spirals are more likely to host classical bulges (e.g. Kormendy & Kennicutt 2004; Drory & Fisher 2007) and although it is oversimplistic to say that all late-type spirals have pseudo-bulges and all early-types have classical bulges (Graham & Worley 2008), there is clearly a trend.

Therefore, we tentatively interpret our observed trends of increased bar fraction with fracdeV and $(g-r)$ colour as hinting that early-type red disc galaxies (preferentially with a classical bulge) have a higher fraction of bars than later type blue disc galaxies (preferentially with pseudo-bulges or no bulge).

4 DISCUSSION

4.1 Comparison with other work

The literature on bar fractions is extensive going back to seminal early work on optical galaxy catalogues. Many studies have attempted to separate the bar fraction into galaxies of different morphological types (e.g. Odewahn 1996; Knapen et al. 2000; Elmegreen et al. 2004) and a picture is emerging which suggests that the bar fraction found in a given sample might depend quite sensitively on the morphological and stellar mass make-up of the sample being considered (as recently discussed by Giordano et al. 2010 and Nair & Abraham 2010b). One must of course be careful in comparing any galaxy properties across studies using samples at different redshifts and with different morphological and luminosity/mass distributions, but a review of results from different studies is still useful to put our results into context.

In this work, we observe a significant increase in the bar fraction of disc galaxies as the galaxies become redder and have more prominent bulges. We also observe a small increase in the very bluest galaxies in our sample. This suggests that the bar fraction is the highest in early-type discs, has a minimum somewhere in the blue cloud of spiral discs and increases slightly towards the latest type spirals.

In fact there has been a suggestion for some time that bar fraction does not vary monotonically with galaxy type. Both Odewahn (1996) and Elmegreen et al. (2004), using visual classifications of RC3 galaxies, observe that the (strong) bar fraction (i.e. spiral types SB) decreases from around 60 per cent in S0/a to 30 per cent in Sc, after which it increases again towards very late-type discs. Interestingly both studies also show that the weak (or mixed type SAB) bar fraction is much flatter with Hubble type and if anything shows the opposite trend. Knapen et al. (2000) used the same RC3 data to argue that the bar fraction remains relatively flat across all types of disc galaxies; however, the trend they show in their fig. 1 (for strong bars at least) appears consistent with that used by both Odewahn (1996) and Elmegreen et al. (2004) to argue for variation.

Almost concurrently with this work, Giordano et al. (2010), in a multiwavelength study of galaxies in the Virgo cluster, show that the bar fraction depends sensitively on the morphological composition of a sample. In qualitative agreement with our results, they find in a sample of ∼300 disc galaxies that early-type spirals have a higher bar fraction (45–50 per cent) than late-type spirals (22–36 per cent) and suggest that the difference could be explained by the higher baryon fraction of earlier type spirals.

Also in very recent work, Nair & Abraham (2010b) discuss the bar fraction in 14 043 visually classified galaxies (all classified by PN; Nair & Abraham 2010a) and like us find the bar fraction to depend on morphology with a minimum near the division between the blue and red sequences. They suggest that to reconcile the apparently conflicting results on the bar fraction (and in particular the evolution of the bar fraction with redshift) found in the literature one needs only to consider the different stellar mass ranges of the samples in question.

Other recent work on the bar fraction at low redshifts ($z < 0.1$ or so) also support this broad picture of bar fraction having a minimum at around Sc types and rising towards both earlier and later spiral/disc galaxy types. For example, Laurikainen et al. (2009) study the bar fraction in 127 early-type spirals and find it increases from Sas to S0/a (but then drops significantly in S0s – however distinguishing unbarred S0s from elliptical galaxies is notoriously hard and may bias the S0 bar fraction low). At first glance our results appear in conflict with those of Barazza et al. (2008), Aguerri et al. (2009) and Weinzirl et al. (2009) all of whom argue that the bar fraction increases as bulge prominence decreases; however, we suggest that sample selection may again be the culprit, with these studies actually picking out significantly later spiral types than are found in our sample, and therefore seeing only the bluest end of the trend we show.

For example, Barazza et al. (2008) and Aguerri et al. (2009), who both find larger bar fractions in later/bluer disc galaxies (using a local sample of ∼2000 'disc' or spiral galaxies from the SDSS), both use automated techniques to identify a disc/spiral sample of galaxies based on concentration and velocity dispersion (Aguerri et al. 2009) or colour (Barazza et al. 2008, this study also considered Sersic fits, but the final results were for a colour-selected sample of 'spiral' galaxies). If we restrict our analysis to the range of colours explored by Barazza et al. (2008), then much of the trend we see in Fig. 3 is missed and we would have actually witnessed a mild decrease in bar fraction towards the redder spirals, fully consistent with their findings. In more detail, we mimic the Barazza et al. (2008) selection by using their $U - V$ colour cut (from Bell et al. 2004) with colour transformations from Smith et al. (2002), plus $i < 60^\circ$, and $0.01 < z < 0.03, M_g < -18.5$. For this matched GZ2 sample, we find a flat bar fraction of 25 per cent, with no obvious trend with $(g - r)$ colour, except for a slight upturn for the reddest objects [at $(g - r) \sim 0.6$].

