

**Morphology is a Link to the Past: examining formative
and secular galactic evolution through morphology**

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Abstract

Galaxy morphology is one of the primary keys to understanding a galaxy's evolutionary history. External mechanisms (environment/clustering, mergers) have a strong impact on the formative evolution of the major galactic components (disk, bulge, Hubble type), while internal instabilities created by bars, spiral arms, or other substructures drive secular evolution via the rearrangement of material within the disk. This thesis will explore several ways in which morphology impacts the dynamics and evolution of a galaxy using visual classifications from several Galaxy Zoo projects. The first half of this work will detail the motivations of using morphology to study galaxy evolution, and describe how morphology is measured, debiased, and interpreted using crowdsourced classification data via Galaxy Zoo. The second half will present scientific studies which make use of these classifications; first by focusing on the morphology of galaxies in the local Universe ($z < 0.2$) using data from Galaxy Zoo 2 and Galaxy Zoo UKIDSS. Last, the high-redshift Universe will be explored by examining populations of morphologies at various lookback times, from $z = 0$ out to $z = 1$ using data from Galaxy Zoo Hubble.

The investigation of the physical implications of morphology in the local Universe will first be presented in Chapter 4, in a study of the impact of bars on the fueling of an active galactic nucleus (AGN). Using a sample of 19,756 disk galaxies at $0.01 < z < 0.05$ imaged by the Sloan Digital Sky Survey and morphologically classified by Galaxy Zoo 2 (GZ2), the difference in AGN fraction in barred and unbarred disks was measured. A weak, but statistically significant, effect was found in that the population of AGN hosts exhibited a 16.0% increase in bar fraction as compared to their unbarred counterparts at fixed mass and color. These results are consistent with a cosmological model in which bar-driven fueling contributes to the growth of black holes, but other dynamical mechanisms must also play a significant role.

Next, the morphological dependence on wavelength is studied in Chapter 5 by comparing the optical morphological classifications from GZ2 to classifications done on infrared images in GZ:UKIDSS. Consistent morphologies were found in both sets and similar bar fractions, which confirms that for most galaxies, both old and young stellar populations follow similar spatial distributions.

Last, the morphological changes in galaxy populations are computed as a function of their age using classifications from Galaxy Zoo: Hubble (Chapter 6). The evolution of the passive disc population from $z = 1$ to $z = 0.3$ was studied in a sample of 20,000 galaxies from the COSMOS field and morphologically classified by the Galaxy Zoo: Hubble project. It was found that the fraction of disc galaxies that are red, as well as the fraction of red sequence galaxies that are discs, decreases for the most massive galaxies ($\log(M/M_{\odot}) > 11$) but increases for lower masses. The observations are consistent with a physical scenario in which more massive galaxies are more likely to enter a red disc phase, and more massive red discs are more likely to morphologically transform into ellipticals than their less massive counterparts. Additionally, the challenges of visual classification that are particular to galaxies at high redshift were investigated. To address these biases, a new correction technique is presented using simulated images of nearby SDSS galaxies which were artificially redshifted using the FERENGI code and classified in GZH.

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Chapter 1

Introduction

The clues to galaxy formation and evolution are hidden in the fine details of galaxy structure.

Peng et al., 2002

The processes which govern the formation, growth, and eventual death of galaxies are uniquely difficult to investigate. A galaxy cannot ever be directly observed from its birth to its death; the only data available is a single snapshot of the Universe as it exists at the moment of observing, in its current cosmological state. To begin to map out the complete evolutionary history of a galaxy, astronomers must instead use other clever, indirect methods.

One of the most powerful tools for revealing the physical processes that shape the evolution of galaxies is their morphology. Morphology refers to the visual appearance of a galaxy, which is set by the distributions of its stellar orbits. Particular features may include (but are not limited to) disks, rings, bars, clumps, or spiral arms. What determines which of these features develop in a given galaxy (or, what determines the particular stellar distribution of a galaxy,) is the galaxy's dynamical history, which encompasses environmental interactions, star formation histories, and influences from dark matter and AGN. Specifically, details of a galaxy's structure are known to be linked with its color (Tully, R.B., Mould, J.R., Aaronson, 1982; Strateva et al., 2001; Baldry et al., 2004), recent star-formation (Conselice, 2006; Martin et al., 2007a; Mignoli

et al., 2009), merger rate (Hammer et al., 2009; Oesch et al., 2010; Smethurst et al., 2017), and black hole activity (Athanassoula, 1992; Friedli & Benz, 1993; Schawinski et al., 2010), among others. There is no debate today that morphology is strongly linked to galactic evolution, but the extent to which these relationships hold is still difficult to quantify. Morphological classifications on scales large enough for results to claim statistical significance have been, in the past, unavailable. While expert visual classifications succeeded in accuracy, they lacked in numbers, and the opposite has been true for computational methods.

The research described in this thesis examines the link between morphology and evolution using data from the Galaxy Zoo project, which uses crowd-sourcing to provide a “best-of-both-worlds” approach to morphological classifications. To date, over one million volunteers have identified the structures of over one million galaxies, providing the benefits of both visual inspection and large numbers. With these data, the ways in which morphology drives (or is driven by) a galaxy’s evolution has been investigated on a scale previously unachievable. Three topics will be considered in detail: the influence of bars on AGN activity (Chapter 4), the dependence of observed wavelength on tracing different stellar populations (Chapter 5), and the interplay between quenching mechanisms and morphological transformations of galaxies from redshift $z \sim 1$ (Chapter 6). This thesis also includes a detailed summary of the methodology used in collecting and reducing crowd-sourced data from Galaxy Zoo in the local Universe (Chapter 2) and introduces a new technique for debiasing high-redshift GZ classifications using data from simulated galaxies (Chapter 3). First, this Introduction will describe the typical components of a galaxy resulting from its formation, then give a brief summary of morphological types as have been defined historically, as well as the current evidence linking morphology to galaxies’ past histories.

1.1 Galaxy Formation

Galaxies are believed to have initially formed from primordial density fluctuations shortly after the Big Bang, as predicted by the Λ CDM model of Cosmology (Peebles et al., 1994; Ryden, 2006; Conselice, 2012; Silk et al., 2013). In this model, fluctuations δ can be characterized as the contrast of the local density in a region ρ as compared

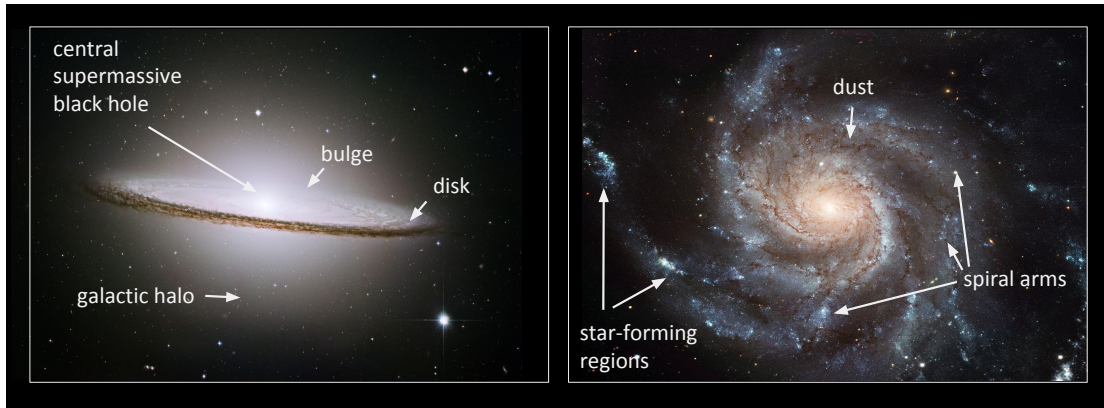


Figure 1.1 A side-on (left) and face-on (right) view of typical spiral galaxies. The edge-on view gives a clear visual of the disk, bulge, and galactic halo components. The face-on view reveals the detailed spiral structure within the disk. **Left:** Hubble image of Sombrero galaxy, M104. Credit: European Space Agency. **Right:** Hubble image of Pinwheel galaxy, M101. Credit: European Space Agency.

to the mean density of the Universe, $\bar{\rho}$: $\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$. Gravitational instabilities will cause even small perturbations ($\delta \ll 1$) to grow exponentially with time; as $\delta \rightarrow 1$, the region collapses and breaks off from the expanding universe, becoming a self-gravitating structure.

The collapse of these protogalactic regions of overdensity triggered the formation of the first stars and galaxies around $z \sim 11$, about 400 thousand years after the Big Bang. At this time in the early Universe’s history, the only baryonic matter in existence was Hydrogen and Helium, in a ratio of H : He $\sim 4 : 1$. The very first stars to form in the first proto-galaxies were thus comprised of only these two elements; for this reason they are classified as “extremely metal-poor stars” (EMPs), or Population III stars. Heavier elements formed later in the cores of EMPs, allowing for the formation of the metal-rich stars more commonly observed in galaxies today. As such, different populations of stars are often classified by their metallicity, measured by the amount of heavier elements they contain relative to Hydrogen $[Z/H]$. Population II stars have metallicities of $[Z/H] < 0.1\%$; while they are still considered metal-poor, the presence of any metal requires that they were formed from gas generated from the deaths of the earlier Population III stars. Population I stars are the youngest observed, with

metallicities $[Z/H] \sim 2 - 3\%$.

The structure and components of a typical galaxy are shown in Figure 1.1. Most galaxies are believed to form with a disk component (Kormendy & Kennicutt, 2004), which is a product of the dynamics governing the initial galaxy formation. As large gas clouds cool and collapse, conservation of angular momentum causes the cloud to flatten and increase rotation speed, resulting in a disk shape. Young, Population I stars tend to form in the spiral arms of the disk, and particularly dense regions of star formation can give the arms a patchy appearance. Most galaxies are believed to contain a supermassive black hole in the center; while not observed directly, their influence on the galaxy in the form of feedback has been intensely studied (see Chapter 4 for details). Surrounding the black hole and often taking up a significant part of the galaxy is the central bulge, which tends to be comprised of older Population II stars. Both the disk and the central bulge can be destroyed as the galaxy evolves, transforming the galaxy’s morphology into a purely elliptical structure. It is believed that this morphological evolution is tied to the shutting-down, or quenching, of star-formation, due to ellipticals tending to host only older stellar populations (see Chapter 6). Permeating the galaxy is the largest observable component: the galactic halo, which contains gas which fuels ongoing star-formation, and stars which extend to the outer regions of the galaxy. Last, all of the luminous components are embedded in a dark matter halo, which cannot be observed directly, but interacts with the baryonic matter gravitationally.

While the preceding describes the elements of a typical galaxy, this does not begin to describe the wide range of morphological features that can be found. Disk galaxies for instance may have any number of spiral arms or no arms at all, or show evidence of rings or bars. Many galaxies do not even exhibit disk or elliptical structure at all but instead have irregular or clumpy appearances. This next section will describe in more detail the variances in the shapes of galaxies, and how the different structures are grouped into morphological classifications.

1.2 Morphological Categorization of Galaxies

The oldest and most well-known system which categorizes galaxies based on their structure was developed by Edwin Hubble, commonly known as the “Hubble Tuning-Fork”

(Hubble, 1926). Using a small sample of images of nearby galaxies, Hubble identified two fundamental morphological classes: spirals, which exhibited well-defined disk structure and clear spiral arms, and ellipticals, whose light distributions were smoothed over a roughly spherical shape. Only 3% of the sample had structures which deviated from these two categories, showing no evidence of rotational symmetry about a dominating nucleus; these were grouped together and labeled “Irregular”. Although Hubble’s system was originally based on a mere 400 galaxies, the classifications are still used for describing the morphologies of the millions of galaxies identifiable today (albeit with some modifications, e.g. DeVaucouleur’s revised system (de Vaucouleurs, 1963)).

An example of Hubble’s Tuning Fork is shown in Figure 1.2. The classifications defined on the Tuning Fork are as follows:

1.2.1 Ellipticals

The left side of the tuning fork contains elliptical galaxies, labeled “E”. These were originally identified as circular through flattened ellipses whose luminosity faded smoothly from the center to “indefinite edges.” The only other structural feature evident to subdivide this class were their ellipticities, defined in the traditional way $e = (a - b)/a$. A number is added to the label that represents the ellipticity, with the decimal omitted, whereby E0 would represent a purely spherical elliptical ($e = 0$), and E7 being the most elongated ($e = 0.7$). Hubble assumed that any galaxy with an ellipticity higher than 0.7 was no longer an elliptical, but more likely a highly-inclined spiral. It should be noted that these labels only classify the *projected* appearance; since ellipticals are tri-axial structures, this classification system is very dependent on the orientation angle of any ellipticals which are not perfectly spherical.

1.2.2 Spirals

The right side of the fork contains the various types of spiral galaxies. These all share the feature of having a flattened disk-shape, and often have a spherical bulge of stars in the center with spiral arms extending outward. Spirals whose arms originate from the central bulge follow the top of the fork, labeled “S”, while those whose arms originate at the ends of a central galactic bar follow the bottom, labeled “SB”. Both types are

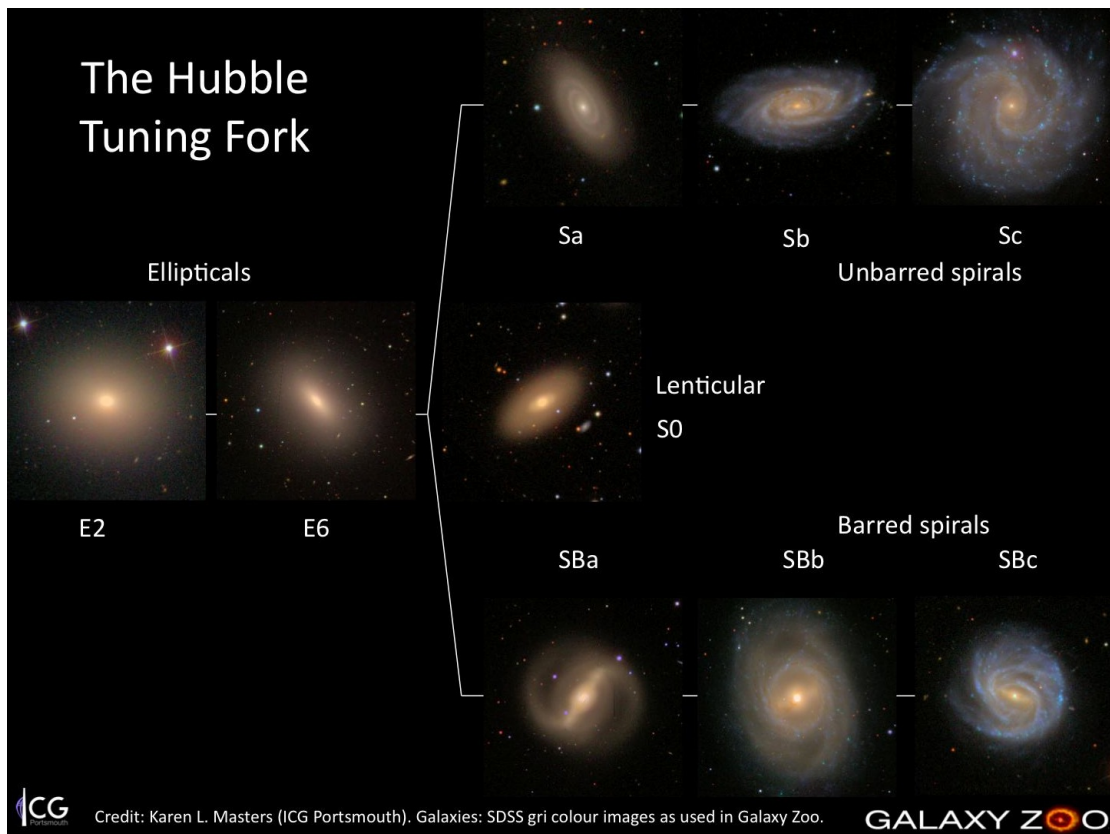


Figure 1.2 The Hubble Tuning fork with SDSS color-composite (gri) images as examples of the various types. Credit: Karen Masters and The Sloan Digital Sky Survey (SDSS) Collaboration.

further classified based on the relative size of the central bulge and tightness of the arms. Those with large bulges and tighter arms are designated with an “a” attached to the spiral symbols, or “b”-“d” for decreasing bulge sizes and looser appearance of arms.

1.2.3 Lenticulars/S0s

Lenticular galaxies are placed at the center of the tuning fork, originally thought to be a transition stage to link the elliptical and spiral types. They exhibit the same overall disk-shape as the spirals, but have a smooth appearance rather than defined arms (which can make them difficult to distinguish from true ellipticals). They may or may not contain a galactic bar, giving them Hubble-type classifications of S0 (unbarred) or S0B (barred).

Hubble originally referred to the galaxies toward the left and right on the fork as “early” or “late”-type, respectively, simply for convenience in describing their relative positions on the sequence. While it is noted in his 1926 paper that any temporal connotation should be disregarded, the terms remain misleading in that it is now well-known that the early types tend to have older stellar populations, and late-types tend to be very young in their evolution. Nevertheless, “early-type” and “late-type” are still today used interchangeably when referring to ellipticals/S0s and disks.

1.3 Morphology as a tracer of galaxy evolution

The previous section describes the most common morphological types of galaxies observed in the Universe. At this point it may be relevant to question why are there different types at all? Do the different shapes exhibit different evolutionary pathways, or is the snapshot we see of the distributions simply showing different stages of a track that all galaxies eventually follow? The answers to these questions aren’t fully known; however, examining the relationships between the different morphological types and their dynamics can provide strong insights to the full picture. This section will provide some examples of well-known links between morphology and galaxies’ evolutionary histories.

1.3.1 Color-Morphology Bimodality

The color of a galaxy is a strong indicator of its recent star formation history. In general, optically blue galaxies are in the process of forming new stars, emitting high energy blue light that is detected abundantly in short-wavelength filters. In contrast, galaxies which have ceased forming stars sometime in the past contribute most of their flux to long-wavelength filters, resulting in redder colors. Perhaps surprisingly, there is also a strong correlation between the color of a galaxy and its morphology. The majority of galaxies ($\sim 80\%$) have been shown out to $z \sim 1$ to follow this relationship: blue galaxies tend to be late-type spirals, and red galaxies tend to be early-type/elliptical (Tully, R.B., Mould, J.R., Aaronson, 1982; Strateva et al., 2001; Baldry et al., 2004; Conselice, 2006; Martin et al., 2007a; Mignoli et al., 2009). An example is shown in Figure 1.3.1. The vertical axis tracks the $u - r$ color, such that larger values are “redder” and smaller values are “bluer”. The horizontal axis tracks the absolute magnitude: more luminous galaxies towards the left, and dimmer towards the right. Bluer galaxies tend to have more featured morphologies; spiral arms appear more flocculant and clumps of star formation are apparent, generating irregular shapes in the extreme cases. Redder galaxies begin to have a much more smoothed-out and symmetric appearance, encompassing both ellipticals and bulge-dominated lenticulars. Color has long been considered such a strong indicator of morphology that it has been often used as a proxy for morphology when large-scale visual inspection has not been practical (Cooray, 2005; Lee & Pen, 2007; Salimbeni et al., 2008; Simon et al., 2009). This link is strong evidence that the processes which drive both morphology and the cessation of star formation are related in some way (Masters et al., 2010; Buta, 2013). This topic is explored in greater detail in Chapter 6.

1.3.2 Morphology and Stellar populations

At the most basic level, morphology is simply a tracer of the observed distribution of light in the galaxy, which in turn traces the distribution of stars, gas, and dust. All light is not emitted equally, however: younger, Population I stars will emit more light in optical and UV wavelengths, while older Population II stars emit more strongly in the infrared. Since these populations may have very different spatial light distributions, there is inherently some dependence on morphology with the wavelengths within which

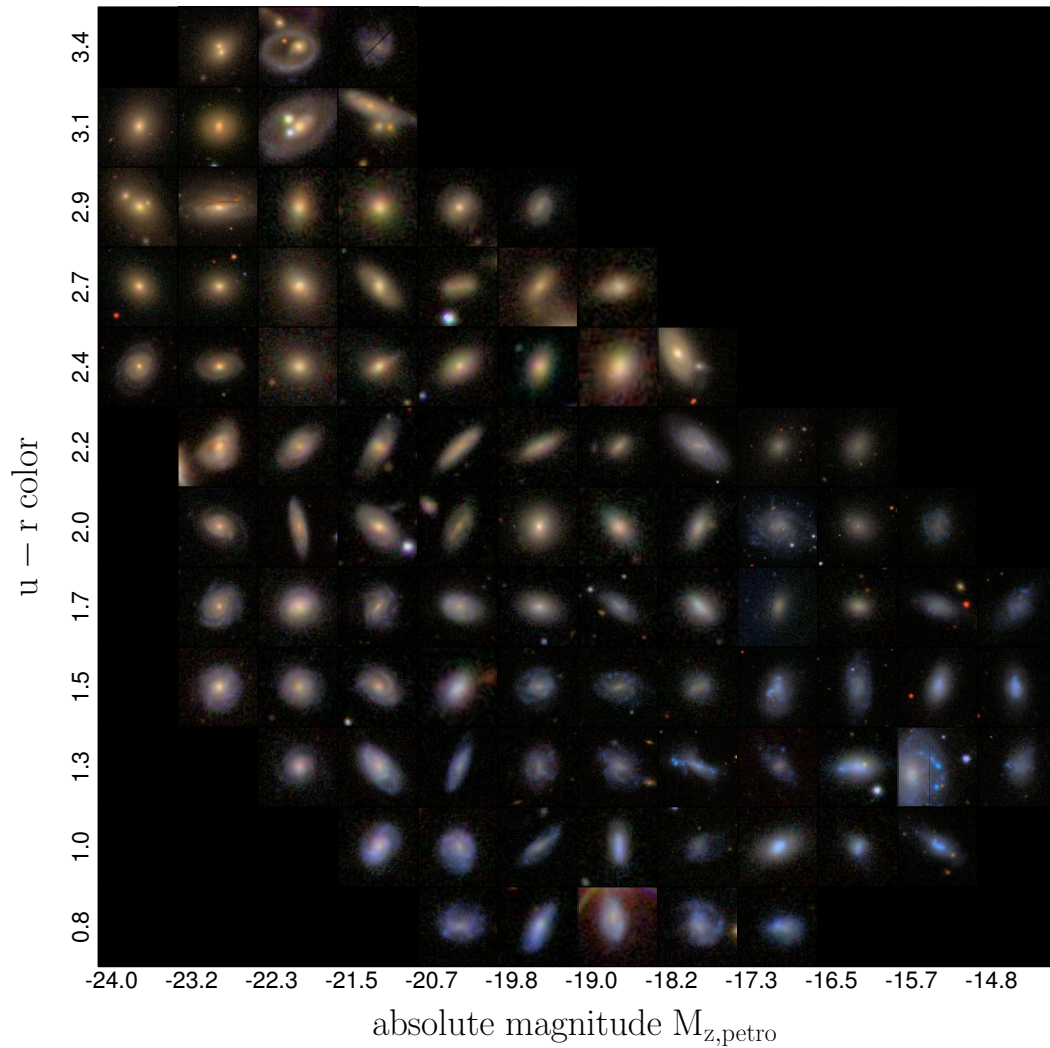


Figure 1.3 Color vs. Absolute Magnitude Diagram, illustrated using SDSS galaxies. In each color-magnitude bin, a random galaxy was selected meeting the criteria defined by that bin. The bottom-left and upper-right regions contain very few or zero galaxies, a consequence of typical galaxy evolution. As galaxies age and continue forming stars, they build up more stellar mass, increasing their total luminosity. Hence the most luminous galaxies tend to be older and more massive, and unlikely to be dominated by younger stellar populations. This results in a dearth of luminous blue galaxies (bottom left) or faint red galaxies (upper right).

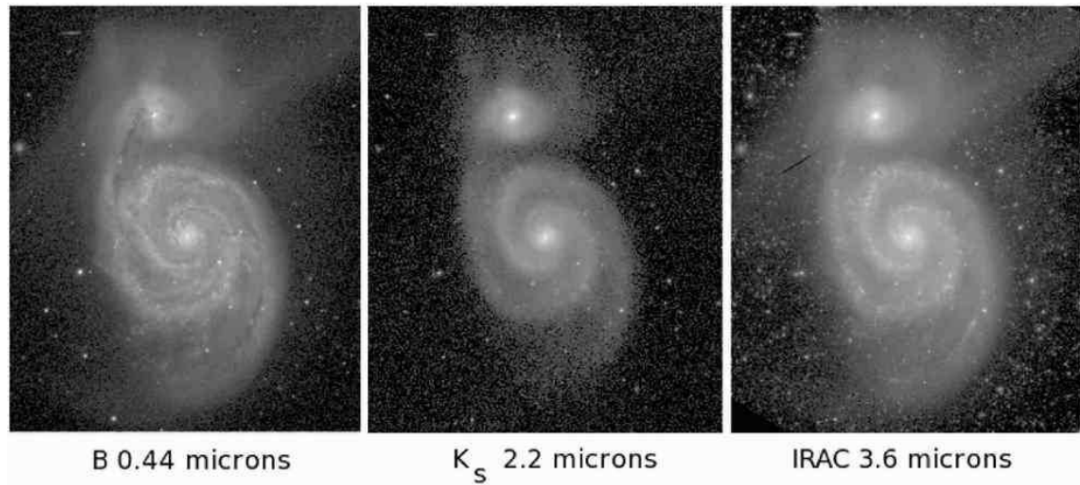


Figure 1.4 Credit: Buta (2013), Figure 2.51. Spiral galaxy M51 observed in optical B-band (left), near-IR (middle), and mid-IR (right). Visible in the B-band image are patchy regions of star-formation and dust lanes, which become invisible in the near-IR, giving an overall smoother appearance. The mid-IR image shows regions where the dust re-radiates light absorbed from star-forming regions, giving a similar appearance to the optical image.

it is observed.

Morphologies observed in optical bands are sensitive to pockets of star-formation regions, but other features can be obscured due to dust extinction, particularly those comprised of older stellar populations (such as bars); this can give galaxies an overall “patchy” appearance. In contrast, they appear smoother in the near-IR, where the effects of dust extinction are reduced and the older stellar populations dominate. An interesting effect occurs as the observation wavelength moves into the mid-IR: here, dust tends to re-radiate the light absorbed from star-formation regions, re-creating the appearance of the optical-band morphology. There has been debate as to whether the optical and near-IR morphologies are de-coupled to the extent that two classification schemes, one for each wavelength range, is justified (e.g. Block & Puerari (1999)). Chapter 5 will examine the optical and near-IR morphologies measured by Galaxy Zoo to add to this debate, as well as investigate whether bars are in fact easier to identify in the near-IR.