Comparing our results to those at higher redshifts must be done with caution (considering the different stellar mass ranges considered – we remind the reader that our sample consists of disc galaxies with stellar masses between 10^9 and 10^{10} $\mathrm{M}_\odot$). However, it is interesting that we observe a similar trend of bar fraction to that shown in the COSMOS sample ($z \sim 0.2$–0.8) by both Sheth et al. (2008, in 2157 spiral galaxies) and Cameron et al. (2010, in 3187 disc galaxies). Both these studies find more bars in redder disc galaxies at intermediate stellar masses of $10^{10.5} < M < 10^{11}$ $\mathrm{M}_\odot$, which is similar to the high end of the mass range of our sample. We note that Cameron et al. (2010) finds this trend changes at masses $>10^{11}$ $\mathrm{M}_\odot$, but there are almost no such galaxies in our volume-limited sample.

While we find a similar overall bar fraction to the STAGES study of barred galaxies in a dense cluster at $z \sim 0.2$ (Marinova et al. 2009) our findings on the trends of bar fraction with other properties differ substantially from that study. They observed that bar fraction (in ∼800 galaxies found from ellipse fitting to B-band images) rises in brighter galaxies and those which have no significant bulge component and that bar fraction had no dependence on disc galaxy colour. While we do see an increase in bar fraction for brighter spirals (from 26 ± 1 per cent for those with $M_r > -20$, to 37 ± 2 per cent for those with $M_r < -22$), we argue that this is driven by the strong colour dependence of the bar fraction and at a fixed colour we see little dependence of bar fraction on luminosity (Fig. 4) – the trend we find is also much smaller than that seen by Marinova et al. (2009).

Similarly, we agree with the overall bar fraction of 25 per cent found for 945 galaxies by Barazza et al. (2009) across both field and cluster environments at $z \sim 0.4$–0.8 (observed in rest frame $B - V$). However, we again find opposite trends of bar fraction with bulge prominence (they find more bars in bluer disc-dominated galaxies).

The source of these discrepancies is unclear. Disc galaxies were identified visually in both studies; so they should be similar to our GZ discs. We do use quite different bar-finding techniques (visual versus ellipse fitting), so perhaps this indicates a difference in the trends for strong (visual) and weaker bars (as also hinted at by Odewahn 1996 and Elmegreen et al. 2004). More interestingly it could be pointing to a difference between disc galaxies in high-density regions and those elsewhere [as also discussed by Giordano et al. (2010) who find similar results to us in Virgo cluster galaxies]. Barazza et al. (2009) explored differences between bar fractions in the field and clusters finding hints that high-density regions are favourable locations for bars; however, this could only be done for a subset of the sample ($N = 241$), making the results of limited statistical significance. These possibilities will be explored in future work exploiting the huge number of bar classifications available to us in GZ2.

There does remain a difference in our overall conclusions with Barazza et al. (2008) and Aguerri et al. (2009) and, in particular, the total bar fraction we find is lower than either of these studies. It has been argued that bars in early-type spiral galaxies tend to be longer (and thus stronger) than those seen in late-type spirals (Athanassoula 2003), so it may be that the remaining differences are due to our sensitivity to these longer, stronger bars, while Barazza et al. (2008) and Aguerri et al. (2009) may detect weaker bars using their ellipse-fitting techniques. The cross-over between the sample used here and that in Barazza et al. (2008) is small (as we have argued above it is this mismatch which explains the different trends we see in bar fraction with colour and bulge prominence), but in ∼400 galaxies found in both samples, we find GZ2 bars in ∼25 per cent of the objects while the number of barred objects rises to roughly twice that in the Barazza et al. (2008) classifications. The two bar classification methods agree ∼75 per cent of the time – most of the difference is from Barazza et al. (2008) identified bars not being found by GZ2. Further studies directly comparing the bars identified from ellipse-fitting methods and the GZ2 identifications will be needed to understand the main reason for this difference. Such a comparison is in progress (Masters et al., in preparation). However, it is interesting that the bar fraction difference between the two techniques is rather similar to the split between strongly barred (SB), weakly barred (SAB) and non-barred (SA) galaxies in both the RC3 (e.g. Sellwood & Wilkinson 1993; Eskridge et al. 2000) and the de Vaucouleurs Atlas of Galaxies (Buta, Corwin & Odewahn 2007). This seems to further indicate that (as we suggested above) GZ2 bars should be identified with strong bars (SB types) only and so the trends we observe should most likely be considered trends in the fraction of strong bars.