1.3.3 Morphology and Environment

A galaxy’s environment can also be a predictor of its morphology. The morphology-density relationship, first quantified by Dressler (1980), observes an abundance of elliptical/ early-type morphologies in denser environments (de Souza et al., 1982; Postman, M. Geller, 1984). Since the merger rate correlates with environment density, it could be suggested that early-types are often the by-products of mergers, as opposed to a stage of isolated secular evolution.

There is also evidence of an environmental impact on morphology even in the absence of direct merging. For example, ram pressure (Gunn & Gott, 1972) exerted by the local intracluster medium can severely distort the gas distribution in a galaxy, resulting in asymmetries in the disk (ex. NGC 4402; see also Chapter 6).

1.3.4 Bars

Galactic bars are found in an estimated 30%-60% of spiral galaxies (Sellwood & Wilkinson, 1993). They are elongated structures passing through the center of their host galaxies, and primarily dominated by older stellar populations (Eskridge et al., 2002) which often gives them a redder appearance with respect to the disk, which tends to be bluer from star-forming components in the spiral arms (see the “SB” types in the bottom row of the diagram in Figure 1.2 for example images of galaxies containing bars). Buta (2013) describes barred galaxies as “the ultimate in galaxy morphology.” His reasoning is simple: just by observing an image of a bar, it is easy to identify it as a major perturbation in an otherwise stable system. There is a great deal of truth in this; such a disruption will no doubt have significant effects on the fate of its host galaxy. In this way, bars are arguably one of the most important structural features that can shape a galaxy’s evolution.

A key feature of bars is their ability to drive gas from the outer regions of the galaxy to the center (Athanasoula, 1992; Friedli & Benz, 1993; Sellwood & Wilkinson, 1993; Shlosman et al., 1989; Ann & Thakur, 2005), which can affect the galaxy’s evolution in numerous ways. One such consequence is the formation of a pseudo-bulge (Kormendy & Kennicutt, 2004; Sheth et al., 2005). While this is seen in simulations, this theory is difficult to confirm observationally, as the bar may or may not be destroyed by this

process (Athanasoula et al., 2005), causing difficulty in identifying a correlation between populations of galaxies with both bars and bulges.

An increased inflow of gas to the center may also increase central star-formation. Several studies have reported an increase in star-formation rates in the central region of barred galaxies vs. their unbarred counterparts (Hawarden et al., 1986; Ho et al., 1997), although this may only be true for strong bars. Martinet & Friedli (1997) and Zhou et al. (2014) find low rates of star-formation in galaxies with weak bars, suggesting they are unable to trigger significant star formation. Galaxies with strong bars, however, show both the highest and lowest rates of star-formation. (Sheth et al., 2005) found a significant portion of barred galaxies with no molecular gas detected in the nuclear region, which may suggest that for these galaxies, the bar has already driven most of the gas to the nuclear region, where it was consumed by star-formation. Bars, then, seem to play two important roles in the star formation history of their host galaxies - both by increasing star formation, and subsequently driving the quenching process.

Bars also may be one of the mechanisms which enable the fueling of an active galactic nucleus (AGN), whose evolution is believed to be strongly linked to that of their host galaxies (Schawinski et al., 2007, 2010; Antonini et al., 2015; Yang et al., 2017; Zubovas & Bourne, 2017) (and Heckman & Best (2014) for a comprehensive review). The requirements for onset of accretion onto the central SMBH are still unclear, but Moles et al. (1995) argues that non-axisymmetric components of the gravitational potential may be a necessary condition; a requirement which bars easily satisfy. While simulations have shown bars to provide the necessary inflow to ultimately fuel an AGN (Athanasoula, 1992; Friedli & Benz, 1993), observations have shown mixed results. Many have found an excess of AGN in barred samples of galaxies (Knapen et al., 2000; Oh et al., 2012), while others find no difference (Ho et al., 1997; Mulchaey & Regan, 1997; Cheung et al., 2015). A discussion of the discrepancies between these results, along with my own investigation of this topic, is the subject of Chapter 4.

The examples listed are only a few of the well-known relationships between the evolution of galaxies and their morphologies. There is little doubt amongst astronomers that morphology and galactic evolution are linked; however, as evident in these examples, some links are still inconclusive and the research of these relationships is still ongoing. Results are becoming more defined now, as methods to classify galaxies according to

their morphologies are constantly improving. Some of the results listed from previous decades suffered from low-sample statistics, where it was only feasible to visually classify handfuls of galaxies in a single study. Today, more robust methods are able to categorize galaxies morphologically in a fraction of the time once required. The next section will explore the evolution of classification methods used to obtain galaxy morphologies for such studies.

1.4 Methods for morphological classification

Historically, morphological classification has been done by visual inspection of small samples of images (e.g. Hubble (1926); Sandage (1961); de Vaucouleurs (1963); Block et al. (1994); Eskridge et al. (2002); Buta et al. (2010)), by either a single person or handful of experts. This method is becoming obsolete as we enter a new era of large data, with surveys such as the Sloan Digital Sky Survey (SDSS) and HST-Legacy surveys, in addition to the upcoming James Webb Space Telescope, the Large Synoptic Survey Telescope, and Euclid, producing high-quality images of hundreds of thousands of galaxies. To date, the largest morphological catalogs created by visual inspection from a small group of experts includes the Nair and Abraham catalog (Nair & Abraham, 2010) with $\sim 14,000$ galaxies, RC3 Catalog (de Vaucouleurs, 1991) with $\sim 23,000$ galaxies, and MOSES (Schawinski et al., 2007) with 50,000 galaxies. Even these catalogs, while successful, do not compare in size to the newly incoming data, and so more powerful and robust efforts are required to obtain morphological information on these scales.

An ideal method for handling the large amounts of data would be an automated classification scheme. Several such algorithms have been developed, with some success (Odewahn et al., 2002; Peng et al., 2002; Conselice, 2003; Scarlata et al., 2007) by using the stellar light distribution of the galaxy to assign it a morphological class. These approaches tend to be limited to identifying the global morphologies (ie, spiral or elliptical), and lack the precision to accurately identify finer, detailed features (such as bars or the number of spiral arms) (Beck et al., 2017). Further, they tend to incorporate proxies for morphology as their input, which are often not reliable (as detailed in the next paragraph). Much more promising techniques are currently being tested which incorporate the use of machine-learning algorithms and neural networks (Dieleman et al.

(2015); Huertas-Company et al. (2015); Beck et al., (2017) (submitted)), but these require massive and accurate training-sets to perform properly.

One alternative to direct visual classification of morphologies is the use of proxies such as color, mass, surface brightness profile, or some combination of several. Color is commonly used as a proxy because of its mostly-tight relationship global morphology, in that spirals tend to be red and ellipticals tend to be blue. This type of morphological classification will always suffer from a high degree of inaccuracy, as there is no perfect physical measurement that is 100% correlated with shape. The morphology of a galaxy typically traces the dynamical history, whereas proxies such as color trace stellar growth; these two properties thus reveal different evolutionary histories on possibly very different timescales (Fortson et al., 2012). Last, while there are several proxies which correlate somewhat with the probability of a galaxy being spiral or elliptical, very few could be used to identify finer substructures or more detailed morphological features within the overall shape.

A best-of-both-worlds approach uses the power of crowdsourcing, which uses the input of tens of thousands of individuals to visually classify galaxies in a fraction of the time achievable by a handful of experts; such a method was developed by Galaxy Zoo, the data from which is used throughout this thesis. The Galaxy Zoo project uses a simple online interface whereby images of galaxies are visually inspected by volunteers, which allows the identification of intricate morphological features to a higher degree of accuracy than computer algorithms today can achieve. Additionally, with a required 40+ independent contributions per galaxy, we obtain information about the accuracy of each classification which could not be determined from a single expert vote. The next chapter will describe how Galaxy Zoo collects data from volunteer citizen scientists, how the data is reduced and debiased, and finally how the data is used to assign morphological classifications to large samples of galaxies.

Chapter 2

Methodology

2.1 A Brief History of Galaxy Zoo

The increasing accessibility of the Internet in the last few decades has allowed scientists to “outsource” tasks online using citizen science, with huge success. The project Seti@Home¹ (Anderson, 2002), launched in May 1999, was one of the first projects that revealed the massive number of people willing and excited to help contribute to science. Since launch, over 5 million participants donated idle time on their computers to assist SETI in analyzing radio telescope data to help in the search for extraterrestrial life. Citizen scientists were also extremely interested in taking an even more active role in research, as seen in a later project Stardust@Home², in which volunteers searched for dust grains in data via a web interface. This project engaged over 20,000 volunteers, and those who discovered dust grains were invited to become co-authors on the announcement papers. Early citizen science projects such as these inspired the launch of Galaxy Zoo.

The real need for a faster method of obtaining galaxy morphologies for large samples was realized in 2007 by graduate student Kevin Schawinski, who was studying populations of elliptical galaxies as work for his PhD thesis at Oxford University. At the time, the accepted and fastest method for identifying early-type galaxies (in large quantities) was to select based on SDSS-measured spectra (Bernardi et al., 2003). He

¹ <http://setiathome.berkeley.edu/>

² <http://stardustathome.ssl.berkeley.edu/>

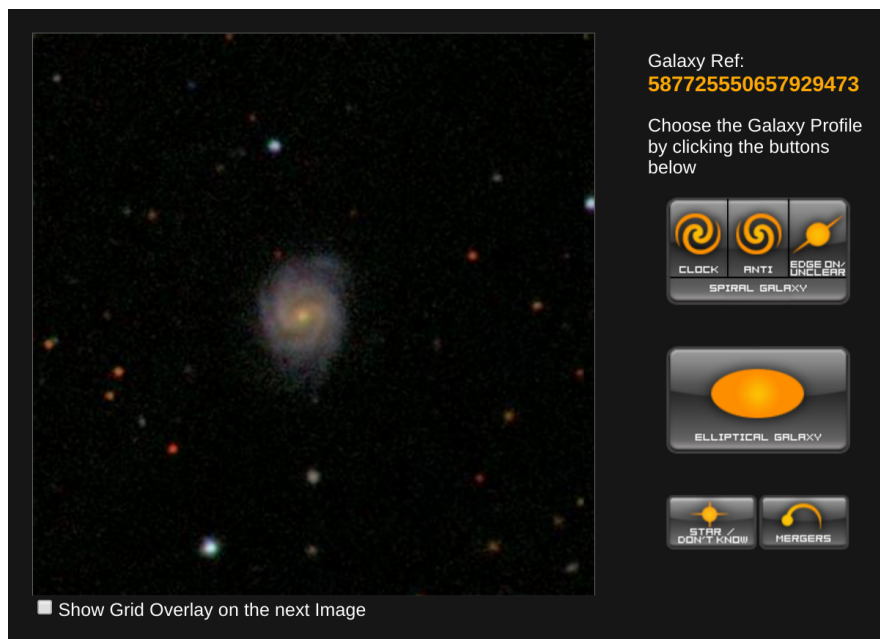


Figure 2.1 Example of the interface seen by users of Galaxy Zoo 1. On the left is an image of a galaxy from the SDSS main sample. On the right are possible features the user may identify about the galaxy by clicking the relevant option(s). Once complete, they are shown another galaxy.

knew, however, that this sort of method would exclude potential star-forming ellipticals (as well as potentially include passive spirals), due to the non-perfect correlation between morphology and color, as mentioned in the previous Chapter. So, realizing that a visual inspection of the direct appearance of the galaxies was necessary to create a complete sample of ellipticals independent of color, Schawinski devoted an entire week to classifying 50,000 galaxies by eye (MOSES, Schawinski et al. (2007)).

The grueling task of classifying only a small fraction of the SDSS main sample ($\sim 900,000$ galaxies) made it apparent that a better method for visual classification was becoming necessary. Inspired by the 20,000 volunteers who participated in the Stardust@Home project, Schawinski and Oxford colleague Chris Lintott realized that it would only take a few years to classify the entire SDSS main sample, assuming a similar participation response as Stardust@Home. This led to the launch of Galaxy Zoo in July, 2007. This first phase (known now as Galaxy Zoo 1, or GZ1), included the brightest (Petrosian magnitude $r < 17.77$ AB mag) 893,212 images from SDSS Data Release 6

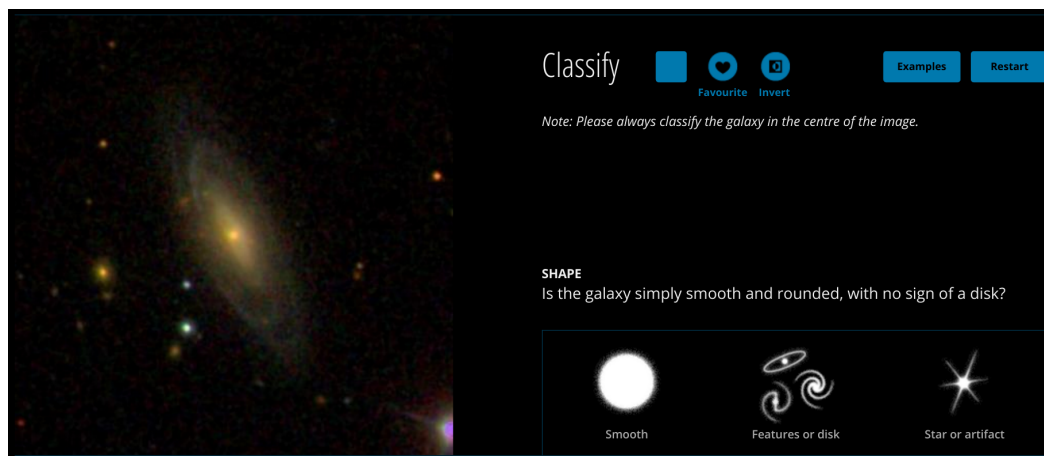


Figure 2.2 Example of the interface seen by users of Galaxy Zoo 2. On the left is an image of a galaxy, on the right are possible features the user may identify about the galaxy by clicking the relevant option. Unlike GZ1, subsequent questions appear about the same galaxy depending on their answers to the preceding questions, following a decision tree format (see Figure 2.3 for a visual of all possible pathways.)

(Strauss et al., 2002; AdelmanMcCarthy et al., 2008). In this project users were asked to identify simple features of a given galaxy, including whether it was elliptical or spiral, clockwise or anticlockwise, a merger, or star/other (the original interface with options is shown in Figure 2.1).

In just the first day of the site being live, 70,000 classifications were coming in each hour - a rate much faster than the developers had ever expected. In less than a year, the entire SDSS main sample was classified by an average of 38 volunteers per galaxy. Following the GZ1 data release paper published in April, 2008 (Lintott et al., 2008), over a dozen scientific publications were released which made use of the GZ1 morphological classifications³. Significant results included the discovery of a large population of passive red spirals in the local universe (Masters et al., 2010), the existence of star-forming blue ellipticals (Schawinski et al., 2009), “green peas,” a new class of galaxies exhibiting extremely high specific star formation rates (Cardamone et al., 2009), and “Hanny’s Voorwerp,” the first example of AGN-photoionized clouds detected near galaxies no longer actively hosting AGN (Lintott et al., 2009).

Galaxy Zoo continued hosting additional sets of galaxy images for crowd-sourced

³ <https://www.zooniverse.org/about/publications>

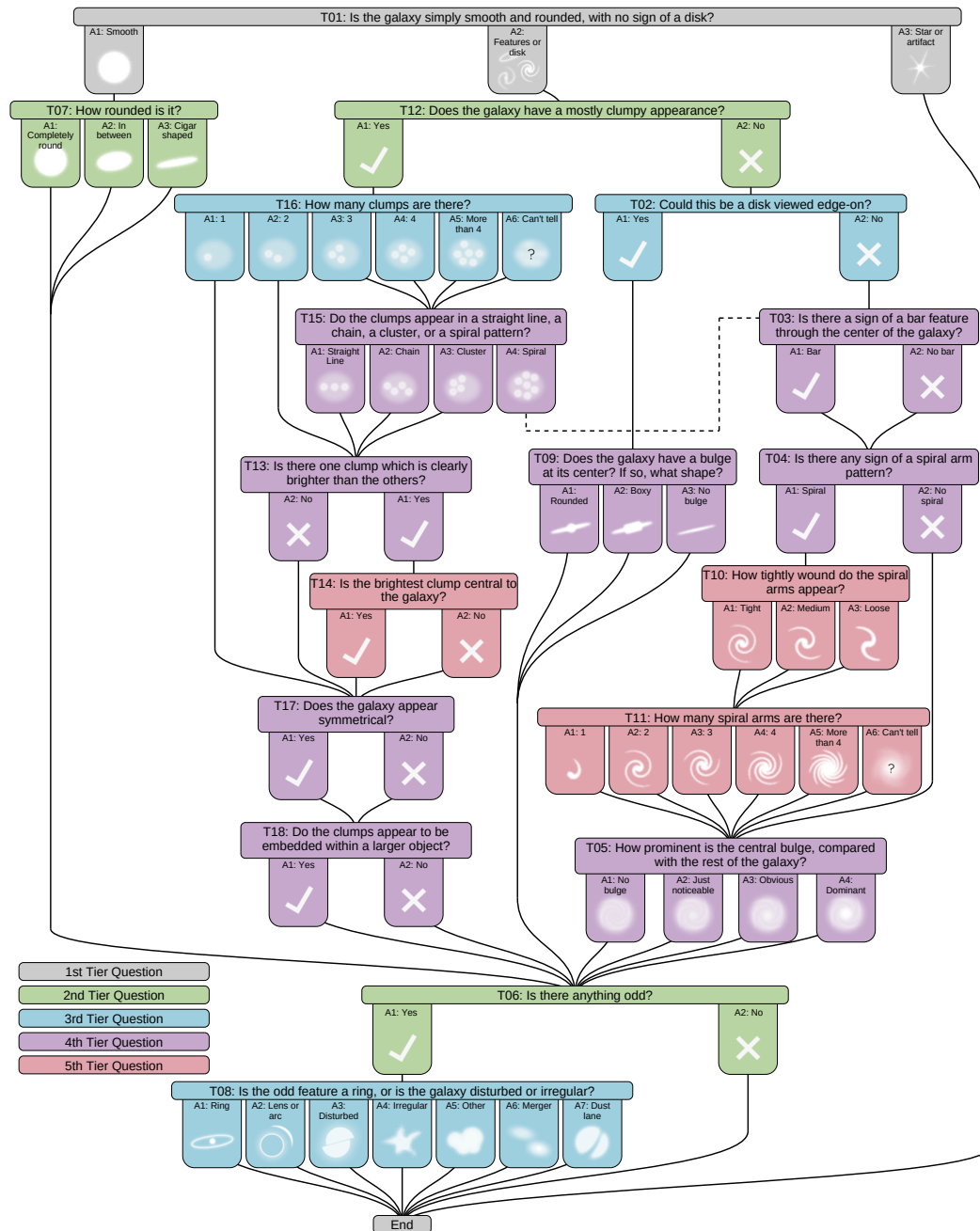


Figure 2.3 Decision tree used in the Galaxy Zoo:Hubble project. The colors indicate the “Tier” level of the question. Gray represents 1st-Tier; these are asked of all users. Green are 2nd-Tier; these are only asked after responding to a 1st-Tier question, and so on. This tree is identical to GZ2 and UKIDSS, except for the addition of the clumpy questions T12-T18.

classification following the success of GZ1. The immediate successor, Galaxy Zoo 2 (GZ2) was a subset of GZ1, consisting of the brightest $\sim 25\%$ of the SDSS main sample, and was the first to implement the decision tree structure (Figures 2.2 and 2.3). Later projects introduced a variety of imaging types, including infrared (GZ:UKIDSS), high-redshift (GZ:Hubble, GZ:CANDELS), and even simulated images (Ferengi (artificially redshifting), GZ:Hubble (color-inversion and simulated AGN), Illustris). A summary of all major projects is given in Table 2.1.

It is also worth highlighting the educational impact of a citizen science approach to data collection. Science education research has shown that active participation is a critical component in scientific learning. S. Michaels, A. W. Shouse (2008) define four “strands” of skills that students must obtain to be considered scientifically proficient, the fourth being “participating productively in science.” Citizen science provides both students and the general public the opportunity to actively participate in science without having to already be experts in the field, and it has been obvious so far that the volunteers are enthusiastic to do so. Raddick et al. (2010) investigated the motivations driving the participation of GZ users through surveys and interviews, and found the desire to contribute significantly to important research was one of the primary examples (other motivations including enjoying the beauty of the galaxy images and a general interest in astronomy).

The remainder of this Chapter will outline the common practices used to turn Galaxy Zoo data “from clicks to classifications,” through the use of consistency-weighting the user votes and adjusting vote fractions for redshift bias.

2.2 Galaxy Zoo Data Reduction

2.2.1 User weighting by consistency

A typical Galaxy Zoo project collects classifications from over 10,000 unique volunteers. With such large numbers of classifiers, there exists the possibility that some fraction of these are “unreliable”, that is, their votes are consistent with random clicking. To ensure that all votes collected represent real classifications, a weighting technique is implemented to detect and down-weight unreliable votes.

The weighting scheme used for all GZ projects represented in this thesis (GZ2,

Table 2.1 List of major completed Galaxy Zoo projects since 08/2017. All projects have used optical images of galaxies, with the exception of UKIDSS (infrared, see Chapter 5). N_{images} refers to the number of *subjects* classified in the project, which may include duplicate unique galaxies (see data release publications for details). $N_{\text{classifications}}$ refers to the sum of classifications received for each subject, not the number of *clicks* a subject received (so a user answering 3 questions for a single galaxy would count as 1 classification, not 3). *Surveys included in HST Legacy are AEGIS, COSMOS, GEMS, GOODS-N and GOODS-S single and 5-epoch.

	dates active	source	N_{images}	$N_{\text{classifications}}$
GZ1	7/07 - 2/09	SDSS DR6 main sample	893,212	34,617,406
GZ2	2/09 - 4/10	SDSS DR7 $r < 17$ + stripe-82	366,178	16,340,298
GZ:Hubble	4/10 - 9/12	HST Legacy* + SDSS stripe-82	182,525	10,349,357
GZ: CANDELS	9/12 - 11/13	CANDELS	52,073	2,149,206
Ferengi	10/13 - 1/14	SDSS, artificially redshifted	6,624	265,092
GZ:UKIDSS	10/13 - 5/14	UKIDSS	70,977	2,749,010
DECaLS	9/15 -	DECaLS	94,024	4,192,479
Illustris	9/15 -	Illustris, simulation	63,640	1,174,018
Ferengi 2	12/16 - 2/17	SDSS, artificially redshifted	7,488	300,890
GAMA	1/17 -	GAMA-KiDS	19,605	533,671
Totals			1,756,346	72,671,427

GZ:UKIDSS, and GZ:Hubble) evaluates the consistency of each user by how often their votes agree with the majority for each task in the decision tree. The consistency rating κ for a single task is defined as:

$$\kappa = \frac{1}{N_r} \sum_{i=1}^{N_r} \kappa_i. \quad (2.1)$$

N_r represents the total number of responses to the task, $\kappa_i = f_r$ if the user's vote corresponds to response i , and $\kappa_i = (1 - f_r)$ if it does not, where f_r is the vote fraction for each response in the task. In this system, κ is then high if the vote agrees with the majority, and low if it does not.

The mean consistency computed for each response given is defined as the user's overall consistency $\bar{\kappa}$, summed over all tasks. The user is then assigned a weight w defined as:

$$w = \min(1.0, (\bar{\kappa}/0.6)^{8.5}). \quad (2.2)$$

The constants 0.6 and 8.5 were chosen to effectively downweight only users with the lowest consistencies (Willett et al., 2013). All votes are then recalculated using the user weights, and the process is repeated as many as three times to ensure convergence. It can be seen in Equation 2.2 that a user's weight value is always less than or equal to one; in other words, users are only downweighted in cases of noticeable inconsistency, and never upweighted. Willett et al. (2013) show that most users with low consistencies tend to only have contributed a handful of classifications, which could either indicate that users become more accurate as they classify more galaxies, or that inconsistent users are inherently less likely to be interested in the project.

2.2.2 Classification bias in the local Universe

For samples of galaxies limited to the local universe ($z \lesssim 0.2$), there is no expected redshift dependence on the morphological classifications. Therefore, we would expect vote fractions representing different morphological features to be constant with respect to redshift. However, this is not the case - the average vote fraction for features, bars, spirals, and several others actually tend to *decrease* with redshift. Since we assume

such features should be equally prevalent at any redshift in this small range, some bias unrelated to any true morphological evolution must be affecting the vote fractions.

The source of this bias comes from the apparent size and brightness of the images of the galaxies being classified, which are strongly affected by redshift. Images of more distant galaxies appear smaller and dimmer, and therefore finer features are simply more difficult to detect. This sort of classification bias is a problem with any morphological classification, whether it be expert classifiers, automated detection, or crowd-sourced visual inspection.

This section will describe the methods used to correct this type of classification bias for galaxies in the local Universe, where no true morphological evolution is a factor. Beyond the local Universe this assumption is no longer valid, so techniques implementing classifications of artificially-redshifted galaxies are used for calibration; these are described in detail in Chapter 3.

Debiasing Galaxy Zoo 2: W13 method

The first technique for debiasing Galaxy Zoo classifications was developed by Bamford et al. (2009). This method was used again for the GZ2 classifications in Willett et al. (2013), with slight modifications to account for 1) the GZ2 classifications were derived from votes through a decision tree, rather than a single response per galaxy, and 2) answers to tasks in GZ2 are not all binary as they were with GZ1. This section will describe the technique in the context of GZ2, noting that the physical assumptions used are the same in both methods. It will hereafter be referred to as the W13 method (to differentiate from the methods in subsequent sections).

The debiasing technique used in GZ2 assumed firstly that galaxies with similar brightnesses and sizes should, on average, share similar mixes of morphologies at any redshift in the small range of this sample $0 < z < 0.25$. Using this assumption, galaxies were grouped into bins of absolute magnitude M_r , Petrosian effective radius R_{50} , and redshift. For each task in the GZ2 decision tree, the vote fractions for each response in any size/magnitude bin were adjusted so that their average matched the average vote fraction of its lowest-redshift bin. This method is described in detail in Willett et al. (2013), but the main approach is as follows:

For a given size/magnitude bin, the ratio of vote fractions for a pair of responses i

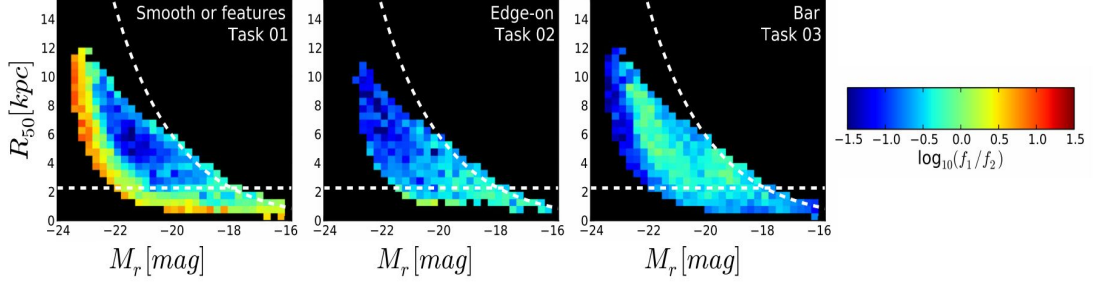


Figure 2.4 Local ratios of morphologies for the first three tasks in the GZ2 decision tree, used to derive debiased votes for the GZ2 sample. The full figure which includes baseline ratios for all tasks in the GZ2 decision tree is shown in Willett et al. (2013), Figure 5.

and j for a single task can be written as f_i/f_j . Due to the classification bias described above, this ratio may not reflect the “true” ratio for this size/magnitude range, but can be written in terms of the true ratio with a multiplicative constant $K_{i,j}$:

$$\left(\frac{f_i}{f_j}\right)_{z=z'} = \left(\frac{f_i}{f_j}\right)_{z=0} \times K_{i,j}, \quad (2.3)$$

where $(f_i/f_j)_{z=z'}$ represents the ratio measured in a size/magnitude bin at $z = z'$, and $(f_i/f_j)_{z=0}$ is the “true,” or intrinsic ratio of vote fractions, defined as the ratio measured in the lowest redshift bin.

Figure 2.4 shows the local ($z = 0$) ratios of f_i/f_j for the first two responses i and j for the first three tasks of the GZ2 decision tree, which are used to calculate the debiased vote fractions as outlined above. For Task 01, f_i/f_j corresponds to $f_{smooth}/f_{features}$, for Task 02 $f_{edgeon}/f_{not\ edgeon}$, and for Task 03 $f_{bar}/f_{no\ bar}$. The figure demonstrates the size and magnitude dependence of the most local morphological populations: for example, in Task 01, the largest and brightest galaxies tend to have more votes for “smooth” than “featured”, which is consistent with our current understanding that ellipticals tend to be larger and more massive than spirals.

Figure 2.5 shows the results of both the W13 method and of an alternate approach (which will be described next in Section 2.2.2) for the first three Tasks in the GZ2 decision tree. For each response in each Task, the average vote fraction is calculated as a function of redshift. Solid lines represent the weighted/non-debiased votes and

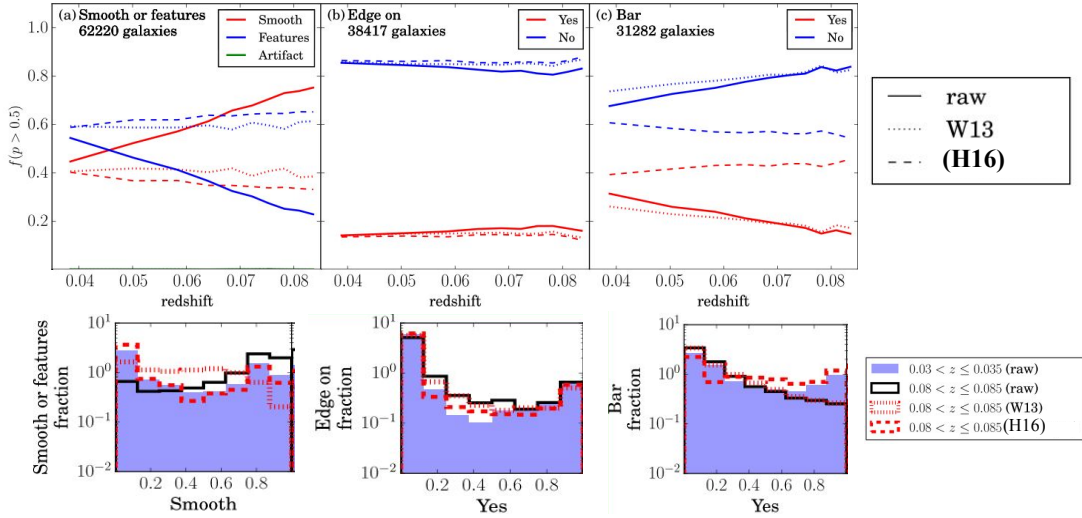


Figure 2.5 Credit: Hart et al. (2016), Figures 8 and 9. **Top:** Plotted are the fraction of galaxies with vote fractions greater than 0.5 for each response to the first 3 tasks, where the solid lines are the raw vote fractions, dotted are the W13 debiased vote fractions, and dashed-dotted lines are debiased with the H16 method. As an example of the effect of the debiasing, see panel (a): without the debiasing, the number of galaxies with a “smooth” majority vote fraction increases sharply from $z = 0.04$ to $z = 0.8$, a range assumed to be local enough such that no true morphological evolution should be observed. Both debiasing methods work to keep the fractions constant over this redshift range, although the H16 method is more effective at higher-tier questions. **Bottom:** Distributions of vote fractions for the first answer to the first 3 tasks, for the low-redshift raw data (solid blue), higher redshift raw data (black solid line), W13 debiased (red thin-dashed line), and H16 debiased (red thick-dashed line). Both methods are successful at shifting the high-redshift distributions to match the low-redshift distribution, with H16 being slightly more effective at matching the shape of the distributions.

the dotted lines are the debiased votes using this method. The redshift dependence on vote fraction is very apparent in the downward trend of the solid lines corresponding to responses which detect features, such as $f_{features}$ and f_{bar} in this example. The dashed lines show the effect of the debiasing which attempts to flatten out the distribution. Full figures showing the results for all Tasks in the tree are available in Willett et al. (2013) (Figure 3) and Hart et al. (2016) (Figure 8). From 2013-2017, the debiased vote fractions calculated in this method were used in the majority of published Galaxy Zoo papers, and are used in the study described by Chapter 4.

Debiasing GZ2 and UKIDSS: H16 method

The W13 debiasing method is successful at adjusting the vote fractions to more accurately resemble the “true” distribution of morphologies at low redshift, but has two primary limitations, related to the binning of the data and the inability to replicate the low-redshift vote distributions. First, the rectangular binning of all three parameters (size, magnitude, and redshift) is only effective when the parent sample is large enough that sufficient data per bin remains available after the three dimensional binning. (For example, to require 10 bins in each parameter with at least 50 galaxies per bin, a parent sample must contain at minimum $N=10 \times 10 \times 10 \times 50=50,000$ galaxies, assuming a perfectly even distribution of values in each parameter). GZ2 is not so affected by this limitation, with a parent sample size of $\sim 250,000$ galaxies. However, this is only true when considering the debiasing of the first Task, which is asked of every galaxy. After this Task, the parent sample for computing a correction term decreases as not all Tasks are asked of every galaxy; for example, the Tier 4 Task which asks for the number of spiral arms is only seen by the majority of volunteers in 33,000 galaxies of the full GZ2 sample. Thus debiasing this Task would require a smaller limit on the number of bins per dimension or the number of galaxies per bin, both of which decrease the robustness of the method. Even with a large parent sample for any Task, the rectangular binning is also limited by the inability to account for data which lie on the outer edges of the parameter space, as there tends to be insufficient data in the outer bins.

A new debiasing technique (hereafter H16) was developed by Galaxy Zoo member Ross Hart (Hart et al., 2016) which substitutes Voronoi binning for the rectangular method. Voronoi binning optimizes the shape and location of bins based on the desired

signal for each bin; in this case, the number of galaxies per bin is set initially, and the bins are drawn to fulfill that requirement. In this way, the number of galaxies available for measuring the change in vote fractions for each bin is maximized. Thus, this method is more effective at debiasing smaller samples (such as GZ:UKIDSS which contains only $\sim 70,000$ galaxies; see Chapter 5), where the three dimensional binning preserves the signal in each bin. An example of Voronoi binning GZ2 data in size and magnitude is shown in the left panel of Figure 2.6. Each size and magnitude bin is then Voronoi-binned by redshift.

The second limitation of the W13 method is that while it effectively corrects the vote fractions for any Task so that the average morphology is constant as a function of redshift, it does not account for the *distribution* of morphologies at low redshift. This produces reasonable results when the corrected values are used for population studies, where the percentage of galaxies exhibiting a particular morphology are desired, but may not always reproduce accurate *individual* vote fractions. The H16 method instead corrects the high redshift vote fractions based on the change in distribution of vote fractions observed at low redshift, rather than comparing to only the average values. The first step of this method is shown in the right panel of Figure 2.6. For the low redshift bin of a given task, the cumulative distribution of vote fractions for each response is fit with a continuous function, which is used as the baseline distribution (similar to the baseline average votes in the W13 method.) The vote fractions making up the cumulative distributions at higher redshifts are then adjusted as needed to match the low redshift distribution as closely as possible.

Results of this method are shown and compared to W13 in Figure 2.5. Plotted on the top panel are the fraction of galaxies with vote fractions greater than 0.5 for each response to the first three tasks, where the solid lines are the raw vote fractions, dotted are the W13 debiased vote fractions, and dashed-dotted lines are the debiased with the H16 method. Both methods are successful in stabilizing the average morphologies over this local redshift range. The bottom panel shows the distribution of vote fractions of a low-redshift bin (solid blue histogram) and high redshift bin, again for the raw votes (black solid line), W13 method (light dashed red), and H16 method (solid dashed red). It can be seen here that while both methods can reproduce the average vote fractions at low redshift, the H16 method is more successful in reproducing the distribution of votes

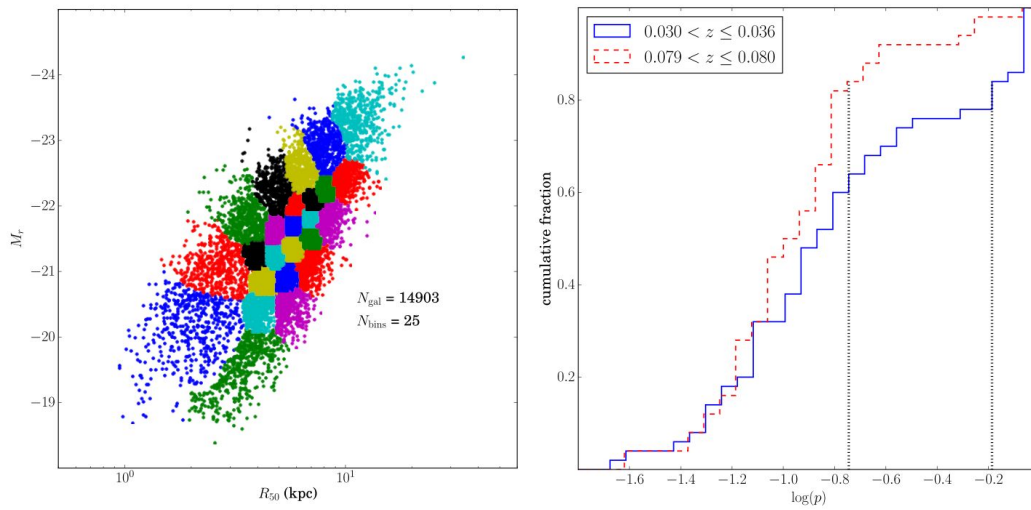


Figure 2.6 Credit: Hart et al. (2016), Figures 5 and 6. **Left:** Voronoi bin distribution for the “> 4” answer to the spiral arm question in GZ2. Each bin is further divided into Voronoi bins, such that each final $R_{50} - M_r - z$ bin contains at least 50 galaxies. **Right:** Cumulative distribution of vote fractions (in log-space) of a single $R_{50} - M_r$ bin, split between a high redshift bin (red dashed line) and a low redshift bin (blue solid line). The debiasing method adjusts the high-redshift vote fractions to match the distribution of the low-redshift distribution.

at low redshift. In this thesis, W13 debiased vote fractions were used in Chapter 4 to conduct the study examining the relationship between bars and AGN using GZ2 data, specifically votes from the first three Tasks in the tree. Chapter 5 examines a smaller data set, the UKIDSS sample, which contains 70,000 galaxies, much smaller than GZ2. For the reasons given in this section, the H16 method was used to debias the votes used in that study.

The science in Chapter 6 examines galaxies residing far beyond the local Universe ($0.2 \leq z \leq 1.0$), whose morphologies were classified in the Galaxy Zoo: Hubble project (Willett et al., 2017), using images from the HST-Legacy surveys. One of the key assumptions in the local-Universe debiasing techniques outlined in this chapter was that no significant morphological evolution exists in that redshift range. This is not a valid assumption for high-redshift galaxies, which are known to exhibit very different morphological populations at earlier epochs. A new debiasing technique was thus developed for the GZH data catalogue, using classifications from artificially-redshifted galaxies to quantify the effect of the redshift bias. The next Chapter will describe the creation and implementation of the simulated data set into the debiasing method applicable for high-redshift galaxies.

Chapter 3

FERENGI: debiasing beyond the local Universe

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3.1 Introduction

The GZ vote fraction f_{features} plays a crucial role in the majority of science cases that use Galaxy Zoo classifications. It represents the fraction of users who answered “feature or disk” to the first question in the decision tree, and is used to distinguish elliptical/spheroidal galaxies from those with features. Many studies aim to measure the population of galaxies exhibiting certain features such as bars (Masters et al., 2010, 2012; Melvin et al., 2014; Simmons et al., 2014; Cheung et al., 2015; Kruk et al., 2017), spiral arms (Willett et al., 2015; Hart et al., 2017), or bulges (Skibba et al., 2012; Simmons et al., 2012), among others. In each of these, f_{features} is necessary for creating the sample of galaxies which could potentially contain the feature in question. This is typically achieved by setting a cut, such that all galaxies with f_{features} greater than that threshold are considered to be candidates for that study.

While f_{features} is not a true probability, the measurement is intended to be consistent

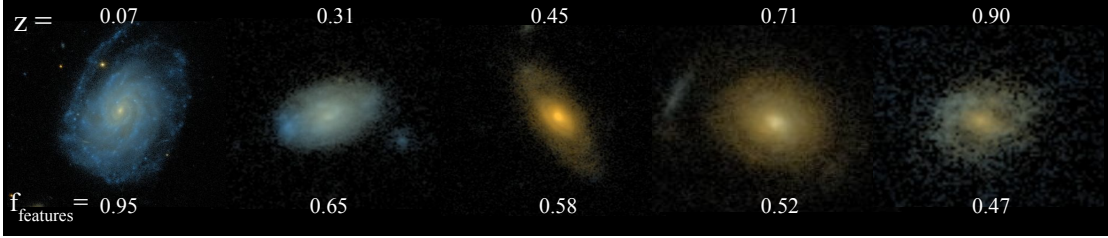


Figure 3.1 Example of the redshift-induced bias in f_{features} . Five images of disc galaxies from the GZH dataset are shown in order of increasing redshift, from left to right. Above each galaxy is its redshift and below is its f_{features} vote fraction. Although all galaxies appear to be discs with features, the vote fraction decreases steadily as redshift increases, as the details in each image become more difficult to distinguish.

among all galaxies; that is, two galaxies with similar f_{features} values should have similar likelihoods of being featured (or not featured). This has been shown to be true at low redshift by comparing the f_{features} values to expert classifications (Willett et al., 2013); there is a strong correlation between this vote fraction and whether the galaxy was expertly classified as a disk or an elliptical.

For distant galaxies, however, we observe that f_{features} is not consistent with nearby galaxies. As galaxies are observed at higher redshift, the images are inherently less resolved, and smaller features are more difficult to identify. This results in a decrease in f_{features} compared to what would be expected if the galaxy had been observed at $z = 0$. Figure 3.1 shows this effect: although each of the five galaxies displayed appear to be discs with features, the fraction of users who identify the images in this way decreases with increasing redshift, as the finer features in each, while still present, become more difficult to resolve. Therefore, two intrinsically identical galaxies, but imaged at different redshifts, may have small to drastic differences in their f_{features} measurements. In order to keep f_{features} a value correlated with the likelihood of having features that is consistent for *all* galaxies, this bias must be corrected.

A method for correcting redshift bias in the GZ vote fractions was developed and implemented in early Galaxy Zoo projects GZ1 (Lintott et al., 2009) and GZ2 (Willett et al., 2013), which both contained nearby ($z < 0.2$) galaxies imaged by SDSS. A correction factor to the classification fractions measured at the higher redshifts was applied by matching the mean vote fractions of those at the lowest redshift. This

technique was valid under the assumption that, within this redshift range, there would be no cosmological evolution of galaxies, and therefore any change in the mean vote fraction for any morphology with redshift was purely due to this observational bias, and not due to a genuine difference in morphological populations. For a full description, see Chapter 2.

In the Galaxy Zoo: Hubble project (hereafter GZH), the redshift range is large enough that cosmological evolution of the morphologies of galaxies is expected, and therefore the previous method of correcting redshift-bias will not work. Instead, a new method of measuring the change in f_{features} as a function of redshift was developed using a set of simulated FERENGI images of galaxies, described in the next section. These images have been classified by volunteers in Galaxy Zoo in the same way as the GZH sample. This chapter will describe how a correction factor for f_{features} is measured using these data as a function of redshift at fixed surface brightness, and subsequently used to debias the GZH sample.

3.1.1 The FERENGI code

The Full and Efficient Redshifting of Ensembles of Nearby Galaxy Images code (FERENGI, Barden et al. (2008)) is an IDL procedure that generates simulated images of nearby galaxies viewed at higher redshifts, taking into account cosmological effects such as surface brightness dimming and bandpass shifting. Artificially redshifted samples of galaxies, for which the intrinsic morphologies are already known from low-redshift observations, are useful for studying the impact these effects have on observed galaxy morphologies. For Galaxy Zoo, such images are particularly useful for measuring the effects of redshift on the volunteer classifications. Through classifications made on a set of artificially redshifted galaxies, any dependence they might have as a function of redshift can be measured, allowing a correction to be applied to classifications on images of real, high-redshift galaxies. The details of this type of debiasing technique will be described in Section 3.3. This section will first provide a brief summary of how the FERENGI code performs the artificial redshifting.

To create realistic images that mimic the seeing and resolution of the HST ACS, the FERENGI redshifting procedure consists of three primary steps (explained in detail in Barden et al. (2008), but here a simplified outline):

i: Modify angular size and surface brightness

FERENGI first rescales the input image by computing the angular size transformation of the galaxy from its input redshift z_i to output redshift z_o . The angular size a of a distant object is proportional to $a \propto d/(1+z)^2$ (using $\tan(a)=a$ for small angles), where d is the luminosity distance to the object. In units of pixels, the transformation from input angular size n_i to output n_o can be expressed as:

$$\frac{n_o}{n_i} = \frac{d_i/(1+z_i)^2 p_i}{d_o/(1+z_o)^2 p_o} \quad (3.1)$$

with an input pixel scale p_i (in this thesis $p_i = 0.396''/\text{pix}$ corresponding to SDSS) and p_o ($0.03''/\text{pix}$, corresponding to ACS). From here a transformation between the observed fluxes is computed, assuming the absolute magnitude is conserved at both redshifts.

FERENGI also offers an option to apply an evolutionary correction to the absolute magnitude, which is helpful for a fair comparison of real and artificial high redshift morphologies. Artificially redshifted galaxies will appear much dimmer than their low redshift counterparts if absolute magnitude is conserved. Since galaxies intrinsically tend to be brighter at high redshift, visual classification of real galaxies cannot be compared as accurately to dimmer, simulated galaxies. To brighten galaxies in a similar way to real galaxies, a magnitude correction e can be input using a linear function:

$$M_{evo} = e \times z + M \quad (3.2)$$

where e represents the magnitude difference between two redshifts separated by $\Delta z = 1$.

ii: Account for bandpass shifting

As a consequence of cosmological expansion, the flux from a source measured using a broadband filter will not, in general, perfectly correspond to the rest-frame flux emitted at the target wavelength range of the filter. Rather, since observed wavelengths are redder than emitted wavelengths as a function of redshift ($\lambda_{obs} = \lambda_{rest-frame}(1+z)$), filters will tend to pick up light that is bluer (in the galaxy's rest-frame) than its target wavelength; this effect is known as *bandpass shifting*. In order to produce fluxes that mimic those measured by ACS at high redshifts, FERENGI simulates the bandpass shifting effects by applying a correction to the output flux calculated via the IDL routine KCORRECT, which incorporates spectral template models from Bruzual & Charlot

(2003), to measure the expected shifts in flux for a given output filter.

iii: Point Spread Function and noise

In order to best mimic the HST ACS resolution, the image is then convolved with a PSF created to be as close as possible in shape and width to the ACS PSF. This is done by deconvolving a typical ACS PSF with the input SDSS PSF for each galaxy. This technique works well in general but has limitations - mainly, the widths of the in- and output PSFs must be sufficiently different. If they are comparable, the convolving function can become too narrow. In these cases, noise overwhelms the output image and results in ringing patterns and other oddities (examples of images with this effect are shown in Section 3.4.1). Since the difference in PSF widths increases with redshift, this imposes a minimum redshift at which FERENGI can successfully create images for any given galaxy (discussed more in Section 3.2). Last, Poissonian noise is added to each pixel.

3.2 The FERENGI sample

To generate an artificially redshifted sample of galaxies to be used in debiasing the Galaxy Zoo: Hubble catalog, a source sample was generated¹ consisting of 288 galaxies from SDSS, all of which were previously classified in GZ2. These galaxies were chosen to span a wide range of morphologies, surface brightnesses, and redshifts. Seven morphological classes were considered: spiral galaxies, edge-on disks without a bulge, edge-on disks with a bulge, face-on disks with a bulge, galaxies with any features, galaxies undergoing mergers, and barred galaxies. For each of these categories, galaxies were chosen from three “strength” bins, defined using the GZ2 vote fractions. Weak strengths were defined as having $f_{class} < 0.2$, intermediate as $0.2 < f_{class} < 0.8$, and strong as $f_{class} > 0.8$. In each strength bin, galaxies were also chosen to represent three different surface brightnesses: $\mu_r > 21.5$, $20.5 < \mu_r < 21.5$, and $\mu_r < 20.5$. Finally, from each morphological class, strength, and surface brightness bin, one galaxy was chosen for four redshift bins: $z < 0.013$, $0.013 < z < 0.02$, $0.02 < z < 0.025$, and $z > 0.025$, with the exception of the bar class, in which two galaxies were chosen for each redshift bin, doubling the sample size for that class.

¹ The source sample for FERENGI was created by the Galaxy Zoo science team in 2012.

The 288 SDSS galaxies were processed with the FERENGI code to mimic *HST* imaging parameters², in order to ultimately measure and correct any redshift-dependent biases in the classifications of the real *HST* images. I-814 and V-606 images, chosen to match the *HST*ACS AEGIS imaging, were output for each subject at a range of redshifts and with a range of applied evolution factors. The range of simulated redshifts possible for any galaxy is dependent on the intrinsic redshift and size of the source galaxy, since the simulated images cannot be resampled at better angular resolution than the original SDSS data. This imposes a minimum simulated “target” redshift that can be achieved for each galaxy. For the lowest redshift bin in the source sample ($z < 0.013$), galaxies could be redshifted the full range of $0.3 < z < 1.0$, in increments of $dz = 0.1$. For the second lowest redshift bin, galaxies could only be redshifted in the range $0.5 < z < 1.0$, for the third, galaxies could be redshifted in the range $0.8 < z < 1.0$, and for the highest redshift bin, galaxies were only redshifted in FERENGI to $z = 1.0$. Only galaxies which were redshifted the full range were considered in the debiasing procedure outlined in the next section (3.3.1), because the method calibrates galaxies to a low redshift of $z = 0.3$, data for which is not available for galaxies in the remaining three redshift bins. Last, for each simulated redshift, a range of evolution factors was applied from $0 < e < 3$ in increments of $de = 0.5$.

The final FERENGI sample totals 6,624 simulated images which were classified as part of GZ4, using the same decision tree as used in GZH. The debiasing technique described next (Section 3.3) used only the 4,446 images corresponding to the 72 galaxies which were redshifted the full $0.3 < z < 1.0$ range. Because the debiasing method takes into account surface brightness as a parameter, photometry was measured for all images using SExtractor³. The mean surface brightness μ within an effective radius (R_e) was calculated as:

$$\mu = m + 2.5 * \log_{10} (2 \times (b/a) \times \pi R_e^2) \quad (3.3)$$

where m is MAG_AUTO in the I_{814W} band, (b/a) is the galaxy ellipticity (the profile RMS along the semi-major and -minor axes), and R_e is the 50% FLUX_RADIUS converted into

² This work was done by Edmond Cheung, a Galaxy Zoo science team member.

³ SExtractor measurements for the original FERENGI sample were done by Tom Melvin, a former Galaxy Zoo science team member.

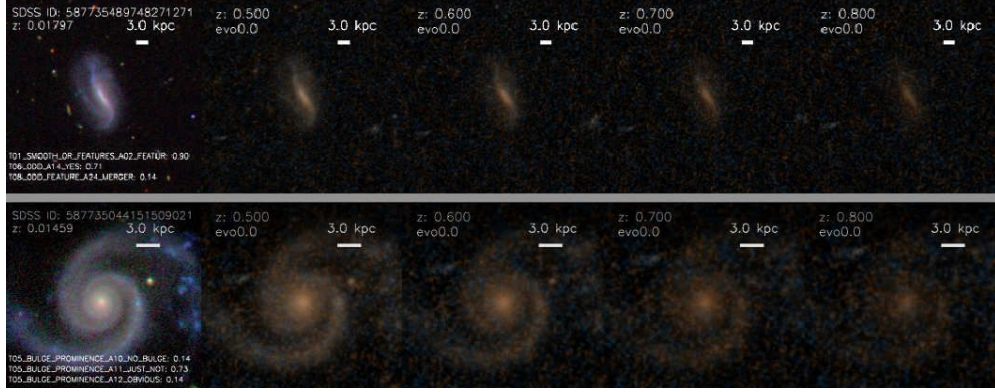


Figure 3.2 Examples of two SDSS galaxies which have been processed by the FERENGI code to produce simulated *HST* images. The measured value of f_{features} from GZH for the images in each panel are (1) Top row: $f_{\text{features}} = (0.900, 0.625, 0.350, 0.350, 0.225)$ and (2) Bottom row: $f_{\text{features}} = (1.000, 0.875, 0.875, 0.625, 0.375)$.

arcsec.

3.3 Measuring the dependence of z and μ on f_{features} using the FERENGI classifications

3.3.1 Identifying “correctable” and “lower limit” samples.

The objective is to use the simulated data from FERENGI to predict, for a galaxy imaged at a redshift z and with a measured $f_{\text{features},z}$ value, what its f_{features} value *would have been* if it had been viewed at $z = 0.3$. This predicted value is defined as the “debiased” vote fraction $f_{\text{features,debiased}}$, and is calculated by applying a correction to the measured value of f_{features} .