4.2 The impact of bars on disc galaxies

Given the trends we have observed, we now focus on the interpretations we can make for the effect of bars on the secular and dynamical evolution of disc galaxies. We observe a significant increase in bar fraction as disc galaxies become redder and have larger (classical) bulges; over half of red, bulge-dominated disc galaxies have a bar.

Our observations suggest an important link between the presence of a bulge (perhaps preferentially a classical bulge with a de Vaucouleur profile) and the existence of a bar instability. Bar instabilities are often invoked as a way to form pseudo-bulges (with an exponential profile) by moving material around in the disc of a spiral galaxy (see Kormendy & Kennicutt 2004 for a comprehensive review of this subject), but classical bulges are usually thought to have formed during a fast, dissipative process (most likely related to galaxy mergers), which would have likely disrupted any bar. However, using a sample of 143 local galaxies with bulge–disc–bar decompositions, Weinzirl et al. (2009) argue that most bright spirals have (almost) pseudo-bulges and comparing with cosmological simulations argue that most of these must have been made by a combination of minor mergers and secular evolution. Perhaps it is this link we are seeing in the Galaxy Zoo sample.

In Giordano et al. (2010) the observation that the barred fraction is higher in early-type disc galaxies in their Virgo cluster sample is tentatively explained by a combination of the higher baryon fraction in early-type galaxies (which makes their discs heavier and therefore more susceptible to bar instabilities) and environmental effects which might destroy a late-type spiral but would leave an early-type spiral with a bar. Further studies of the environmental dependence of the bar fraction are planned with GZ2 data (Skibba et al., in preparation) and will be used to test this scenario.

We finish by returning to the suggestion that we see two populations of disc galaxies. Both Figs 3 and 7 suggest a split between disc galaxies on the ‘red sequence’, which have large (possibly classical) bulges (may be formed during merger processes), and disc galaxies in the ‘blue cloud’ with either no bulge or a pseudo-bulge. The red sequence population show little change in their bar fraction with luminosity and colour and overall have a high fraction of (strong) bars, approaching 50 per cent. The blue cloud population also show little trend with colour with low bar fractions of 10–20 per cent.

5 SUMMARY

We present here an analysis of the bar fraction of 13 665 disc galaxies selected from the new Galaxy Zoo 2 data set. This sample is volume limited, with $z < 0.06$ and $M_r < -19.38$, and overall we find that 29.4 ± 0.4 per cent of these galaxies have a bar. We split this sample as a function of global colour and luminosity, as well as the prominence of the bulge, and find that redder disc galaxies, with larger bulges have a high fraction of bars (up to 50 per cent). At a fixed colour, bar fraction is seen to decrease slightly with luminosity. These results are consistent with previous visual studies of spiral galaxies (from the RC3 catalogue) as well as several recent studies (Giordano et al. 2010; Nair & Abraham 2010b).

We discuss the implication of our results for different scenarios of disc and bulge formation. Our results suggest a strong link between the presence of a bar and the existence of a large (possibly classical) bulge. We see hints that pseudo-bulges, if most likely found in blue, disc galaxies, will be preferentially in galaxies with no strong bar. This may be contrary to expectations which suggest that pseudo-bulges are built via the redistribution of stellar mass (or induced star formation) driven by a bar instability while classic bulges are formed in merger like events. Furthermore, we observe a colour bimodality in our GZ2 disc galaxies with a ‘red sequence’ hosting large (possibly classical) bulges and possessing a bar fraction of up to 50 per cent, while the majority of disc galaxies are in the ‘blue cloud’ which have either no bulge (or a pseudo-bulge) and possess low bar fractions of 10–20 per cent. These results will now need to be explained in any successful model of disc galaxy formation.

This paper provides the first results from the GZ2 project on bars in disc galaxies. In the future, we will explore the dependence of bar fraction on stellar mass and environment (Skibba et al., in preparation). We will also report on a satellite Galaxy Zoo project, which invited the GZ2 users to measure the length, strength and orientation of bars (detected in the GZ2 sample) via an interactive Google Maps interface, as well as identify the links between the bar and spiral structure (Hoyle et al. 2010). Such data will allow us to extend this work to studies of the correlation of the bar lengths (and bar colours) with global galaxy properties.

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