The amount that a galaxy’s f_{features} vote fraction must be corrected is assumed to depend primarily on the apparent size and brightness of the galaxy. As described in 3.1, these factors will affect the overall clarity of the image viewed by the GZ volunteers, which in turn affects the likelihood of being able to identify distinct features. The apparent size and brightness are controlled by both intrinsic parameters (absolute size and luminosity), and extrinsic (distance to the galaxy). The change in f_{features} then is measured as a function of redshift (z , an extrinsic feature, measuring distance to

the galaxy), and surface brightness (μ , an intrinsic feature, taking into account both brightness and size).

Figure 3.3 shows the change in f_{features} for FERENGI galaxies in bins of redshift and surface brightness. Points in each z, μ bin represent individual FERENGI galaxies. On the x-axis of each bin is the value of f_{features} measured in that galaxy's $z = 0.3$ image (the lowest redshift of the simulated images). On the y-axis of each bin is the value of f_{features} measured in that galaxy's $z = z$ image, where z corresponds to the redshift associated with that bin. As predicted, the value of f_{features} measured at a higher redshift, z , is, in general, *lower* than the value measured at lower redshift, $z = 0.3$, *for the same galaxy*. This effect is strongest as redshift increases (to the right in Figure 3.3) and as surface brightness decreases (upwards in Figure 3.3).

A reliable predicted value can be obtained so long as the relationship between $f_{\text{features},z}$ and $f_{\text{features},z=0.3}$ is single-valued; that is, for a given $f_{\text{features},z}$, there is exactly one corresponding value of f_{features} at $z = 0.3$. Unfortunately, this is *not* always the case. Figure 3.4 shows f_{features} measured at $z = 1$ vs f_{features} measured at $z = 0.3$ for FERENGI galaxies with average surface brightnesses $\langle \mu \rangle = 20.8$ (a zoomed-in version of the dark outlined bin in Figure 3.3). This figure shows that if the value of f_{features} measured for a galaxy at $z = 1$ is particularly low, there is a wide range that f_{features} could have been if measured at $z = 0.3$. Therefore, a low measured value of f_{features} at high redshift could represent two morphological types of galaxies: 1) The galaxy has no distinguishable features and may be classified as a smooth elliptical, or 2) the galaxy *does* have features, but these have become blurred and too difficult to detect at high redshift.

It is important to identify such regions of surface brightness/redshift/ f_{features} space since vote fractions cannot be confidently corrected to a single value for galaxies in these regions. The criteria for determining whether a region of this space is single-valued, and therefore correctable, is as follows: in each surface brightness and redshift bin, the relationship between $f_{\text{features},z}$ and $f_{\text{features},z=0.3}$ is modelled by fitting the data with polynomials of degrees $n=3, 2$, and 1 , and using the best formal fit out of the three as measured by the sum of the residuals. These fits are shown as the dashed black lines in Figures 3.3 and 3.4. Flat regions of the bins are areas in which there is *not* a clear single-valued relationship between $f_{\text{features},z}$ and $f_{\text{features},z=0.3}$. This is quantified

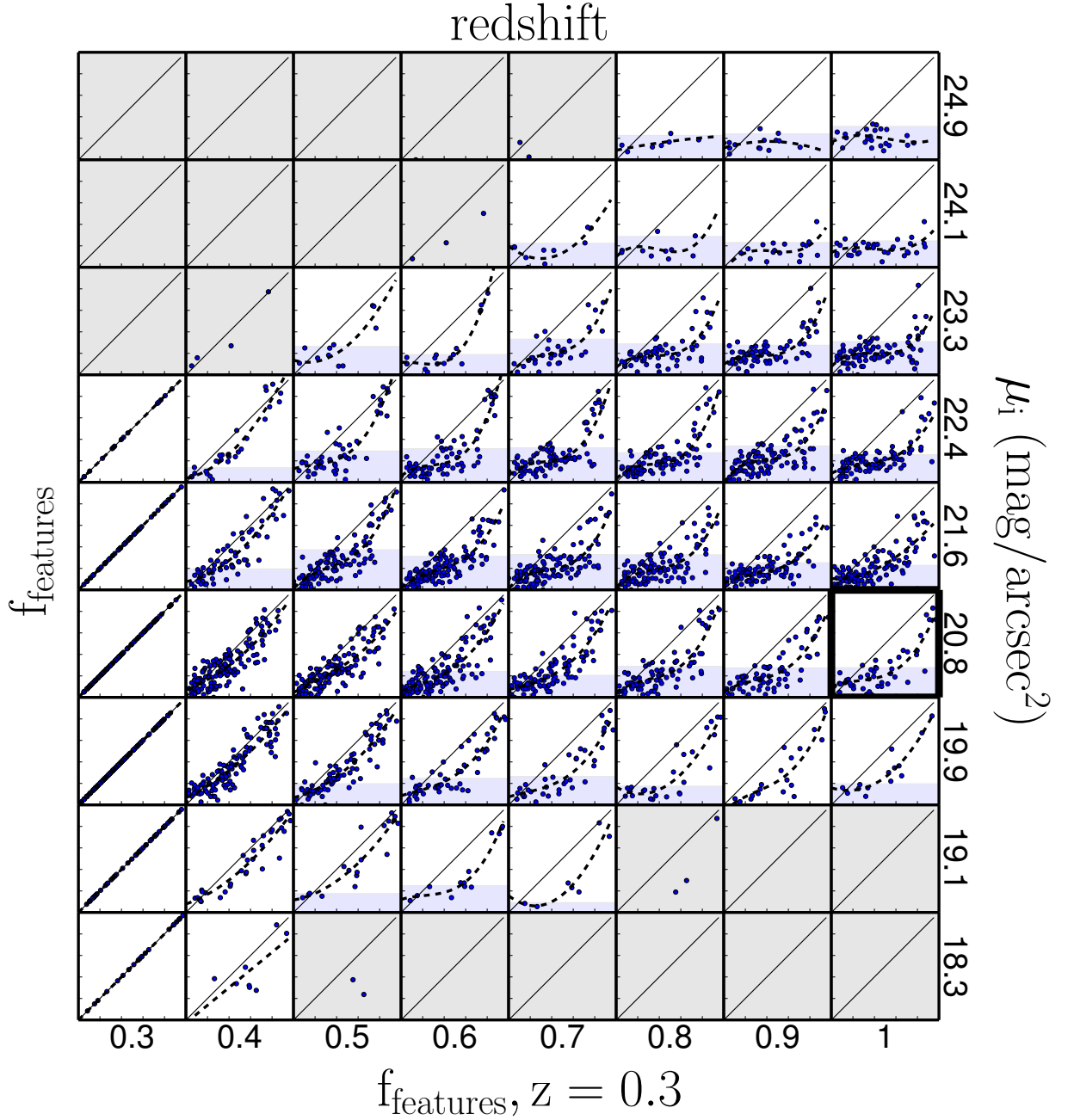


Figure 3.3 Effects of redshift bias in 3,449 images in the FERENGI sample. Each point *in a given redshift and surface brightness bin* represents a unique galaxy. On the y -axis in each bin is the f_{features} value of the image of that galaxy redshifted to the value corresponding to that redshift bin. On the x -axis is the f_{features} value of the image of the same galaxy redshifted to $z = 0.3$. The dashed black lines represent the best-fit polynomials to the data in each square. The solid black line represents $f_{\text{features},z} = f_{\text{features},z=0.3}$. Regions in which there is a single-valued relationship between f_{features} at high redshift and at $z = 0.3$ are white; those in which there is not are blue, and those with not enough data ($N < 5$) are grey. A larger version of the bin outlined at $z = 1.0$ and $20.3 < \mu < 21.0$ (mag/arcsec²) is shown in Figure 3.4.

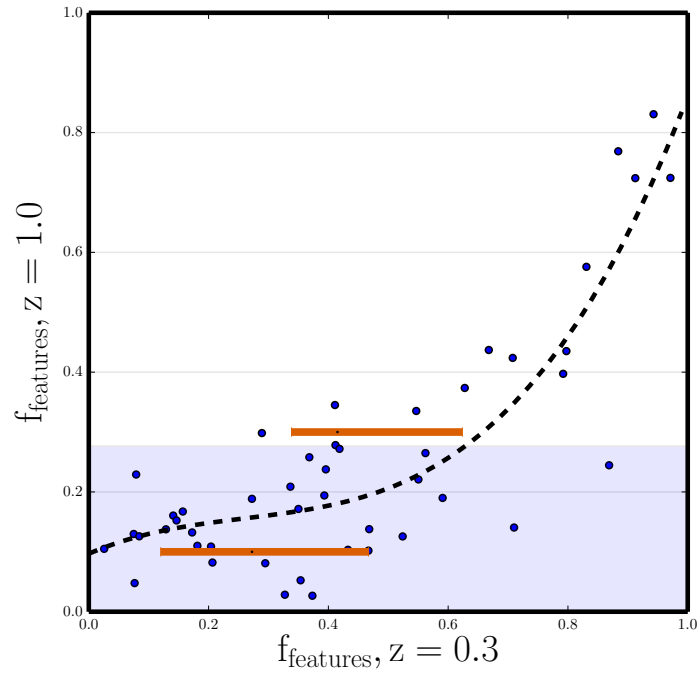


Figure 3.4 A larger version of the dark-outlined square in Figure 3.3, containing FERENGI galaxies that have been artificially redshifted to $z = 1.0$ and have surface brightnesses between $20.3 < \mu < 21.0$ ($\text{mag}/\text{arcsec}^2$). The orange bars represent the inner 68% (1σ) of the uncorrectable f_{features} quantiles, which are used to compute the limits on the range of debiased values.

by measuring the slope of the best-fit polynomial to the vote fractions; regions of the bins with a slope less than 0.4 are considered *not* one-to-one, and therefore $f_{\text{features},z}$ cannot be boosted to its $f_{\text{features},z=0.3}$ value. These are colored blue in Figure 3.3 and are referred to as the *lower limit* sample, because the most stringent correction available is that the weighted f_{features} is a lower limit to the true value.

Correctable and lower-limit regions of $z-\mu$ space can only be identified in bins where there exists a sufficient number of FERENGI galaxies to model a polynomial. Bins with fewer than 5 points were not considered sufficiently populated to derive a relationship, and are represented by the grey shaded bins in Figure 3.3. Galaxies in the GZH sample whose z, μ values lie in these shaded regions shown in the Figure were assigned to the “not enough information,” or “NEI” sample, because there were not enough FERENGI galaxies to quantify the bias in f_{features} in that parameter space. Figure 3.5 displays the overlap of z, μ bivariate distributions of the GZH and FERENGI samples. Ideally, the FERENGI space would overlap the GZH parameter space as close as possible. However, the unfortunate consequence of the simulated set being derived from galaxies in the local Universe puts an upper limit on the maximum surface brightness achievable for the FERENGI set. The earlier Universe simply has many more galaxies at the high surface brightness end, which were reproduced as best as possible by applying the magnitude correction, but ultimately can only result in a distribution that spans, but not completely reproduces, the bivariate distribution of the real data. The mismatch should not affect the overall calibration accuracy of the debiasing method, since only galaxies in particular $z-\mu$ bins are being corrected. It was stressed in the data release (Willett et al., 2017) however that due to this limitation in parameter space, all corrected values should be used with caution when using them for population studies.

The unshaded regions of Figure 3.4 thus define discrete ranges of redshift, surface brightness, and f_{features} within which a galaxy must lie in order for the debiased vote fraction to be confidently applied. While the appropriate correctable regions were defined as discrete bins, the true correctable region is assumed to be a smooth function of z, μ , and f_{features} . To define this smooth space, a convex hull was calculated to enclose the correctable and lower-limit FERENGI galaxies in the $z-\mu-f_{\text{features}}$ space (see Figure 3.6). The space defined by this hull was used to separate the GZH galaxies into correctable samples (those for which a correction to f_{features} can confidently be applied,

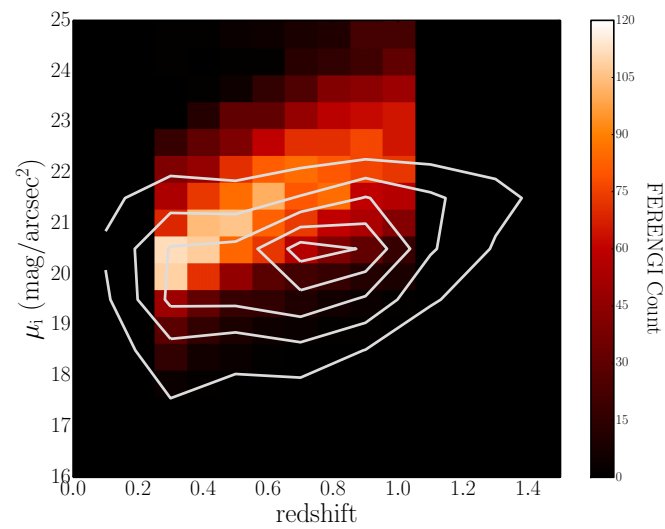


Figure 3.5 Surface brightness as a function of redshift for 3,449 FERENGI images and the 102,548 `main` galaxies with measured μ and z values. The color histogram shows the number of FERENGI images as a function of μ and z_{sim} . White contours show counts for the galaxies in the `main` sample, with the outermost contour starting at $N = 1500$ and separated by intervals of 1500.

Table 3.1 Number of correctable galaxies for the top-level task in GZH, split by *HST* survey.

	Correction type	AEGIS	COSMOS	GEMS	GOODS-N 5-epoch	GOODS-S 5-epoch	Total
correctable	0	2,908	21,169	2,802	1,459	1,189	29,527
lower-limit	1	833	5,169	1,021	1,377	1,267	9,667
$z \leq 0.3$	2	955	10,870	1,175	415	400	13,815
NEI	3	2,677	43,058	3,559	2,077	2,184	53,555
no z info	4	1,134	4,688	530	687	102	7,141
total		8,507	84,954	9,087	6,015	5,142	113,705

see next section) and lower-limit samples (those for which a single-valued correction cannot be applied). The final categorization of the GZH sample, split by imaging survey, is shown in Table 3.1.

For the “lower limit” galaxies, since a single debiased f_{features} value cannot be confidently assigned, a *range* of debiased values is estimated. In each z, μ bin in Figure 3.3, the spread of intrinsic values of $f_{\text{features}, z=0.3}$ for five quantiles of observed f_{features} is computed - these are denoted by the grey lines in the close-up Figure 3.4. The range of intrinsic values of f_{features} is defined by the upper and lower 1σ limits, enclosing the inner 68% of the data; this is represented by the orange bars in Figure 3.4. For any galaxy which cannot be directly debiased, these ranges are used to denote the upper and lower limits on the expected values $f_{\text{features}, z=0.3}$ as a function of the observed f_{features} .

3.3.2 The debiasing correction equation, ζ

For the “correctable” sample of simulated FERENGI galaxies, an equation was derived to model the dropoff in f_{features} with redshift for each galaxy. Such a model is assumed to have the following criteria: (1) For a given galaxy, f_{features} should decrease relative to its $f_{\text{features}, z=0.3}$ as redshift increases. (2) The corrected f_{features} value must be contained within 0 and 1, since it is a fraction. (3) The degree of dropoff may depend on the surface brightness of the galaxy. Given these three assumptions, a simple exponential function was derived:

$$f_{\mu, z} = 1 - (1 - f_{\mu, z=0.3})e^{-\frac{z-z_0}{\zeta}}, \quad (3.4)$$

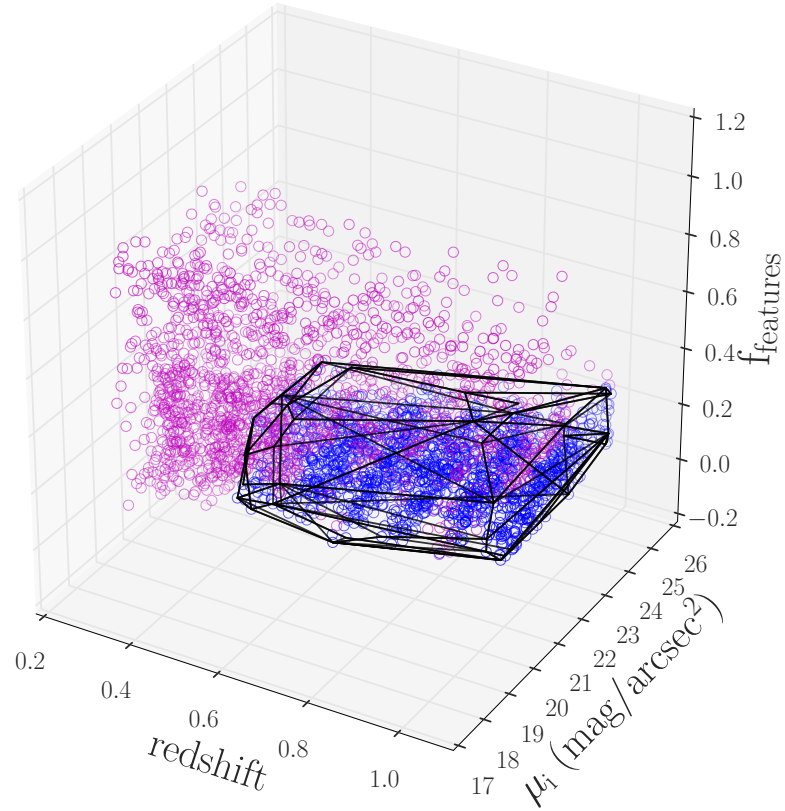


Figure 3.6 The final separation of the correctable and lower-limit samples in redshift/surface brightness/ f_{features} space. **Pink** points are all FERENGI galaxies in the **unshaded** regions of Figure 3.3. **Blue** points are all FERENGI galaxies in the **blue shaded** regions of Figure 3.3. The solid black line is the convex hull which encloses the uncorrectable points and defines the region of the lower-limit sample.

where $f_{\mu, z=0.3}$ is the vote fraction at the lowest redshift in the artificially-redshifted FERENGI sample ($z_0 = 0.3$). ζ is a parameter that controls the rate at which f_{features} decreases with redshift.

Equation 3.4 was then fit to each galaxy in the “correctable” FERENGI sample, and ζ is measured for each. Figure 3.7 shows the best fit equations for 16 galaxies, and the ζ corresponding to the best fit is displayed with each galaxy. As it was assumed that surface brightness likely plays a role in the level of dropoff in f_{features} , and hence the value of ζ which controls this dropoff, it is assumed that ζ follows a simple linear dependence with surface brightness:

$$\log_{10}(\hat{\zeta}) = \zeta_0 + (\zeta_1 \times \mu), \quad (3.5)$$

where $\hat{\zeta}$ is the correction factor applied to each galaxy. Figure 3.8 shows the relationship between the derived ζ values and the surface brightness μ of the FERENGI galaxies, which is fit with equation 3.5. The best-fit parameters to this linear fit from least-squares optimization are $\zeta_0 = 0.50$, $\zeta_1 = -0.03$. Interestingly, only a very weak surface brightness dependence is detected. It is difficult to determine from these data whether the weak detection is due to a true lack of dependence, or insufficient data (only 28 galaxies had sufficient data to accurately measure ζ).

Using the ζ parameters measured in the FERENGI sample, a final debiased correction equation is derived to correct the f_{features} vote fractions in the HST data:

$$f_{\text{features,debiased}} = 1 - (1 - f_{\text{features,weighted}})e^{\frac{-(z-z_0)}{\hat{\zeta}}} \quad (3.6)$$

where $f_{\text{features,weighted}}$ is the weighted vote fraction, and $f_{\text{features,debiased}}$ is bounded between $f_{\text{features,weighted}}$ and 1.

3.3.3 Debiasing results and limitations of the FERENGI simulated data

Figure 3.9 shows the results of the ζ correction for the correctable sample. Plotted on the left panel is the corrected ($\hat{f}_{\text{features}}$) vs the raw (f_{features}) fractions. Galaxies with low ($f_{\text{features}} < 0.2$) may be corrected to as high as ~ 0.6 , while fractions already large require no additional boost. The limitations of the process can be seen in the right

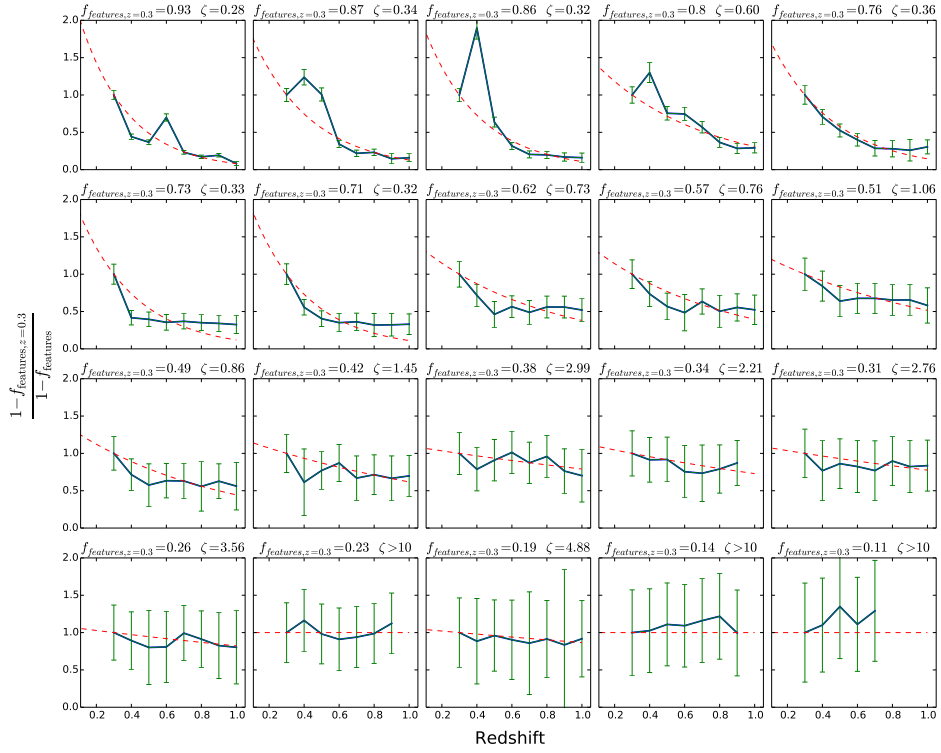


Figure 3.7 Behavior of the normalised, weighted vote fractions of features visible in a galaxy (f_{features}) as a function of redshift in the artificial FERENGI images. Galaxies in this plot were randomly selected from a distribution with evolutionary correction $e = 0$ and at least three detectable images in redshift bins of $z \geq 0.3$. The displayed bins are sorted by $f_{\text{features},z=0.3}$, labeled above each plot. Measured vote fractions (blue solid line) are fit with an exponential function (red dashed line; Equation 3.4); the best-fit parameter for ζ is given above each plot.

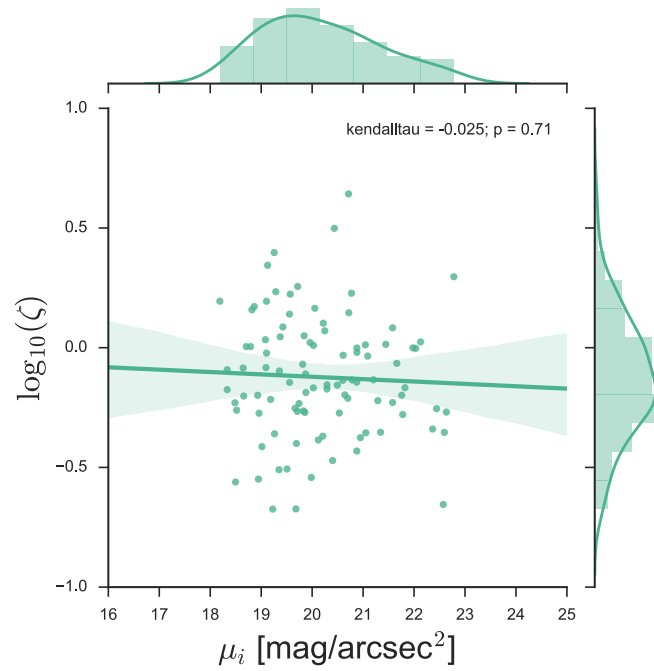


Figure 3.8 All fits for the FERENGI galaxies of the vote fraction dropoff parameter ζ for f_{features} as a function of surface brightness. This includes only the simulated galaxies with a bounded range on the dropoff ($-10 < \zeta < 10$) and sufficient points to fit each function (28 original galaxies, each with varying images artificially redshifted in one to eight bins over a range from $0.3 \lesssim z_{\text{sim}} \lesssim 1.0$).

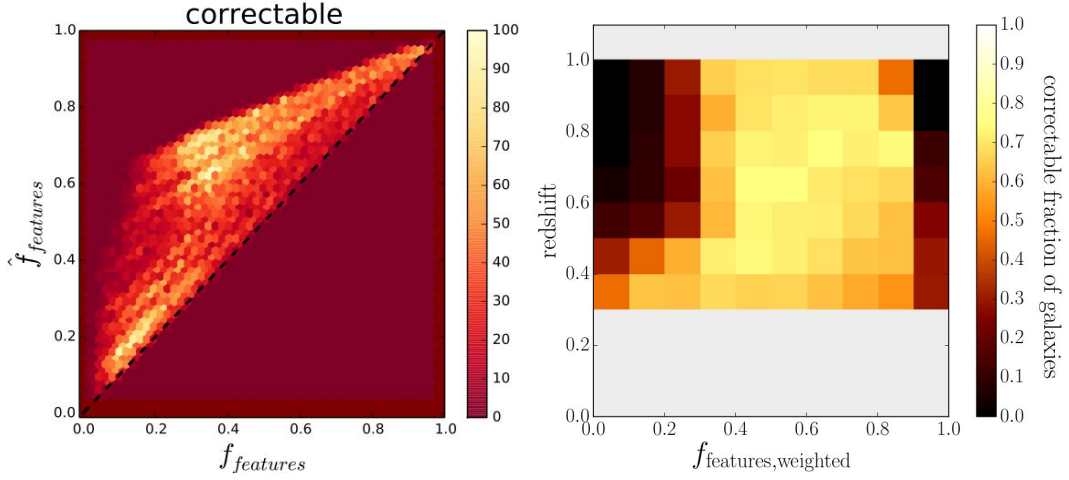


Figure 3.9 **Left:** Debiased vs raw vote fractions for the GZH correctable sample. The colorbar represents the number of galaxies in each bin. **Right:** Histogram showing the fraction of galaxies that have a finite correction for the debiased vote fractions $f_{\text{features,debiased}}$ as a function of f_{features} and redshift. The parameter space for corrections is limited to $0.3 \leq z \leq 1.0$ due to the sampling of the parent SDSS galaxies and detectability in the FERENGI images.

panel of the figure. Displayed is the fraction of galaxies in the correctable sample as a function of redshift and initial f_{features} . At the low end of f_{features} , only galaxies with low redshifts tend to be a part of the sample; this is due to the effect described above where the low resolution of the high-redshift images reaches a point where smooth-appearing featured galaxies are completely indiscernible from ellipticals, and it is not possible to be certain that a boost is necessary. This limitation is unavoidable given the limited sensitivity of any instrument, however this effect will be lessened as imaging technology continues to improve. The resulting debiased votes generated via this method were published in the Galaxy Zoo: Hubble catalog in February, 2016 (Willett et al., 2017), and made publicly available at data.galaxyzoo.org.

3.4 FERENGI 2: using simulated images to measure incompleteness in disk fraction

The FERENGI sample was successful in identifying and correcting the vote fractions of the GZH sample to aid in identifying featured galaxies, albeit with several limitations. Inspired by the utility of the simulated galaxy classifications, a second set was created for a very specific purpose of measuring the incompleteness in disk *fraction* (as opposed to incompleteness in individual vote fractions). The second half of this Chapter will explain the motivations behind and the generation of this second simulated set, which will be used for the science conducted in Chapter 6

3.4.1 The FERENGI 2 Sample

The creation of a second set of FERENGI images was motivated by the scientific goal of measuring the redshift evolution of the fraction of red disk galaxies using the Galaxy Zoo:Hubble dataset. This project is described in full in Chapter 6, but the reasons a new set of simulated images were required will be described briefly here. First, as described in the previous section, the analysis of the first FERENGI set revealed that, for a large area of z - μ parameter space, galaxies with low measured values of f_{features} could not be corrected to a point that could clearly distinguish them as disks with washed-out features or ellipticals. Due to this limitation, any measurement of the number of disk galaxies in a given redshift interval can only be reported as a *lower-limit* to the true value. The difference in the measured lower-limit and the true number of disks is what we will refer to as the *incompleteness* in number of disks detected.

It is possible to use the FERENGI images to measure this incompleteness by measuring the number of disks detected at a given redshift, and comparing to the number of disks detected in the same galaxies at the lowest redshift (this would be considered the true, or intrinsic, number of disks.) The details of this approach will be described in the next section. A complication specific to this project is that the number of disks will be ultimately used to compute the *red disk fraction*, that is, the ratio of the number of red disks to all disks, as a function of redshift. It is then necessary to measure the level of incompleteness for both red and blue galaxies separately, to calculate this fraction most accurately.

The color separation method for the *HST* galaxies in Chapter 6 uses NUV, r, and J magnitudes. To separate the FERENGI sample of galaxies into red and blue samples in the same way, these magnitudes are required. In the first set, however, only 44 of the 288 galaxies had these data available, which were not enough to properly measure any incompleteness, especially after binning the data further in surface brightness and redshift. So, a larger set of galaxies needed to be artificially redshifted, all which had the aforementioned data necessary to separate by color.

This set of new galaxies to be processed by the FERENGI code, hereafter referred to as the FERENGI 2 sample, was selected as follows: All candidates were pulled from a parent sample of all SDSS galaxies which had previously been classified in GZ2. As discussed in Section 3.2, only galaxies with redshifts below $z < 0.013$ were able to be redshifted the full simulated redshift range $0.3 < z < 1.0$, so a redshift cut was implemented of $z < 0.013$. These galaxies were cross-matched with catalogs from GALEX (Martin et al., 2005) for NUV magnitudes and 2MASS (Skrutskie et al., 2006) for J magnitudes. 1,435 galaxies fit these criteria.

Bulk SDSS u, g, r, i, and z-band fits images were then downloaded for all 1,435 galaxy candidates⁴. Cutouts were made for each galaxy, using the 90% r-band petrosian radius to set the size of the cutout (PETROR90_R). The default prescription used was to define the edges as $2.5 * \text{PETROR90_R}$, measured from the galaxy as the center. If the galaxy was within this distance from the edge of the bulk fits image, $2.0 * \text{PETROR90_R}$ was used. Cutouts were not made for galaxies within this distance from the edge, both to ensure the full galaxy was visible in all cutouts in the sample, and to avoid over-zooming the image. 187 galaxies were thus removed from FERENGI2; an example of such a galaxy “too close” to the edge of the image is shown in Figure 3.10.

While all 78 $z < 0.013$ galaxies from the original FERENGI sample were successfully simulated to a minimum redshift of $z_{sim} = 0.3$, this was not always true for the FERENGI2 candidates. Redshift of the source galaxy is the largest factor in determining the minimum possible simulated redshift, but other factors including the size of the PSF and physical size of the source galaxy also come into play. All 1,248 candidates were then put through FERENGI at only the lowest redshift $z_{sim} = 0.3$ to begin, and each image was visually inspected to determine whether the code succeeded. 312 “failures”

⁴ <http://data.sdss3.org/bulkFields>

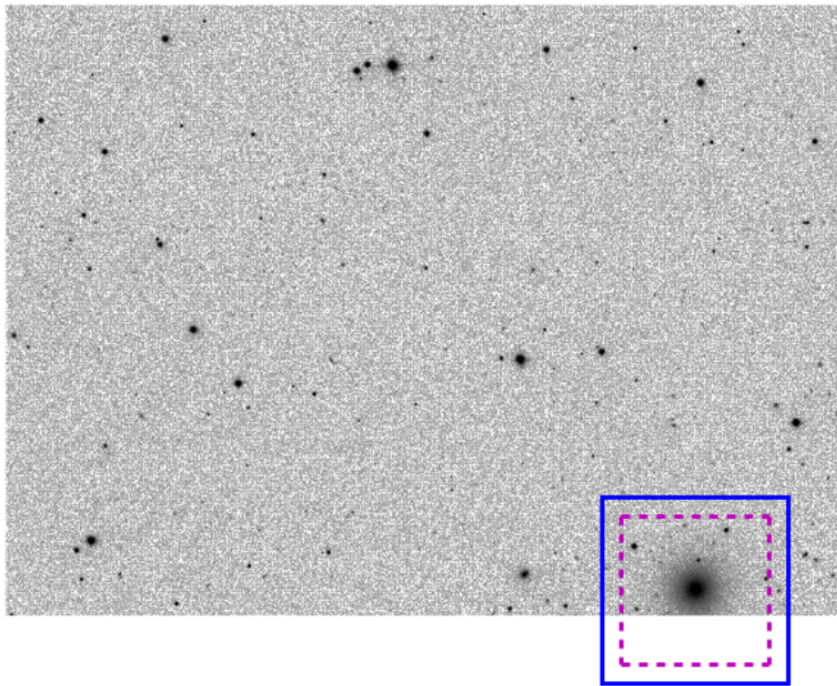


Figure 3.10 Example of a galaxy overlapping the edge of the SDSS frame. Shown is the bulk r-band fits image for SDSS DR12 run 3903, camcol 6, and field 60. The boxed-in galaxy (SDSS DR12 objid 1237662239079268544) is too close to the edge of the image to create a cutout that encloses the entire galaxy. The pink dashed box indicates a cutout size of $2 \times \text{PETROR90_R}$, the blue solid line indicates a cutout size of $2.5 \times \text{PETROR90_R}$.

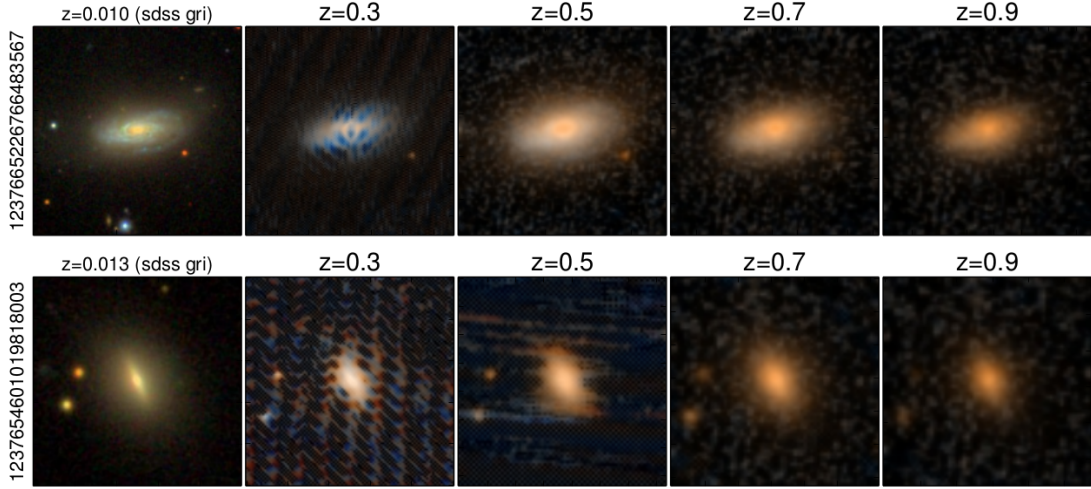


Figure 3.11 Examples of two galaxies whose minimum simulated redshifts in FERENGI were larger than $z_{sim} = 0.3$. These were detected via visual inspection and removed from the final FERENGI2 sample.

were detected; two examples are shown in Figure 3.11. The remaining 936 “successes” were then artificially redshifted through the full simulated range of $0.3 < z < 1.0$ in increments of $dz = 0.1$; these make up the final FERENGI2 sample comprising 7,488 images of the 936 galaxies redshifted 8 times. A single evolution factor, rather than a range, of $e = 1$ was applied to all images. This value was chosen by analyzing the spectra template models of Brinchmann et al. (2004), which showed that the most typical galaxies evolve in brightness by one magnitude per redshift. Example images are shown in Figure 3.12

The 7,488 FERENGI2 images were then put into Galaxy Zoo for classification on December 11, 2016. The images were shown at a probability rate of 1/3, while the other 2/3 shown were images from Illustris or SDSS. Given these occurrence frequencies and classification rates at the time, it was expected that the sample would require 4 months to be fully classified (that is, each image would be seen by 40 users). In an attempt to reduce this time, the Galaxy Zoo team launched a “Save Mel’s Thesis” campaign, whereby details on the project and a request for help were sent to volunteers

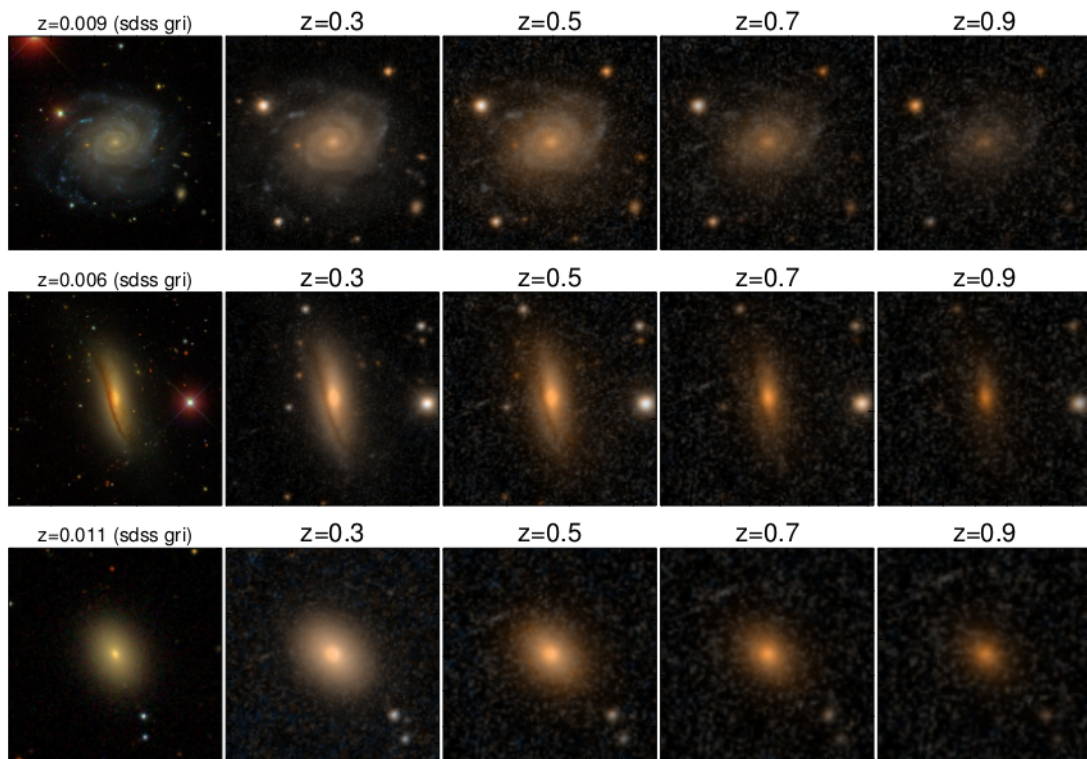


Figure 3.12 Examples of FERENGI2 galaxies. The left is the original gri-composite image of the source galaxy. Images on the right are simulated output from the FERENGI code. Only four of the eight simulated redshifts are shown in the interest of space.

via an e-mail Newsletter, blog post⁵ , and a Daily Zooniverse post which was shared on social media websites Facebook and Twitter. The campaign proved effective, cutting the predicted classification time in half. Future work is needed to explore the details behind the effect of such a campaign and classification rates, which could potentially aid other time-sensitive projects.

Following the completion of the FERENGI2 classifications, the votes were counted and weighted in the method described in Chapter 2. The technique used to measure the incompleteness in disk fraction using this set is described in Chapter 6.

⁵ <https://blog.galaxyzoo.org/2016/12/12/ferengi-2-images-launched/>

Chapter 4

The effect of bar-driven fueling on the presence of an active galactic nucleus

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Supermassive black holes exist at the centres of most (if not all) massive galaxies (Kormendy & Richstone, 1995; Richstone et al., 1998; Kormendy & Gebhardt, 2001; Ghez et al., 2008). The evolution of the black hole is closely tied to that of the host galaxy; hence, understanding the conditions that drive black hole growth is key for a complete picture of galactic evolution. While most black holes are not actively growing, a small fraction are observed to accrete matter and cause the surrounding material to emit powerful pan-chromatic radiation. The central region of a galaxy which encompasses these “active” black holes, along with the surrounding accretion disk and ionized gas clouds, is an active galactic nucleus (AGN). Since the bolometric luminosity of the AGN can be comparable to (or greater than) the integrated stellar luminosity (as high as $L \sim 10^{47}$ erg s⁻¹) the black holes have an important effect on the host galaxy, controlling the amount of star formation via AGN feedback, as well as contributing toward the net

reionization of the intergalactic medium (Heckman & Best, 2014). Understanding the fueling mechanism(s) for AGN is thus critical for studying galaxies, both in the nearby Universe and at higher redshifts.

The precise physics that govern the relationship between AGN and their host galaxies is an area of intense study. This includes the AGN fueling mechanism — while there is strong evidence that there is sufficient gas in the ISM to keep the accretion disc supplied with enough material to radiate at typical bolometric AGN luminosities (Shlosman et al., 1989, 1990), the dynamical mechanisms that drive the gas within the black hole’s sphere of influence are difficult to observe directly, especially at extragalactic distances. In order to initiate (or continue) AGN activity, gas must lose enough angular momentum in a short timeframe to reduce its orbit from scales of kiloparsecs down to parsecs. Shlosman et al. (1989) analytically showed that while gas can lose angular momentum due to turbulent viscous processes, these are too slow to be the only mechanism involved. Later N-body simulations have shown viscous torques on the gas are negligible and do not directly initiate inflows (Bournaud et al., 2005), further arguing for an additional method of radial gas transport.

One possibility is that the presence of a large-scale bar may supplement viscous torques and further drive AGN fueling. Bars efficiently transport angular momentum within the disc (Athanasoula, 2003; Kormendy & Kennicutt, 2004), and are ubiquitous features in disc galaxies in the local Universe (Eskridge et al., 2000; Laurikainen et al., 2004; MenendezDelmestre et al., 2007a; Masters et al., 2011; Cheung et al., 2013). Simulations (Athanasoula, 1992; Friedli & Benz, 1993; Ann & Thakur, 2005) show that stellar bars, whose lengths are on the order of kiloparsecs, do drive gas into the circumnuclear region (scales of 100 pc) of galaxies; observational studies have also shown an increase in the amount of central star formation for barred galaxies (Ellison et al., 2011). This combination of simple analytical models, simulations, and observations clearly points toward galactic bars preferentially driving gas to the centres of their galaxies. It is still an open question, though, whether this gas is ultimately driven to the central 1 – 10 pc scales, which theoretical models suggest are required for accretion around the central black hole of the AGN.

Theoretical models for alternate modes to bar-driven fueling also exist. Numerical

simulations from Hopkins & Quataert (2010) examine several possible mechanisms behind angular momentum transport for a range of galaxy morphologies (bars, spirals, rings, clumpy and irregular shapes, mergers) at different radial scales. For each morphological type, gas transported from larger to smaller (~ 1 kpc) radii “piles up” due to decreasing efficiency in the processes that induce torque. If this pile-up of gas is sufficiently massive, it becomes self-gravitating and can efficiently transport angular momentum down to scales of ~ 10 pc. This “stuff within stuff” model is similar to the second half of Shlosman et al. (1989)’s “bars within bars” model. The difference is that the “bars within bars” model assumes that a large-scale bar is the primary mechanism that transports the gas inward to form the gaseous disc, while Hopkins & Quataert (2010) show that many large-scale morphologies are capable of producing a secondary instability and fueling an AGN, suggesting that this process may not be restricted to classic large-scale bars.

Many studies have focused on observational correlations between the presence of a galactic bar (typically identified at optical wavelengths) and that of an AGN (identified by optical line ratios or widths). Some studies (eg, Ho et al., 1997; Mulchaey & Regan, 1997; Hunt & Malkan, 1999) find similar bar fractions for both AGN and inactive galaxies and hence report no correlation. The significance of these fractions, however, is hindered by small sample sizes, typically with fewer than 100 barred AGN hosts. More recent studies (Knapen et al., 2000; Laine et al., 2002; Laurikainen et al., 2004) report increases of 20 – 23% in the bar fractions for AGN when compared to non-AGN hosts. Despite larger numbers of AGN, the results are still only significant at the 2.5σ level. Rather than comparing the likelihood of active and inactive galaxies to host bars, as is most common among previous studies, Cisternas et al. (2013) accounted for a continuum of values by quantifying bar strength and activity level in local X-ray identified AGN. While no correlation was found, these data probe only the low-luminosity AGN regime ($L_X \sim 4 \times 10^{38}$ erg s $^{-1}$). In the high redshift universe, Cheung et al. (2015) find no compelling evidence that bars are more likely to lie in AGN hosts than non-AGN hosts.

Several recent studies have focused on optical identifications of bars and AGN, primarily using data from the Sloan Digital Sky Survey (SDSS). We compare these methods and results in Table 4.1. Among these studies, neither Lee et al. (2012) nor Martini et al. (2003) find any correlation between the presence of strong galactic bars and AGN,

but do not rule out the possibility of smaller, nuclear bars influencing AGN activity. In contrast, Oh et al. (2012); Hao et al. (2009); Alonso et al. (2013) all find evidence of bar effects in AGN — however, they disagree on both the strength of the effect and whether it affects both black hole fueling and/or central star formation. One possible reason for the discrepancy is the lack of a consistent scheme for classifying AGN. While the BPT diagram based on optical line ratios (Baldwin et al., 1981) is among the most common methods for identifying AGN, the demarcation between star-forming and AGN host galaxies is not consistent; some use the Kewley et al. (2001) criterion that excludes composite galaxies, while others use Kauffmann et al. (2003c) and include these along with Seyferts as AGN. The inclusion of LINERs can also complicate the picture; the high line ratios in at least some LINERs are spatially extended and thus likely of a non-AGN origin (Sarzi et al., 2010; Yan & Blanton, 2012; Singh et al., 2013).

Other challenges result from the task of identifying galactic bars, which is often done by visual inspection of optical images by individuals or small groups of experts. This introduces potential complications when there is disagreement between classifiers, especially in the cases of weak or nuclear bars. With only a single (or a few) classifications per image, such disagreements are difficult to resolve. Furthermore, individual visual inspection can limit the effective sample size due to the amount of time required to inspect images one by one. Our work avoids these problems by using crowdsourced citizen science classifications to identify galactic bars, where many individuals (an average of 27 classifiers for bar detection in this study) analyze each galaxy, and the presence of a bar is quantified as a calibrated vote fraction.

This paper re-examines the relationship between bars and AGN in disc galaxies by using Galaxy Zoo morphological classifications, and by using a strict AGN classification scheme which only selects Seyfert galaxies. We use this data to consider three physical scenarios for describing the role bars may (or may not) play in AGN fueling: I) Bars are necessary to fuel AGN, II) Bars are one of several ways to fuel AGN, or III) Bars do not fuel AGN. We discuss each of these possibilities in Section 4.3 and suggest the means by which the existence barred AGN, unbarred AGN, barred non-AGN, and unbarred non-AGN may be explained within the context of each model. We then report the scenario which we find to be best supported by both our observations and current theoretical models and simulations.

In Section 4.1 we describe our sample selection. Section 4.2 includes our data, with mass and colour distributions of the different activity types, both barred and unbarred, as well as a comparison between accretion strengths of barred and unbarred AGN. Interpretations of these results are discussed in Section 4.3, and the main conclusions are outlined in Section 6.5. We adopt a Λ CDM cosmology throughout the paper of $\Omega_m = 0.27$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration et al., 2013).

4.1 Data and sample selection

Our parent sample of galaxies is taken from the SDSS Data Release 7 (Abazajian et al., 2009). From the spectroscopic Main Galaxy Sample (Strauss et al., 2002), we select galaxies within the redshift interval $0.01 < z < 0.05$ — the lower limit excludes galaxies whose angular size significantly exceeds the spectroscopic fiber, and the upper limit is chosen so that a reasonable estimate of bar detection can be made by visual inspection. From this, we create a volume-limited sample by applying an additional cut of $M_{z,petro} < -19.5$ AB mag.

Within the volume-limited sample, we use morphological cuts to select only disc galaxies at low inclination angles that are candidates for the presence of galactic bars (described below). These cuts result in the final sample of 19,756 disc galaxies used in the remainder of this paper.

4.1.1 Bar classifications and Galaxy Zoo 2

To select disc galaxies and measure the presence of a bar, we use data from the online citizen science project Galaxy Zoo 2 (GZ2).¹ With the help of over 80,000 volunteers providing over 16 million classifications of over 300,000 galaxies, Galaxy Zoo 2 is the largest extant survey of detailed galaxy morphology. Volunteers are shown colour images of galaxies taken from the SDSS (Figure 4.1), and are then prompted through a decision tree in which they answer questions about the galaxy’s structure. For a detailed discussion on the Galaxy Zoo 2 project and its decision tree, see Willett et al. (2013).

Since bars only appear in disc galaxies, the sample must be limited to disc galaxies in which a bar can be seen via visual inspection. We begin by selecting galaxies for

¹ zoo2.galaxyzoo.org

Table 4.1. Summary of recent studies comparing the presence of galactic bars and active galactic nuclei, including new results from this work. Martini et al. (2003) is the only study with neither uniform selection criteria for galaxies nor a volume-limited sample. AGN classifications from optical line ratios and the BPT diagram are separated by the following demarcations: Ke01 = Kewley et al. (2001); Ka03 = Kauffmann et al. (2003c); S07 = Schawinski et al. (2007).

	Martini2001	Hao2009	Lee2012
Redshift range		$0.01 < z < 0.03$	$0.02 < z < 0.055$
Abs. magnitude range	$z < 0.038$	$18.5 < M_g < -22.0$	$M_r < -19.5 + 5 \log(h)$
Inclination limit	$B_T < 13.4$ $R_{25} < 0.35$	$i < 60^\circ$	$b/a > 0.6$
AGN classification method	varied	$\text{FWHM}(\text{H}\alpha) > 1200 \text{ km/s}$ and Ka03	Ke01
AGN type(s)	Type 1 and 2 Seyferts, LINERs	Type 2 Seyfert, LINER, composite	Type 2 Seyfert, LINER
Bar classification method	visual inspection	ellipse fitting	visual inspection
Number of AGN in sample	28	128	1742
Fraction of AGN hosts that are barred	28.6%	47%	49%
	Oh2012	Alonso2013	This work
Redshift range	$0.01 < z < 0.05$	$z < 0.1$	$0.01 < z < 0.05$
Abs. magnitude range	$M_r < -19$	$M_g < -16.5$	$M_{z,petro} < -19.5$
Inclination limit	$b/a > 0.7$	$b/a > 0.4$	$p_{\text{not_edge-on}} > 0.6$
AGN classification method	Ka03	Ka03	S07, WISE
AGN type(s)	Type 2 Seyfert, LINER, composite	Type 2 Seyfert, LINER, composite	Type 2 Seyfert
Bar classification method	visual inspection	visual inspection	crowdsourced visual inspection
Number of AGN in sample	1397	6772	681
Fraction of AGN hosts that are barred	51%	28.5%	51.8%

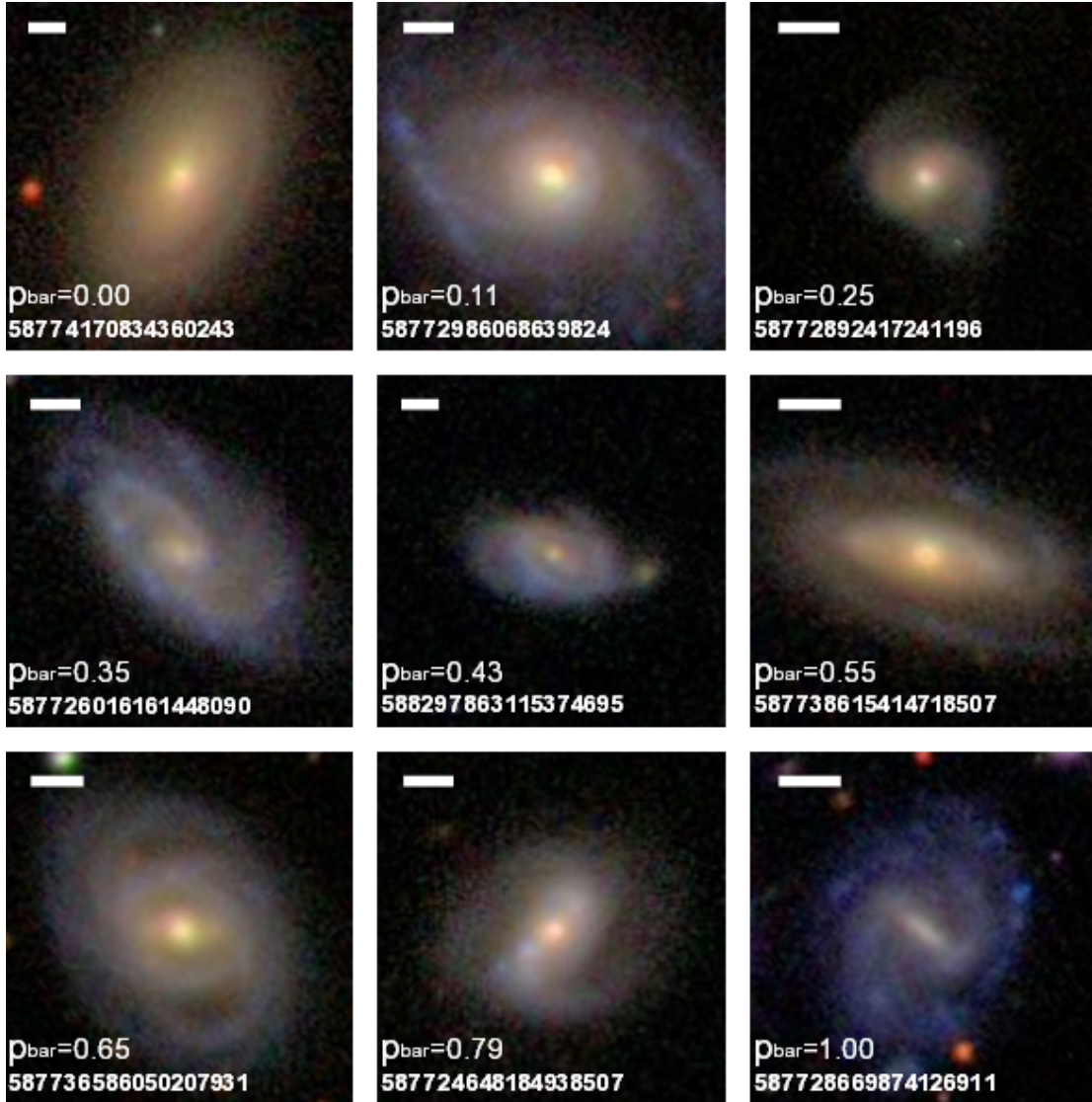


Figure 4.1 Examples of the SDSS images used in Galaxy Zoo 2, sorted by increasing p_{bar} (the weighted percentage of users that detected a bar in each image). All galaxies are from our final analysis sample of “not edge-on” disc galaxies. The white lines in the upper left of each image represent a physical scale of 5 kpc. We also give p_{bar} and the SDSS objectIDs for each galaxy. **Top row:** Galaxies with $p_{\text{bar}} < 0.3$, which in this paper are designated as unbarred. **Middle and bottom rows:** Galaxies with $p_{\text{bar}} \geq 0.3$, which we designate as reliably barred.

which at least 10 people answered the question, “Is there a sign of a bar feature through the centre of the galaxy?”, thus rejecting vote fractions with low statistical significance. Because questions in GZ2 are implemented as part of a decision tree (Willett et al., 2013), users must have identified a galaxy as a disc and as not edge-on before answering the bar question. In this way, the cut of $N_{bar} \geq 10$ increases the likelihood that the galaxy in question is a candidate for having a bar. This cut is not complete, however, for galaxies which have a high number of total classifications. In these cases, the number of users to answer the bar fraction may still be small compared to the number of users identifying the galaxy as either not disc-like, or as an edge-on galaxy. Therefore cuts are also applied to the vote fractions relating to questions preceding the bar question. The first question of the GZ2 tree reads, “Is the galaxy simply smooth and rounded, with no sign of a disc?” Willett et al. (2013) determined the threshold fraction of “features or disc” answers required to classify the galaxy as a disc, when combined with the cut $N_{bar} \geq 10$, to be $p_{features\ or\ disc} \geq 0.227$. We emphasize that the cuts provided in Willett et al. (2013) are intended to be *minimum* values for determining well sampled galaxies. We thus chose to adopt a slightly higher value of $p_{features\ or\ disc} \geq 0.35$ to create the cleanest possible sample, based on a visual inspection of a subsample of galaxies with these cuts. To assess whether the results would be affected by this choice, we also created a sample with the original Willett et al. (2013) cuts. This choice increased the number of AGN in the sample by 24, and did not affect the final results. Therefore we present the sample using our more conservative cuts in this paper.

Following an answer of “features or disc” for the first question, the volunteer is then asked “Could this be a disc viewed edge-on?” Bars become increasingly difficult to detect in galaxies at high inclination angles, and are nearly impossible to detect in edge-on galaxies without careful isophotal mapping. The threshold vote fraction determined by Willett et al. (2013) of a “No” answer to this question is $p_{not\ edge-on} \geq 0.519$. We again adopt a slightly more conservative value of $p_{not\ edge-on} \geq 0.6$ based on visual inspection of a subsample. The combination of feature/disc galaxies that are not edge-on for these two thresholds results in the final sample size of 19,756 galaxies used in this paper.

As a check that our selection of “not edge-on” disc galaxies can be reliably used to identify a bar, we examine the inclination angle of the sample, which is approximated by

the ratio of the best fit of the semi-major and -minor axes $i = \cos^{-1}(a/b)$ as measured in r -band by the SDSS pipeline. Figure 4.2 shows the strong correlation between i and $p_{\text{not edge-on}}$, with a sharp cutoff near $i = 70^\circ$. Our cutoff of $p_{\text{not edge-on}} \geq 0.6$ effectively limits the sample to inclination angles of $i < 67^\circ$. In Figure 4.2 we also show the dependence of the GZ2 bar fraction on $p_{\text{not edge-on}}$. The bar fraction remains roughly constant (± 0.1) between $0.3 < p_{\text{not edge-on}} < 1.0$ and drops to zero at $p_{\text{not edge-on}} < 0.1$. Since the *true* bar fraction is expected to be independent of i (a purely geometrical effect assumed to have a random distribution), any change in the bar fraction would reflect the ability of visual inspection to detect a bar in a highly inclined disc. The constant bar fraction out to our limit of $p_{\text{not edge-on}} \geq 0.6$ (and well beyond) is a necessary requirement for an unbiased selection of barred galaxies; as a result, we are confident that the crowdsourced bar classifications in this sample are reliable.

Finally, if the volunteer answers “No” to the edge-on question, they are asked “Is there a sign of a bar feature through the centre of the galaxy?” Possible answers to this question are either “Bar” or “No bar”. Willett et al. (2013) compared expert classifications of barred galaxies from both Nair & Abraham (2010) and Baillard et al. (2011) to Galaxy Zoo 2 data, and show that a threshold of $p_{\text{bar}} \geq 0.3$ is the most reliable separator of the barred from unbarred population (see their Figure 10). We adopt the same threshold of $p_{\text{bar}} \geq 0.3$ for determining whether a galaxy has a bar (see Figure 4.1 for images of galaxies with different values of p_{bar}).

We compare our morphology cuts to those used by Masters et al. (2011), who used an early release of GZ2 data to identify barred galaxies. Their study also required $N_{\text{bar}} \geq 10$ and claim that this cut alone is sufficient to restrict the sample to disc galaxies without applying an additional cut on $p_{\text{features or disk}}$. This assumption was reasonable at the time since the Galaxy Zoo 2 project was still collecting data, and the number of classifications per galaxy was lower than in the final catalog. The median number of classifications per galaxy is roughly 30% higher, and so our data is more susceptible to contamination by non-disc galaxies with high classification counts. This makes an additional cut on $p_{\text{features or disk}}$ necessary. To remove edge-on discs, Masters et al. (2011) set an inclination limit of $\log(a/b) < 0.3$, or $i \sim 60^\circ$; this is comparable to our $p_{\text{not edge-on}}$ cut, which corresponds to roughly $i \sim 67^\circ$. To select barred galaxies, a majority vote fraction of $p_{\text{bar}} > 0.5$ was required, higher than our value of $p_{\text{bar}} \geq 0.3$. We

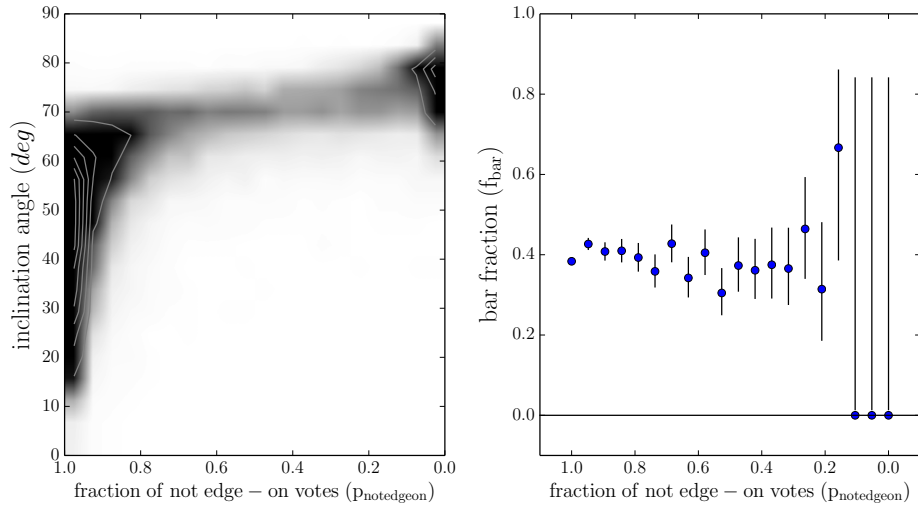


Figure 4.2 Left: Fraction of “not-edge-on” votes vs. inclination angle ($i = \cos^{-1}[a/b]$) for the disc galaxies in our GZ2 sample. An angle of 0° means the galaxy is completely face-on, while 90° is completely edge-on. GZ2 users consider a galaxy as “not edge-on” if the inclination angle is less than $i \sim 70^\circ$. Right: Fraction of barred galaxies vs. fraction of “not edge-on” galaxies. The bar fraction is independent of the edge-on degree of the galaxies (above $p_{\text{notedgeon}} \sim 0.3$); the ability of users to detect bars does not decrease with inclination until $p_{\text{notedgeon}} \sim 0.3$, or $i \sim 70^\circ$. Error bars are 95% Bayesian binomial confidence intervals (Cameron, 2013). This demonstrates that GZ2 data can reliably identify bars even in moderately-inclined disc galaxies.

are nevertheless confident in our threshold which was determined by the more recent and detailed analysis of the GZ2 data by Willett et al. (2013) as described above. Additionally, the data released at the time of Masters et al. (2011) had not yet been reduced via weighting and debiasing; these differences in vote fractions also contribute to the different cuts used in our study.

4.1.2 Activity type classification

We use flux measurements from the 2012 release of the Oh2011 catalogue (Oh et al., 2011) to classify disc galaxies as either star-forming, composite, AGN, LINER, or quiescent (also known as “undetermined”). This method employs ratios of [O III]/H β fluxes as a function of [N II], [S II], or [O I] over H α according to the BPT diagnostics. Our method for selecting AGN is the same as used by Schawinski et al. (2007, 2010). First, we use the [N II]/H α ratio (Figure 4.3a). Any galaxy that does not have S/N > 3 for any of the four lines is unclassifiable via this method (possibly due to being gas-poor) and labeled “undetermined.” Next, any galaxy which falls below the Kewley et al. (2001) extreme starburst line is classified as star-forming, and those that fall between this and the Kauffmann et al. (2003c) empirical starburst line are classified as composite. We note that some of these composite galaxies may be potential AGN, but we cannot cleanly separate the AGN contribution from star formation and thus exclude them from our sample (Schawinski et al., 2010).

Next, we identify the remaining galaxies (above the extreme starburst line) as either Seyfert AGNs or LINERs. Kewley et al. (2006) showed that both [O I]/H α and [S II]/H α diagrams are better-suited to distinguish AGN from LINERs; we thus use diagram (c) in Figure 4.3 if these galaxies also have S/N > 3 in [O I]. For galaxies which do not have S/N > 3 in [O I], but do in [S II], we use diagram (b). In both cases, we use the AGN-LINER division line of Kewley et al. (2006). For the remaining galaxies, we use diagram (a) and implement the AGN-LINER division line of Schawinski et al. (2007).

Finally, to detect any AGN that may have been optically mis-classified due to obscuration, we identify AGN based on their infrared continuum shape using data from the Wide-field Infrared Survey Explorer (Wright et al., 2010, WISE). We identify as an AGN any galaxy with $(W1 - W2) \geq 0.8$ (Stern et al., 2012). Based on infrared data, we re-classified fourteen galaxies (originally classified optically as three star-forming, ten

Activity type	All discs		Barred discs	
	Number	$f_{\text{total}}(\%)$	Number	$f_{\text{bar}}(\%)$
star-forming	11282	$57.1 \pm +0.7 - 0.7$	4183	$37.1 \pm +0.9 - 0.9$
composite	2853	$14.4 \pm +0.6 - 0.4$	1301	$45.6 \pm +1.8 - 1.8$
AGN	681	$3.4 \pm +0.3 - 0.2$	353	$51.8 \pm +3.8 - 3.7$
LINER	1321	$6.7 \pm +0.4 - 0.4$	695	$52.6 \pm +2.7 - 2.7$
undetermined	3619	$18.3 \pm +0.6 - 0.5$	1654	$45.7 \pm +1.6 - 1.6$
total	19756	100	8186	$41.4 \pm +0.7 - 0.7$

Table 4.2 Results of activity classification for our sample of 19,756 not edge-on disc galaxies. f_{total} is the percentage of the total sample represented by each activity (number of galaxies of that type / total number of galaxies). f_{bar} is the percentage of each subsample that are barred (number of galaxies of that type that are barred / total number of galaxies in that type). Errors are 95% Bayesian binomial confidence intervals (Cameron, 2013).

composites, and one LINER) as AGN.

We show the results of the activity type and morphological classifications in Table 4.2. The numbers and fractions of each activity type with respect to the full sample are shown, as well as the numbers and fractions of barred galaxies within each activity type. These results are discussed in Section 4.2.

4.2 Results

To determine whether a correlation exists between galaxies that host an AGN and those that contain large-scale stellar bars, we examine the fractions of barred and unbarred AGN with respect to mass, colour, and AGN strength. We use stellar masses from the AVERAGE values in the MPA-JHU DR7 catalogue (Kauffmann et al., 2003a). Colours are $^{0.0}(u - r)$ values from SDSS DR7, which have been both de-reddened for Galactic extinction and k -corrected to redshift $z = 0.0$ (Csabai et al., 2003). Stellar velocity dispersions are taken from Oh et al. (2011).

4.2.1 Barred AGN fraction at a fixed mass and colour

Figure 4.4 shows the distributions of mass and colour for AGN and star-forming activity types, split into barred and unbarred subsamples. The median AGN is more massive

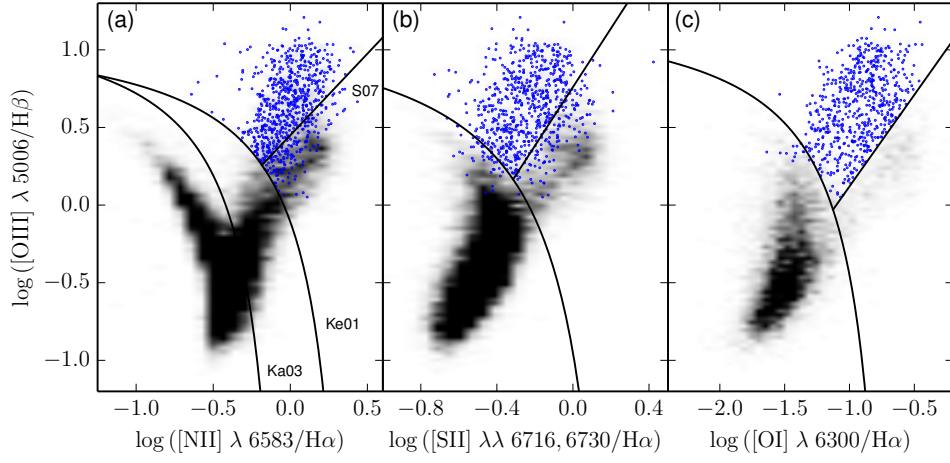


Figure 4.3 Optical line diagnostics for activity types of 19,756 disc galaxies. Any galaxy with $S/N < 3$ for $[\text{O III}]$, $\text{H}\beta$, $[\text{N II}]$, or $\text{H}\alpha$ is unclassifiable using this method and labeled as “undetermined”. The 3,619 undetermined galaxies do not appear on the diagram above. The remaining 16,137 galaxies were categorized according to the above diagrams in the following order, based on the method of Schawinski et al. (2007). First, diagram (a) was used to identify star-forming and composite galaxies. Any galaxy below the Ka03 line was classified as star-forming, while those that fell between the Ka03 and Ke01 lines were classified as composite. Next, to distinguish AGN from LINERs, we use diagrams (b) and (c). If a galaxy had $S/N > 3$ for $[\text{O I}]$, diagram (c) was used. If a galaxy did not have $S/N > 3$ for $[\text{O I}]$, but did for $[\text{S II}]$, diagram (b) was used. Last, if a galaxy did not have $S/N > 3$ for $[\text{O I}]$ or $[\text{S II}]$, but did for $[\text{N II}]$, diagram (a) was used. In each panel, only galaxies with $S/N > 3$ for all four lines required by that diagram are shown. Galaxies designated AGN by any of the three optical line diagnostics are plotted as blue points, while the black shading represents the full sample of emission-line galaxies.

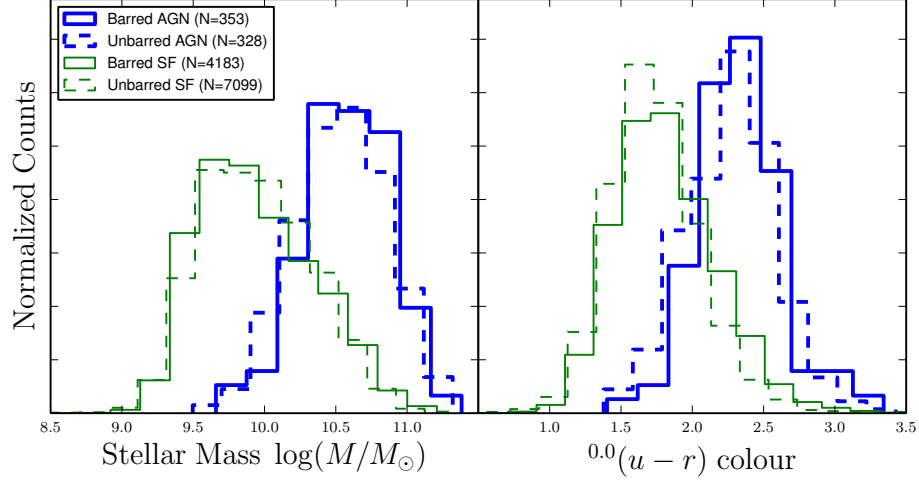


Figure 4.4 Mass and colour distributions for disc galaxies in the GZ2 sample, separated by both activity type (either AGN or star-forming as in Table 4.2) and the presence of a galactic bar. AGN (green) are on average both significantly redder and more massive than star-forming galaxies (blue). When splitting the disc galaxies into barred (solid lines) and unbarred (dashed lines), however, there is no significant difference between the two populations. Counts are normalized so that the sum of bins is equal to 1 for each sample.

(by 0.6 dex) and redder (by 0.5 mag) than the median star-forming galaxy. This agrees with previous optical studies of AGN and star-forming galaxies in the local Universe (Schawinski et al., 2007; Lee et al., 2012; Oh et al., 2012; Alonso et al., 2013). Aird et al. (2012) demonstrate that this difference is primarily caused by selection effects relating to the underlying Eddington ratio distribution. The probability of a galaxy hosting an AGN is assumed to be independent of stellar mass, and thus AGN are prevalent at all masses in the range $9.5 < \log(M/M_{\odot}) < 12$, despite only being observable at higher masses. As a result, we expect higher absolute numbers of barred AGN in a flux-limited sample since barred disc galaxies are also on average redder and more massive than unbarred disc galaxies (Masters et al., 2011, 2012). We interpret this as the primary cause for the higher fraction of barred AGN (51.8%) versus barred star-forming (37.1%) galaxies in Table 4.2.

To control for this selection effect, we examine the fraction of AGN at fixed masses

and colours (Figure 4.5). The total disc galaxy sample spans a mass range from $9.0 < \log(M/M_\odot) < 11.5$, while the colour range extends from $1.0 < (u - r) < 3.5$. AGN hosts are found throughout the disc galaxy sample, but most appear in galaxies with $\log(M) > 10^{10} M_\odot$. When examining the fraction of galaxies with an AGN as a function of mass and colour, redder and more massive galaxies have AGN fractions as high as 10%. Bins with fewer than 10 total AGN (barred AGN + unbarred AGN) are masked to minimize variance from small sample sizes. The same trend is also seen when splitting the disc galaxy sample into barred and unbarred subsamples.

To analyze the difference between the barred and unbarred AGN populations, we plot the difference in barred and unbarred AGN fractions in Figure 4.6. This quantity is defined as:

$$d_{\text{B-NB}} = \text{barred AGN fraction} - \text{unbarred AGN fraction} \quad (4.1)$$

and is calculated in each of the mass/colour bins in Figure 4.5. For each bin, a positive value represents a greater fraction of barred AGN and is coloured blue; a negative value represents a greater fraction of unbarred AGN and is coloured red.

Since our AGN sample is divided into relatively small subsamples, we examine how the size and placement of the mass/colour bins affect the results of Figure 4.6. To control for this effect, we examine the average value of $d_{\text{B-NB}}$ and the fraction of bins with $d_{\text{B-NB}} > 0$, defined as:

$$f_{\text{B>NB}} = \frac{\text{number of bins with higher barred AGN fraction}}{\text{total number of bins}}. \quad (4.2)$$

We compute $f_{\text{B>NB}}$ for 400 combinations of mass and colour bin widths between $0.2 \leq \Delta \log(M/M_\odot) \leq 0.6$ and $0.12 \leq \Delta(u - r) \leq 0.35$. The distribution of results from all combinations is shown in Figure 4.7. Our final bin choice (as seen in Figure 4.6) has a mass width of $\Delta \log(M/M_\odot) = 0.375$ (16 bins) and colour width of $\Delta(u - r) = 0.16$ (22 bins). This choice lies near the peak of the distributions for both $f_{\text{B>NB}}$ and $d_{\text{B-NB}}$, while maximizing the total number of bins to decrease the uncertainty on statistical tests.

For the first time among recently published studies, we quantify the level of correlation between the presence of a bar and AGN through statistical analysis. We test the

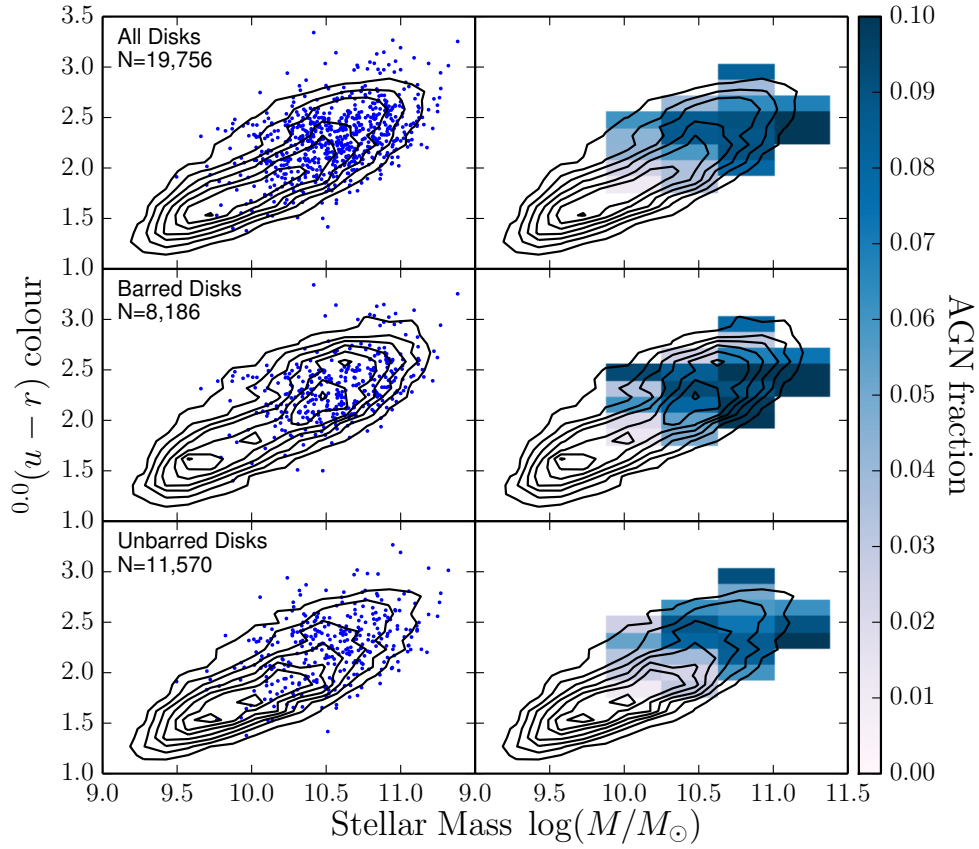


Figure 4.5 Optical colour vs. stellar mass for disc galaxies in GZ2. Black contours represent all disc galaxies (top), all barred galaxies (middle), or all unbarred galaxies (bottom). All AGN (top), barred AGN (middle), and unbarred AGN (bottom) are plotted in the left panels as blue dots; the right panels show the AGN fraction in each colour/mass bin. Bins with $N_{AGN} < 10$ are masked.

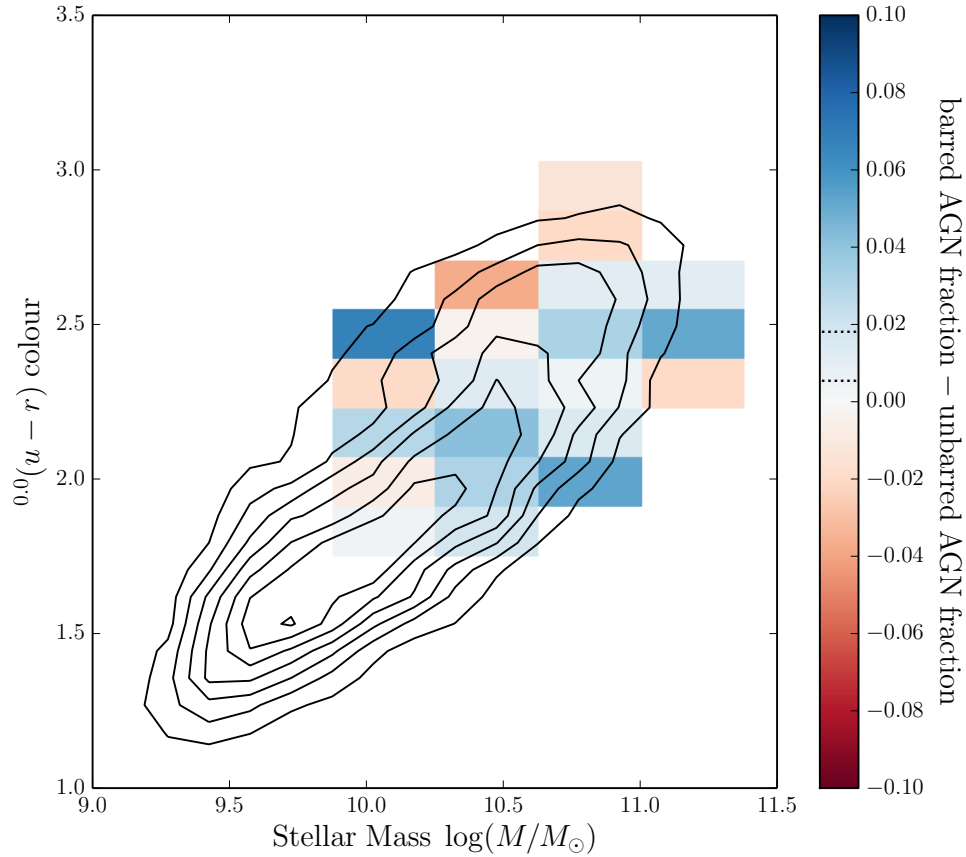


Figure 4.6 Optical colour vs. stellar mass for barred and unbarred disc galaxies in GZ2. Coloured bins show the difference between the AGN fractions for barred and unbarred galaxies. Blue bins have higher fractions of barred galaxies, red bins have more unbarred galaxies, and pale/white indicates no difference. The region on the colourbar enclosed by the dotted lines represents the mean of the data determined by the Anderson-Darling test. The colour gradient is on the same scale as Figure 4.5. Bins with $N_{AGN} < 10$ are masked. A colour version of this plot may be found in the electronic edition of the journal.

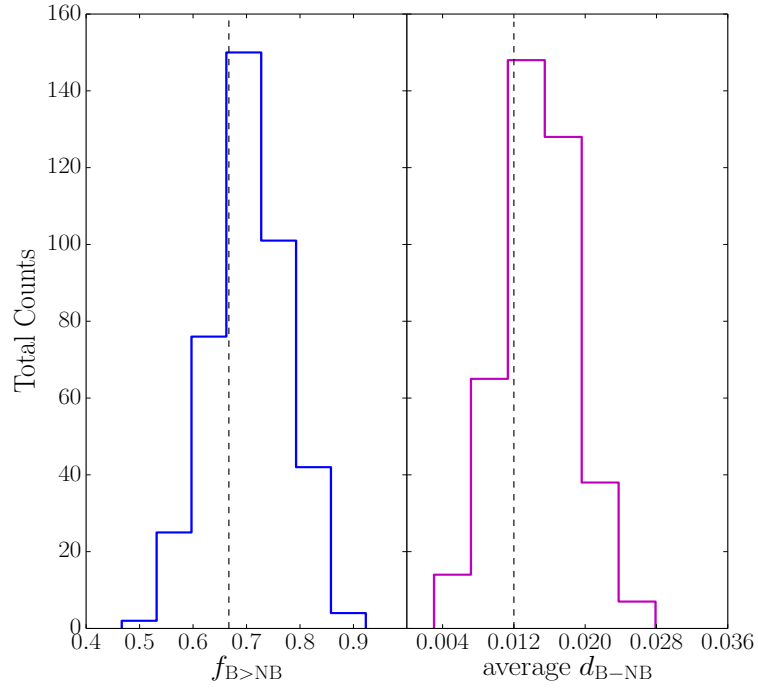


Figure 4.7 Distributions of the difference in the fraction of bins with excesses of barred AGN ($f_{B>NB}$) and the average difference between barred and unbarred AGN fractions (d_{B-NB}). Both values are computed for 400 variations in the mass and colour bin widths. *Left*: The average fraction of bins with a higher barred AGN fraction is $f_{B>NB} = 0.705 \pm 0.073$. *Right*: The average difference in barred and unbarred AGN fractions is $d_{B-NB} = 0.015 \pm 0.004$. Dashed black lines indicate the values of $f_{B>NB}$ and average d_{B-NB} used in Figure 4.6 and subsequent analysis.

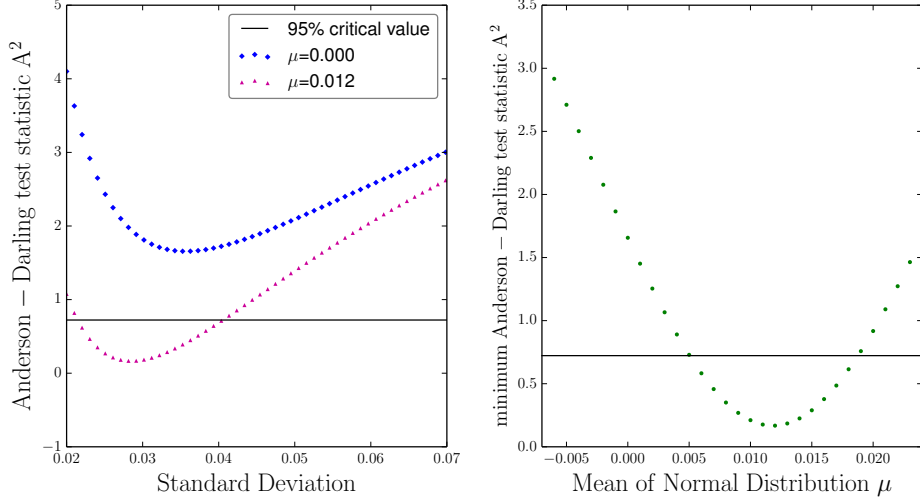


Figure 4.8 Fits of the binned fraction of barred vs. unbarred AGN fractions to a normal distribution. *Left*: value of the Anderson-Darling test (A^2) as a function of the standard deviation of the normal distribution being fit (σ_d). The horizontal black line shows the critical value of A^2 corresponding to 95%; a model must fall below this line to be considered an acceptable fit at this level of confidence. Two models are shown: the null hypothesis (blue diamonds) and the best fit to the data in Figure 4.6 (purple triangles). *Right*: Plot of the minimum A^2 for the full range of means ($d_{\text{B-NB}}$) tested for the data. This shows that acceptable fits can be found for $0.005 < d_{\text{B-NB}} < 0.019$, but that the null hypothesis is ruled out at 95% confidence.

null hypothesis that in the absence of a causal link, the difference between barred and unbarred AGN fractions when binned by mass and colour should be centered around zero. The null hypothesis also requires that the likelihood distribution decreases symmetrically from zero in both directions; as a result, we assume a normal distribution with mean $\mu = 0$ and standard deviation σ . Other models of the null hypothesis could of course also be tested, but we adopt this as the simplest reasonable scenario that fits the constraints of the problem.

To assess the level of statistical significance, we fit the data in Figure 4.6 with a range of models with varying mean ($d_{\text{B-NB}}$) and standard deviation (σ_d) and then apply an Anderson-Darling test. We selected this test because it has been empirically shown to be more powerful and reliable at testing normality than traditional χ^2 or Kolmogorov-Smirnov tests, especially with small ($n < 30$) sample sizes (Hou et al.,

2009). The confidence threshold required for the model to pass at fitting the data is 95%. In Figure 4.8, we show the distribution of the Anderson-Darling statistic A^2 as a function of σ_d for two of the tested models: the null hypothesis ($d_{\text{B-NB}} = 0$) and the best fit to the data ($d_{\text{B-NB}} = 0.012$). The null hypothesis fails the Anderson-Darling test for all values of σ_d , indicating that the 66.7% $pm+16.1\%$ –21.6% fraction of bins that have a higher barred than unbarred AGN fraction is statistically significant. The best fit to the data, by contrast, has a mean of $d_{\text{B-NB}} = 0.012pm+0.007-0.007$ and $\sigma_d = 0.028$. The positive value of $d_{\text{B-NB}}$ indicates an increase in the AGN fraction for barred galaxies, consistent with the hypothesis that at least some fraction of AGN activity is triggered or sustained by bar-driven fueling.

4.2.2 Comparing barred and unbarred AGN accretion strengths

If the presence of a bar does contribute to AGN fueling, one possible result would be an increase in the accretion rate for barred AGN hosts vs. those that are unbarred. To assess this, we compare relative accretion strengths using the quantity $R = L_{[\text{O III}]} / M_{\text{BH}}$, with $L_{[\text{O III}]}$ as a proxy for the AGN bolometric luminosity. $[\text{O III}]$ luminosities were calculated using fluxes from Oh et al. (2011), and black hole masses estimated using the $M_{\text{BH}}-\sigma$ relation:

$$\log \left(\frac{M_{\text{BH}}}{M_{\odot}} \right) = \alpha + \beta \log \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right). \quad (4.3)$$

Here α and β are empirical values determined from the observed relationship between black hole mass and velocity dispersion σ . We adopt the parameters measured by Gültekin et al. (2009) of $(\alpha, \beta) = (8.12 \pm 0.08, 4.24 \pm 0.41)$.

It has been demonstrated for smaller samples of galaxies that the parameters α and β vary as a function of morphological type (Graham et al., 2011; Gültekin et al., 2009; Brown et al., 2013), including differences between barred and unbarred galaxies. We choose not to use (α, β) parameters where (α, β) are derived from separate subsamples for two reasons. First, since the $M_{\text{BH}}-\sigma$ relation is calibrated from small samples of nearby galaxies, the statistical error on the parameters increases as galaxies are divided into smaller sub-groups. The calibration of Gültekin et al. (2009), for instance, is based on measurements of only eight barred galaxies. The error in β for the barred $M_{\text{BH}}-\sigma$

relation is $\sigma_\beta = \pm 0.751$, almost twice the error obtained by fitting to the full sample of disc galaxies. Second, while different studies report consistent values for α and β when all disc galaxies are considered, the values can vary significantly when splitting by morphological type. Lee et al. (2012) and Alonso et al. (2013) use separate values for (α, β) and report conflicting levels of agreement, depending on which parameters are used. This raises the possibility that differences in AGN strength are simply due to differences in calibration parameters, and not in the true distribution of accretion efficiencies.

Figure 4.9 shows the relative accretion strengths R for our sample as a function of mass and colour for both barred and unbarred AGN; these values are inversely correlated with both mass and $(u - r)$ colour. This trend is likely driven by the same selection effects described in §4.2.1 (Aird et al., 2012). At a fixed $L_{[\text{O III}]}/M_{\text{BH}}$ ratio, AGN with lower mass black holes are less likely to be detected due to the signal to noise requirements on their spectral lines. This biases the distribution of R toward higher mass black holes. Since stellar mass is strongly correlated with black hole mass (Hring & Rix, 2004; Gültekin et al., 2009; Merloni et al., 2010), and stellar mass correlates with optical colour (Kauffmann et al., 2003a), this explains the trend seen in both parameters for an uncorrected sample.

Since these observationally-driven selection effects are likely to affect barred and unbarred galaxies equally, we compare the values of R of both groups without any corrections. A two-sided KS-test yields a p -value of $p = 0.127$ for the two distributions. This is consistent with both the barred and unbarred galaxies being drawn from the same distribution. We thus conclude that there is no strong evidence for a difference in accretion strength between barred and unbarred AGN.

This result contradicts Alonso et al. (2013), who found an excess of barred AGN with high values of R . We conjecture that this may be the result of their sample selection, which excluded galaxies with $M_\star < 10^{10} M_\odot$ in favor of a higher redshift limit of $z = 0.1$. However, low mass galaxies have higher $L_{[\text{O III}]}/M_{\text{BH}}$ ratios and are more likely to be unbarred than their higher mass counterparts (Lee et al., 2012). If this effect is real, it appears to be limited to high-mass galaxies (which themselves are subject to selection effects due to the methods used to measure R). Additionally, Alonso et al. (2013) include composites and LINERs in their sample of AGN. If the activity from these galaxies is

not primarily from black hole accretion, R is not a true proxy for accretion strength, and comparisons between barred and unbarred galaxies do not accurately probe differences between the two populations. To test this, we compare R distributions for barred and unbarred composite + AGN + LINER galaxies with $M_\star > 10^{10} M_\odot$. For these galaxies, the difference in the average values of R for the barred and unbarred samples is $0.09 (L_\odot/M_\odot)^{-1}$ (compared to a difference of $0.06 (L_\odot/M_\odot)^{-1}$ when considering only AGN with no cut on stellar mass), and a KS-test for the distributions yields a p-value < 0.01 , which agrees with the results of Alonso et al. (2013). We note that our results are consistent with Lee et al. (2012), who have a similar mass range to our sample of disc galaxies, and do not include composites in their sample.

4.3 Discussion

We have compared a sample of 353 barred Seyfert AGNs to 328 unbarred Seyferts and measure the potential correlation between the presence of the bar and the AGN. We find that at fixed mass and colour, AGN hosts show a small increase in the fraction of galaxies that are barred. The average difference is $d_{\text{B-NB}} = 0.012$, or roughly 16.0% of the average barred AGN fraction. We find no difference in the $L_{[\text{O III}]}/M_{\text{BH}}$ ratio between barred and unbarred AGN at either fixed mass or colour. We conclude that while AGN hosts have moderately higher probabilities of hosting a bar, the presence of the bar does not seem to affect either the quantity or efficiency of fueling the central black hole.

If bars are not required to initiate AGN fueling, then what is the source? There must be a process that transports angular momentum through the galactic disc and creates/maintains an accretion disc. Both theoretical models (Shlosman et al., 1989, 1990) and numerical simulations (Hopkins & Quataert, 2010) indicate that this process requires two stages. First, the gas must be driven from a radial scale of megaparsecs down to kiloparsecs. Standard viscous torques on the gas are too inefficient to initiate gas inflow by themselves Shlosman et al. (1989); Bournaud et al. (2005); therefore, some other mechanism is required. Within the central kiloparsec, a secondary instability must take over within the gaseous disc for AGN fueling to occur.

In the context of this general model, we consider three possibilities: (I) Bars are

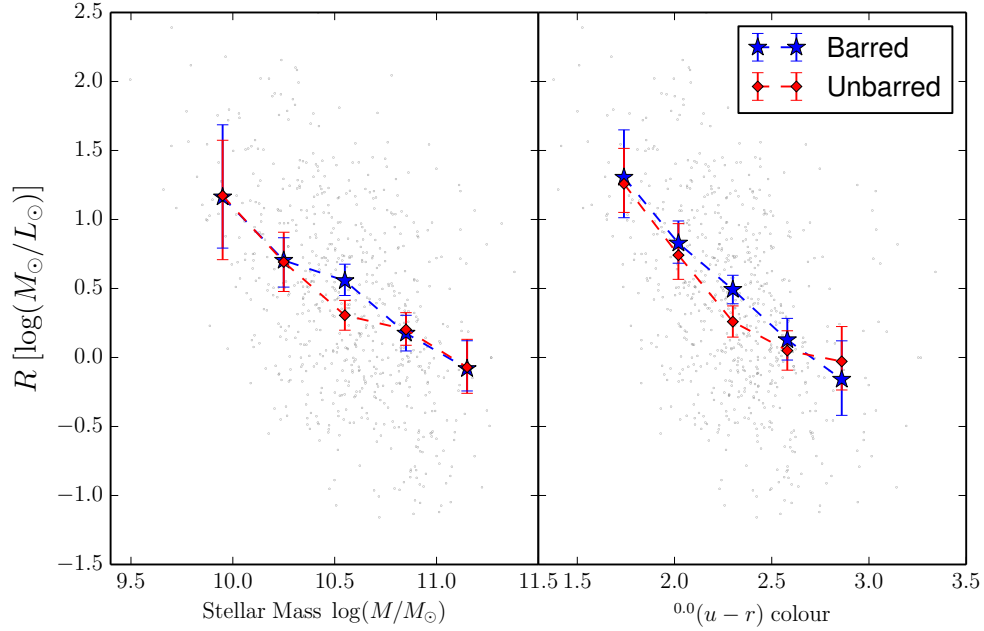


Figure 4.9 **Left:** Relative accretion strength R vs stellar mass for barred (blue) and unbarred (red) AGN in our sample. R is plotted as the mean of values within five equal-width bins in the range $9.8 < \log(M/M_{\odot}) < 11.3$, which includes 98% of the AGN sample. Points are drawn at the midpoint of each bin. **Right:** R vs colour for barred and unbarred AGN. R is plotted as the mean of values within five equal width bins in the colour range $1.6 < (u - r) < 3.0$, which includes 96% of the AGN sample. Error bars for each plot are 95% confidence intervals, calculated by bootstrapping with 1000 times resampling. There is no significant difference in accretion strengths for barred and unbarred AGN as a function of either mass or colour.

a necessary ingredient for fueling AGN, (II) Bars are one of multiple processes that fuel AGN, or (III) Bars play no role in fueling AGN. We also discuss in each scenario possible explanations for the existence of all four observed combinations: barred AGN, unbarred AGN, barred non-AGN, and unbarred non-AGN.

4.3.1 Scenario I: Bars are necessary to fuel AGN

If the presence of a stellar bar is the only mechanism by which gas can be driven to the ~ 1 kpc scale, there must be a reason both barred and unbarred AGN are observed in large numbers. One possibility is that a galactic bar *initiates* fueling of the black hole, but is subsequently destroyed in a dynamic timescale shorter than the lifetime of the AGN. These separate timescales are not currently known with certainty, but estimates place the lifetime of an AGN from 10^6 — 10^8 years (eg, Schawinski et al., 2010; Martini, 2004). The range of bar lifetimes is not yet firmly established; some models show bars to be transient features that are destroyed either due to buckling from angular momentum transport or from the build-up of a central mass concentration (CMC) (Bournaud et al., 2005; Combes, 2007). In these models, the lifetime of a bar is estimated to be 1 – 2 Gyr. Kraljic et al. (2012) also found bars to be short-lived in their simulations, but only early bars (formed at $z > 1$). Bars formed later (at $z < 1$) were maintained down to $z = 0$, giving a lifetime of at least 8 Gyr.

Other simulations (Debattista et al., 2004, 2006; Athanassoula et al., 2005, 2013; Shen & Sellwood, 2004) do not observe bar destruction due to buckling. In these cases, only a sufficiently massive CMC is capable of destroying the bar on Gyr timescales. The mass of the CMC required in these models is at least several percent of the total mass of the disc — this is significantly larger than the mass measured in local disc galaxies. If the CMC is insufficiently large, the bar is maintained for the lifetime of the disc (up to 10 Gyr; Athanassoula et al., 2013), and thus should be observable for at least the lifetime of the AGN.

If bars are truly long-lived structures in all disc galaxies and are necessary to fuel AGN, we would expect a much higher value of the ratio of barred to unbarred AGN hosts. Since the observed numbers are nearly 1:1, we consider this scenario highly unlikely. It is possible that bars are necessary to fuel AGN, but the number of observed unbarred AGN can only be explained if the factor of ~ 10 difference between the upper

end of the AGN lifetime and the lower end of the bar lifetime can be resolved. While this is possible, we consider it unlikely given the assumptions required.

4.3.2 Scenario II: Bars are one of several ways to fuel AGN

If stellar bars are only one of several ways to fuel AGN, then both barred and unbarred AGN should exist (as should both barred and unbarred star-forming galaxies). The simulations conducted by Hopkins & Quataert (2010) support this model, which show that multiple large-scale mechanisms (including a stellar bar) can be responsible for transporting gas to scales required for AGN fueling. Further, if bar-driven fueling is responsible for some fraction of the AGN, this model predicts an increase in the fraction of barred AGN, which our data supports.

While the existence of unbarred AGN is explained by this model, there is no immediate explanation for the existence of barred galaxies that do not host AGN; here we suggest several possibilities. First, a bar that initiates AGN fueling may simply outlive the AGN (see 4.3.1), which agrees with estimates of both bar and AGN lifetimes. Second, there could be a correlation between bar strength and AGN activity, where only sufficiently strong bars initiate fueling. This is consistent with Lee et al. (2012), who find a higher AGN fraction in barred galaxies where the bar length is at least 1/4 of the total disc diameter. They did not test, however, whether this relationship remains at fixed mass and colour. Finally, the emission from an AGN is expected to be highly variable with time, driven by processes such as accretion disc instabilities and/or feedback within the accreting material (Hickox et al., 2014). In this case, barred galaxies without AGN are simply observed in low parts of their duty cycle, with Eddington ratios too low to be detected at the limits of our observations.

4.3.3 Scenario III: Bars do not fuel AGN

Finally, we consider the possibility that stellar bars do not trigger AGN activity in any way. This is inconsistent (although marginally so) with the increase in barred vs. unbarred AGN fractions that we find at fixed mass and colour. One possibility is that the model used for the null hypothesis (a normal distribution centered at $d_{B-NB} = 0$) does not apply. Detailed simulations of cosmological volumes that include both AGN

	sample	$f_{\text{B}>\text{NB}}$	Mean $d_{\text{B-NB}}$
low mass	$\log(M/M_{\odot}) < 10.625$	0.70	0.0125
high mass	$\log(M/M_{\odot}) > 10.625$	0.64	0.0123
blue	$(u - r) < 2.22$	0.88	0.023
red	$(u - r) > 2.22$	0.54	0.006

Table 4.3 Difference between barred and unbarred AGN fractions for disc galaxies when splitting the sample in two by both mass and colour. $f_{\text{B}>\text{NB}}$ is the fraction of bins that show an excess of barred AGN (compared to unbarred), while $d_{\text{B-NB}}$ is the average value of the differences over all bins. Since the number of bins in each subsample is only $\sim 8 - 13$ when splitting by mass or colour, the uncertainty in $f_{\text{B}>\text{NB}}$ is correspondingly large.

and detailed disc morphology, such as *Illustris* (Vogelsberger et al., 2014) and EAGLE (Schaye et al., 2014) should ultimately provide more well-defined priors for this.

In addition, our test of the null hypothesis could still be consistent with a strong effect even if the total number of barred and unbarred bins were equal. For example, if bar-driven fueling is strongly mass-dependent, the $d_{\text{B-NB}}$ bins could have excesses of barred AGN at high masses and deficits at low masses; this would still be consistent with a distribution centered at zero. We test the simplest cases by simply splitting the sample into two in both mass and colour (Table 4.3). Low- and high-mass disc galaxies (dividing the sample at $\log(M/M_{\odot}) = 10.625$) have nearly identical values of $f_{\text{B}>\text{NB}}$ and mean $d_{\text{B-NB}}$; there is no evidence of a mass-dependent effect on bar-driven AGN fueling. When splitting discs into red vs. blue (at a colour of $(u - r) = 2.22$), bluer galaxies do have significantly more bins with an excess of barred AGN ($f_{\text{B}>\text{NB}} = 0.88$) than redder galaxies ($f_{\text{B}>\text{NB}} = 0.54$). The uncertainties on $f_{\text{B}>\text{NB}}$ are quite large, though, since each subsample has less than a dozen bins. Our splits by colour agree with (Oh et al., 2012), who find that bar effects on AGN are more pronounced in bluer and less massive galaxies. Lee et al. (2012), in contrast, find that $f_{\text{B}>\text{NB}}$ depends on neither mass nor colour.

If bars have no impact at all on the likelihood of a disc galaxy hosting an observable AGN, this is inconsistent with both the models and simulations that demonstrate efficient gas-driven inflow by bar structures (Hopkins & Quataert, 2010). If the efficiencies of other morphologies that drive gas inflow are much higher than bars, though, this

could also be consistent with our data. A lack of bar-driven fueling is consistent with the existence of both barred and unbarred AGN and star-forming galaxies, and the nearly equal numbers found in both pairs.

Given the limits on the data set (which is driven by binning the total number of disc galaxies by mass and colour), we do not completely rule out this model. However, given the small (but measurable) increase in the bar fraction from our data and the current constraints on both bar and AGN timescales, we propose that bar-driven fueling must account for at least some fraction of observed AGN activity (§4.3.2).

4.4 Conclusions

We have created a sample of 19,756 disc galaxies from SDSS DR7, using data from the Galaxy Zoo 2 project for morphological classifications of strong, large-scale bars. We studied the effects of stellar bars on 681 AGN and compared these effects to a control sample of disc galaxies both without bars and without AGN. The Galaxy Zoo 2 data provides a very large sample of disc morphologies for which the bar likelihood can be empirically quantified, based on crowdsourced visual classifications.

We find that the fraction of barred AGN (51%) is significantly greater than the fraction of barred galaxies with central star formation (37%). However, this is driven both by selection effects for detecting optically-identified AGN and by known correlations between black-hole mass and stellar mass, as well as stellar mass and optical colour. When examining the fraction of barred AGN as a function of a fixed mass and colour, we still find a small increase in the number of barred AGN hosts. The null hypothesis of no relationship between the two cannot be ruled out at the 95% confidence level. The $L_{[\text{O III}]}/M_{\text{BH}}$ ratio R (a proxy for the overall accretion rate) shows no dependence on the presence of a bar, once the same mass and colour constraints are applied.

Our results are consistent with a small relationship between the presence of a large-scale galactic bar and the presence of an AGN. We propose that while bar-driven fueling does indeed contribute to some fraction of the current observed population of growing black holes, other dynamical mechanisms, such as lopsided or eccentric stellar disk, must also contribute to the redistribution of angular momentum and thus the fueling of the accretion disk at small galactic radii.

Even with the advent of the large-scale SDSS data and the morphological classifications from Galaxy Zoo 2, this result is still constrained by the total number of galaxies in our study. Larger samples of disk galaxies with activity and morphological classifications, notably the Dark Energy Survey (DES) and the Large Synoptic Survey Telescope (LSST), should increase the sample sizes by factors of at least a few and help to confirm these results. Further development on the theoretical side is also critical — with state-of-the-art simulations now able to reproduce both the morphology distributions and the observed black hole mass function, these results can be compared to theory in a cosmological context.

Chapter 5

A comparison of optical and infrared morphologies with Galaxy Zoo 2 and Galaxy Zoo: UKIDSS

5.1 Introduction: morphological dependence on wavelength: optical and infrared

Historically, visual morphological classification of galaxies has been conducted on optical images. Blue B-band images were the primary source dating back to Hubble’s classic tuning-fork classification scheme (Hubble, 1926) and in the subsequent modifications by Sandage (1961) and de Vaucouleurs (1963). The more recent and larger morphological catalogs also derive their classifications from rest-frame optical images, either single-band (de Vaucouleurs (1991) (B-band), Scarlata et al. (2007) (ACS I-F814W), Fukugita et al. (2007) and Nair & Abraham (2010) (SDSS g-band)) or color-composite (Lintott et al. (2008), Willett et al. (2013) (SDSS-gri)).

In the optical regime, the flux is dominated by young, hot stars; this results in an emphasis of spiral structure in the images, but they tend to have patchy appearances due to the abundance of star-formation regions in the arms. Optical images also are impacted

by extinction due to dust, which can obscure features that tend to be composed of older stellar components (such as bars and bulges). Longer wavelengths are free of these effects, making them ideal for revealing the underlying “stellar backbone” of galaxies.

It is possible, then, to consider two morphologically distinct components of a galaxy: a gas-dominated Population I disk, and a star-dominated Population II disk. The Population I disk is most easily seen in the optical, revealing HII regions, cold HI gas, and emission from young OB stars; these regions will tend to highlight flocculence in spiral structure. The Population II disk, on the other hand, traces the underlying mass distribution; consisting of the old, cooler stellar population, it is more easily seen at longer wavelengths. Block & Puerari (1999) even suggests that two separate classification schemes should be required for all galaxies; one for the Population I disk, which can be probed in optical and ultraviolet images, and another for the Population II disk, for which longer wavelength images, free of dust extinction, would be required.

The extent to which the morphologies of the younger and older stellar populations are decoupled, however, is not yet clear. Early studies which directly compared optical and near-IR images found very significant differences between the two morphologies (Hackwell & Schweizer, 1983; Thronson et al., 1989; D. Block, 1991; Block et al., 1994). Block & Puerari (1999) go as far as to suggest that there is no correlation between the two, and that the optically-defined Hubble tuning fork “does not constrain the morphology of the old stellar Population II disks.” However, all of the aforementioned studies only compared morphologies of either a single galaxy, or at most a handful, so these conclusions cannot be applied generally.

The advent of larger surveys incorporating near and mid-IR detectors enabled morphological comparisons between the two wavelength regimes on a much grander scale than had previously been achieved. New results contradicted those of the previous case-studies: in general, IR morphology was found to be well-correlated with optical morphology in larger samples of galaxies. Eskridge et al. (2002) compared near-IR H-band ($1.65\mu\text{m}$) Hubble-type classifications to B-band in a sample of 205 nearby spiral galaxies from the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS). Applying deVaucouler’s classification system, they found a overall a good correlation between the two morphologies, but on average galaxies from Sa through Scd appeared one T-type earlier in the H band than in the B band. In the IR images the bulge tended

to appear more prominent and the spiral arms less knotty, which resulted in the slightly lower T-types. For the earliest (optically S0/a and Sa) and latest-type galaxies (optically Scd through Sm), no difference in morphologies was found. This is an expected result for the earlier-types, since these have little ongoing star formation and very little dust, so it is expected that both optical and IR morphologies are dominated by old stars. This result is less intuitive for the later-type galaxies, as these are dominated by ongoing star formation. However, these galaxies are defined as having very weak or nonexistent bulges and poorly defined spiral structure. Since the main driver in the differences in morphology across wavebands was found in the intermediate spirals to be the relative prevalence of a bulge and difference in contrast and appearance of spiral arms, galaxies lacking these features should not, in fact, be expected to look different in the IR than the optical.

Buta et al. (2010) obtained similar results comparing optical and mid-IR ($3.6 \mu\text{m}$) images from the *Spitzer* Survey of Stellar Structure in Galaxies (S⁴G, Sheth et al. (2010)) in a sample of 207 spiral galaxies. Like Eskridge et al. (2002), the optical and IR classifications were very well correlated, with the most significant differences occurring for S0/a to Sc galaxies, where the $3.6 \mu\text{m}$ were on average slightly earlier than the B-band classifications.

Infrared imaging is also often used in place of (or in addition to) optical to identify stellar bars (e.g. Mulchaey & Regan (1997); Knapen et al. (2000); Block et al. (2004); Sheth et al. (2008)). Like bulges, bars are primarily composed of old, red stars, and therefore better traced by longer wavelengths. In fact, it is not uncommon for an infrared bar to be completely invisible in the optical. Notable examples include NGC 1566 (Hackwell & Schweizer, 1983), NGC 1068 (Thronson et al., 1989; Scoville et al., 1988), NGC 309 (D. Block, 1991), NGC 4736 (Block et al., 1994), and NGC 4303 (Figure 1, Sheth et al. (2003)). This trend is not only limited to case-studies; for example, in a larger sample of 29 galaxies classified as unbarred in the optical, 50% of these were found to be barred in the near-IR images (Mulchaey & Regan, 1997).

The fraction of spiral galaxies which exhibit bars (defined as the bar fraction) has been measured extensively in optical images, and typically falls near 50% when bars of all strengths are considered, as observed in Chapter 4 and in other studies (Sheth et al., 2008; Masters et al., 2010; Consolandi et al., 2017). Since it is much more common to

find an infrared bar in an optically unbarred galaxy than the reverse, it is expected that the bar fraction in the infrared will, in general, be higher than what has been measured in the optical. Some studies find a substantial increase: Seigar & James (1998) for example speculate that “bars may always be present in disks at some level”, based on finding a bar fraction of 90% when using infrared images (as compared to their optical measurement of 68%). Although their sample consisted of only 45 galaxies total, they claim this measurement should represent the general population of spirals, because their selection was not biased towards barred galaxies. Other studies report similar increases in bar fraction in the infrared, albeit not quite as large. Knapen et al. (2000) in a similar sample size of 50 galaxies find a bar fraction in the infrared of 70%, a strong increase from the optical 50%. Eskridge et al. (2000) in a sample of 186 galaxies measure a bar fraction of 72% in the infrared which is *double* that of their optical measurement. While these studies report significant increases in bar fraction as a function of wavelength, they do dispute the claim by Seigar & James (1998), emphasizing that at least 30% of galaxies in their sample are truly unbarred across all wavelengths.

Other more recent studies find larger bar fractions in the infrared, but not significantly so. Whyte et al. (2002) measure an increase from 72% to 79% in a sample of 72 galaxies, while Sheth et al. (2008) reports 60% for both wavelengths. MenendezDelmestre et al. (2007b) also found a slight increase from 63% to 67% in a sample of 151 galaxies, noting that although bars tended to appear stronger in the near-IR, on average they were not so weak in the optical as to become undetectable. Finally, Buta et al. (2010) also reported a similar result of 60% barred spirals, which was consistent with the fraction computed in optical RC3 classifications.

This Chapter will investigate the significance of waveband on visual morphologies using a sample an order of magnitude larger than achieved by the aforementioned studies. The morphologies of a sample of over 6000 galaxies which have been visually classified in optical wavebands (via GZ2) and infrared (via GZ:UKIDSS) will be compared to assess whether 1) IR galaxies tend to have earlier morphologies, and 2) whether more bars are able to be detected in the IR images.

5.2 UKIDSS sample

The UKIDSS sample is comprised of 71,052 infrared images of galaxies which had been previously optically classified in GZ2. The images were taken with the United Kingdom Infrared Telescope (UKIRT) as part of the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. (2007); Warren et al. (2007)). The Large Area Survey (LAS) portion of UKIDSS covered the SDSS observations at high Galactic altitudes, allowing for full YZJHK coverage.

Morphological classifications for the UKIDSS sample were obtained via Galaxy Zoo, where users were shown YJK color-composite images. The classification tree used was identical to that in GZ2, allowing a direct comparison of morphologies using the same vote fractions. Raw votes were counted and weighted by user consistency in the same manner as the GZ2 sample (details of this process are given in Chapter 2).

One major challenge in comparing the UKIDSS and GZ2 morphologies is to ensure that any differences measured are mostly driven by actual morphological differences between wavebands, and not due to varying instrumental parameters. Details of the instrumentation for both samples is shown in Table 5.1. The resolution of both sets are comparable - with similar pixel size and PSF widths, the ability to resolve finer features in the images should be consistent for both. The difference in depth, however, is significant: the SDSS gri bands used to create the color-composite images in GZ2 are on average ~ 1 magnitude deeper than what is achieved for the LAS YJK bands in UKIDSS. To minimize the impact the difference in depth may have in comparing the two sets of images, the comparison sample is limited to the nearest and brightest galaxies. The sample is thus restricted to a volume-limit of $z < 0.06$ and $M_{r,petro} < -20.0$, which consists of 10,395 galaxies of the 54,238 with spectroscopic redshifts.

To further ensure that any observed difference in morphologies are due to physical (wavelength) dependencies, and not instrumentation, the sample is further restricted to only include galaxies for which the signal detected in the IR image extends to a significant fraction of the galaxy's total light profile. During preliminary visual inspection of side-by-side IR/optical images of the subjects, it was seen that for many of the optically-classified spirals, the arms in the IR images appeared so faint with respect to the bulge that there could be no fair comparison of morphologies using vote fractions.

UKIDSS		GZ2	
Filter	Depth (AB mag)	Filter	Depth (AB mag)
Y	21.13	g	22.2
J	20.91	r	22.2
K	20.25	i	21.3
seeing:	<1.2"	PSF width:	1.4" (median in r)
pixel scale:	0.4"	pixel scale:	0.396"

Table 5.1 Comparison of depth and resolution of the UKIDSS and GZ2 images. The resolution between the two surveys is comparable, but the UKIDSS images are an average of ~ 1 magnitude shallower in all bands used to create the color-composite images that were classified.

An example of this effect occurred in GZ2-classified spiral galaxies which the majority voted as “smooth” in UKIDSS, due to the bulge being the only visible feature in the IR images (see Figure 5.1).

5.2.1 Method for selecting equally-sized galaxies

To identify which galaxies are sufficiently detected in both the IR and optical images, the S/N profile of the IR J-band images is compared to the petrosian radius in the r-band. For disk galaxies whose surface brightness distribution follows an exponential profile, 99% of the galaxy’s total flux is enclosed by the Petrosian magnitude (Graham et al., 2005), which is defined as the flux measured within two Petrosian radii. Therefore, we can let $2 \times r_{petro}$ represent the radius that encloses the entire disk, which will be hereafter denoted as r_{2petro}^r . To properly compare morphologies of disk galaxies in IR and optical images, it must be ensured that a signal is detected in the J-band out to a significant fraction of that radius. This is done by computing the surface brightness profile in the J-band, and measuring the radius within which the S/N is greater than 3, which will be hereafter denoted as r_3^J . A cut is then placed on the volume-limited sample such that $r_3^J \geq 0.75r_{2petro}^r$, which retains $\sim 60\%$, or 6,484 galaxies considered suitable for a robust morphological comparison. The details of this process and justification for this cut are described here.

The J-band cutouts were downloaded directly using the WFCAM Science Archive¹ .

¹ http://wsa.roe.ac.uk:8080/wsa/MultiGetImage_form.jsp



Figure 5.1 Example of a galaxy whose morphological change between optical and IR wavelengths was driven by a lack of light detectable in the IR relative to optical. This image was classified as featured and spiral in the optical using GZ2 vote fractions (left), but smooth in the IR using UKIDSS vote fractions (right) (dr7objid: 587726014553587781).

The signal to noise profiles are then computed on J-band sky-subtracted cutouts, where the sky subtraction is done using the PYTHON package PHOTUTILS BACKGROUND2D function. The noise is defined as the dispersion in the background flux, shown in the top-left panel of Figure 5.2. The background was fit to a Gaussian, and the noise was taken as the resulting standard deviation value given by the fit. The signal was computed by calculating the average flux per pixel within circular apertures of varying radii from the center of the galaxy to the edge of the cutout. From these a signal-to-noise profile was generated for each galaxy; an example is shown in the top-right panel of Figure 5.2. The radius at which the S/N profile falls below $S/N=3$ (or in other words, the radius within which the S/N remains greater than 3, r_3^J), is recorded for each galaxy, represented as the green dashed line. The blue dashed line is drawn at r_{2petro}^r , representing the radius containing 99% of the flux, as described above. The ratio of r_3^J to r_{2petro}^r is then used to evaluate whether the galaxy is sufficiently detectable in both wavelengths for a fair morphological comparison. The bottom row of Figure 5.2 shows the results of this method displayed on the color-composite images that are seen by GZ users. The circle on the optical image (left) shows r_{2petro}^r , and the circle on the IR image (right) shows

the J-band radius within which $(S/N)_J > 3$, r_3^J . In this example, $r_3^J = 0.62 \times r_{2petro}^r$, indicating that the radius at which the galaxy is detectable in the J band is only 62% that of what is visible in the r band. Given that the threshold for inclusion in the sample is $r_3^J/r_{2petro}^r \geq 0.75$, this galaxy is considered too faint in the IR with respect to the optical to fairly compare vote fractions.

Figure 5.3 shows the optical and IR images of galaxies, overlaid with circles of radii r_{2petro}^r (optical, left) and r_3^J (IR, right), sorted by the ratio r_3^J/r_{2petro}^r . For small ratios (towards top of figure) it is obvious that the IR image is much too faint with respect to the optical image for a fair comparison of vote fractions, while for ratios closer to unity (towards bottom of figure), the images are much more comparable. The effect of r_3^J/r_{2petro}^r on the difference in vote fractions is displayed in Figure 5.4. The left shows the distribution of the change in $f_{features}$ vote fractions (explicitly: $GZ2 f_{features} - UKIDSS f_{features}$) for the optical and IR images as a function of r_3^J/r_{2petro}^r ; the right shows the average change in $f_{features}$ as a function of r_3^J/r_{2petro}^r . As expected, there is a much larger difference in vote fractions when the IR image does not show the full extent of the galaxy relative to the optical image (low r_3^J/r_{2petro}^r). This difference cannot be confidently attributed to a true morphological change, but rather a limitation on the instrumentation and therefore visibility of the galaxy. A cut of $r_3^J/r_{2petro}^r \geq 0.75$ (dashed line in Figure 5.4, right), is chosen as a threshold that restricts the sample to a region which is mostly flat in $\langle GZ2 f_{features} - UKIDSS f_{features} \rangle$ vs r_3^J/r_{2petro}^r , but is large enough to retain a large number of galaxies.

5.3 Comparison of Hubble Types in Spirals

In this section the global morphologies seen in the infrared and optical are compared. As described above, the most recent studies found similar results when comparing the Hubble T-types of both wavelengths; in general, the morphologies are well-correlated, with the IR T-types being on average one T-type earlier than in the optical. The strongest difference occurred for the optically intermediate-type spirals. In the most early type spirals (with very dominant bulge and very tight spiral arms), these features showed up equally well in the infrared. On the other extreme end, the very late type spirals (with almost no bulge and not well-defined arms) also showed no large change,

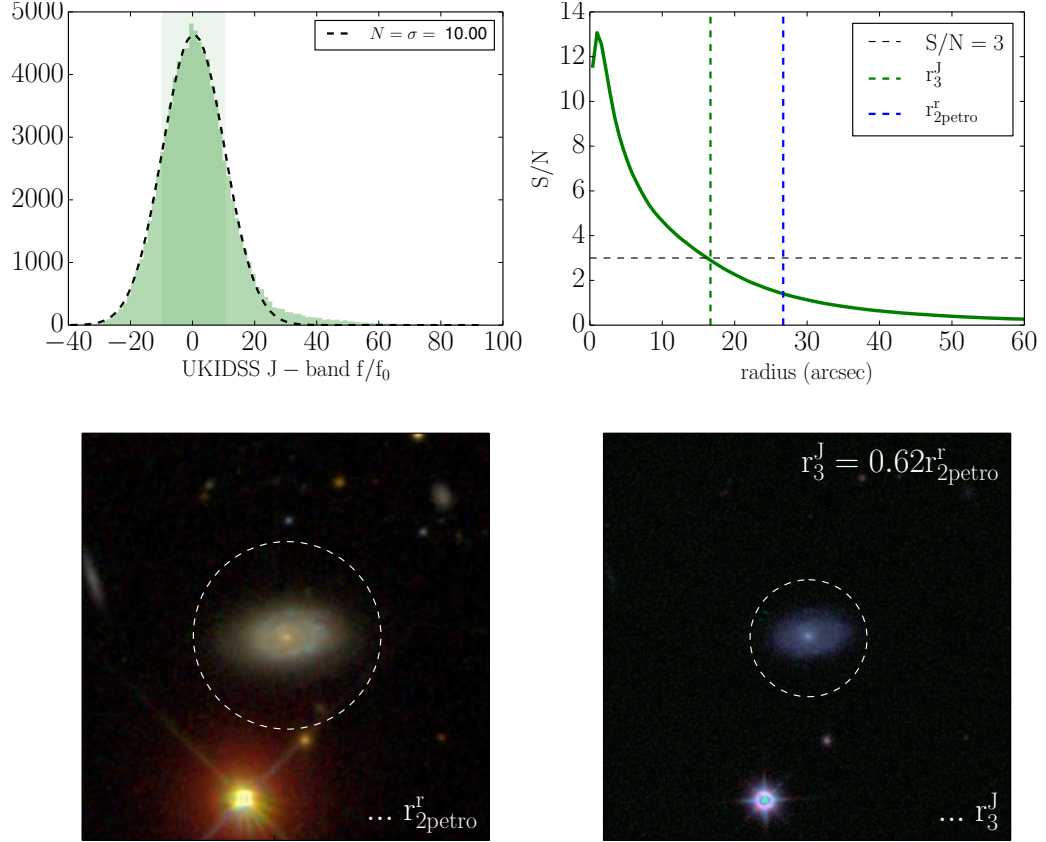


Figure 5.2 Example of the r_3^J/r_{2petro}^r calculation of one galaxy (dr7objid=587722981747392587). **Top Left:** The sky-subtracted background of the J-band images are fit to a Gaussian to derive the noise N , which is given as the standard deviation of the fit. **Top right:** The signal to noise profiles of the J-band images. The radius at which the signal-to-noise falls below three is indicated by the green dashed line, and the threshold $S/N = 3$ is indicated by the horizontal black dashed line. The blue line shows twice the r-band petrosian radius r_{2petro}^r for comparison. **Bottom:** Color-composite of the optical gri image (left) and IR YJK image (right). The dashed circles represent the radius r_{2petro}^r (left) and r_3^J (right), derived as shown in the top row. The ratio of the two radii is given, showing that for this galaxy, the light in the IR image extends to 62% of the optical image.

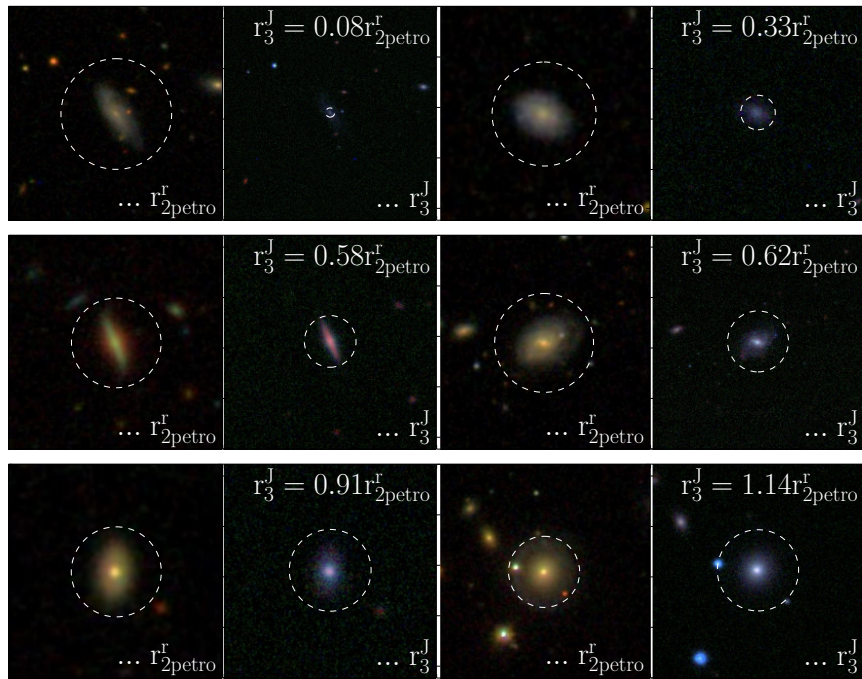


Figure 5.3 Example optical gri (left) and IR YJK (right) images of galaxies, sorted by r_3^J / r_{2petro}^r . The circle on the optical image (left) shows r_{2petro}^r , and circle on the IR image (right) shows the J-band radius within which $(S/N)_J > 3$, r_3^J .

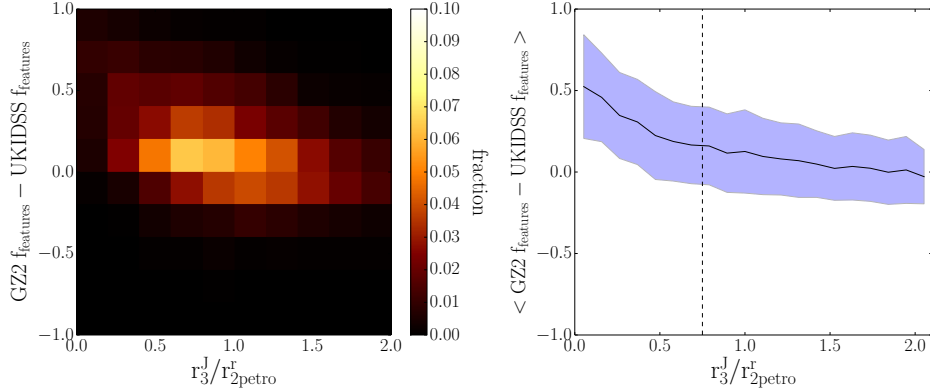


Figure 5.4 The change in GZ2 and UKIDSS vote fractions is strongest at low values of $r_3^J/r_{2\text{petro}}^r$, where the light detectable in the J-band extends to a significantly smaller area than the r-band images. **Left:** Distribution of the change in f_{features} from GZ2 to UKIDSS as a function of $r_3^J/r_{2\text{petro}}^r$. **Right:** The average change in f_{features} from GZ2 to UKIDSS as a function of $r_3^J/r_{2\text{petro}}^r$. The shaded region indicates the 1- σ dispersion around the mean. The dashed line at $r_3^J/r_{2\text{petro}}^r = 0.75$ indicates the threshold below which galaxies are excluded from the comparison sample, due to the coverage of light in the J-band not reaching a significant area as represented in the r-band.

since the relative size of the bulge and relative tightness of the arms were the main driver of the morphological differences between wavelengths. For the intermediate T-types, there was much more “wiggle room” for the bulges and arms to show more significant differences.

The first portion of this comparison will consider galaxies whose spiral arms are detected in both optical and infrared wavelengths. As a proxy for Hubble types, the responses to the GZ Tasks related to tightness of the spiral arms and dominance of the bulge will be used, since these probe similar features to those that influence T-type classification. The Task related to arm tightness asks, “How tightly would do the spiral arms appear?”, to which a user can choose one of three responses: “tight”, “medium”, or “loose”. For this analysis the fraction of users who answered “tight”, $f_{\text{tight arms}}$, will be used to assess the relative appearance of the arms from optical to IR. The task related to bulge prominence asks, “How prominent is the central bulge, compared to the rest of the galaxy?” to which a user can respond “dominant,” “obvious,” “just noticeable,” or “no bulge.” For this analysis the sum of vote fractions for the first two responses

$f_{\text{obv+dom}}$ will be used to measure the apparent size of the bulge relative to the galaxy.

Figure 5.5 shows the difference in vote fractions for arm tightness and bulge dominance between the GZ2 optical and UKIDSS infrared classifications, as a function of optical classification. The left plot shows that on average, spiral arms have a tighter appearance in optical wavelengths: $68.7\% \pm 4.0\%$ of spiral galaxies have lower $f_{\text{tight arms}}$ vote fractions in the IR images. For galaxies with optically very loose arms ($f_{\text{tight arms}} \sim 0$) or very tight arms ($f_{\text{tight arms}} \sim 1$), the infrared classifications tend to agree. For intermediately tight optical spiral arms ($0.2 < f_{\text{tight arms}} < 0.8$), the UKIDSS vote fraction tends to be lower than the optical by ~ 0.3 on average. This is contrary to the work by Eskridge et al. (2002) and Buta et al. (2010) who find slightly earlier IR classifications in intermediate-type spirals; by the Hubble Sequence classification scheme, tighter arms correspond to earlier types, and looser arms correspond to later types. However, both studies do emphasize that the primary driving factor of their T-type classifications are from the prominence of the central bulge. In Figure 5.5, the right panel shows the change in bulge prominence of this study as a function of optical bulge prominence. Here the effect is much stronger than the difference in arm tightness: the fraction $f_{\text{obv+dom}}$ is larger for the IR images in $95.8\% \pm 1.8\%$ of the galaxies, indicating the bulge is almost always more prominent in IR images than optical images. This result is in agreement with studies (eg. Eskridge et al. (2002)) who conclude that the main drivers of the change in T-type in spirals are “the relative prevalence of the bulge and the difference in contrast and appearance of spiral arms”. Here we see the same effect, and can add to the discussion that the appearance of the bulge is a stronger driver of the observed change in T-type than the spiral arm contrast. These results differ slightly from Eskridge et al. (2002) in the case of galaxies with significantly small or no bulges; in their sample, if a bulge is not detectable in one band, it generally will not be detected in the other: “Galaxies with no bulge... will not look substantially different in the near-IR than in the optical, and will thus be classified essentially the same on average.” However our sample finds a small population of galaxies where this is not the case, as seen in the left-most columns of the right plot in Figure 5.5. Here little to no bulge is seen in the optical images (signified by a vote fraction $f_{\text{obv+dom}} \leq 0.2$), while the IR images of the same galaxies have vote fractions up to $f_{\text{obv+dom}} \sim 1$.

So far the appearance of spiral arms visible in both the optical and infrared have been

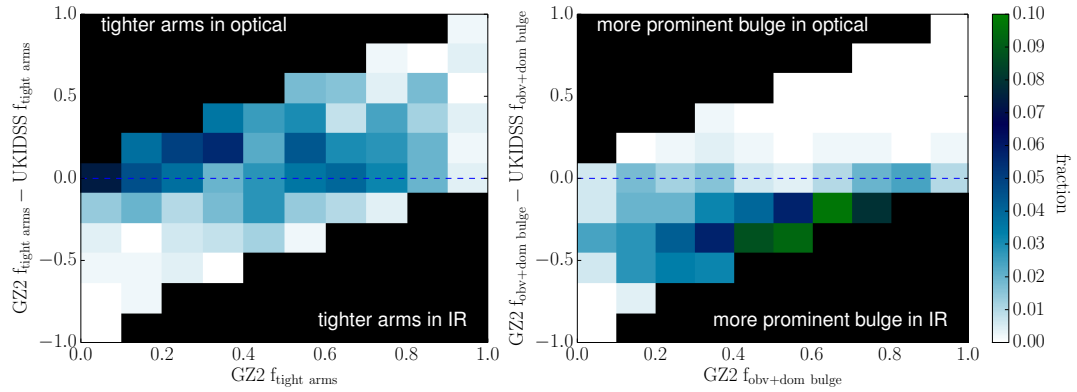


Figure 5.5 IR images of galaxies tend to have a looser appearance of arms and more prominent bulges than in optical images. Shown is the difference between optical and IR $f_{\text{tight arms}}$ as a function of optical/GZ2 $f_{\text{tight arms}}$ (**left**), and difference between optical and IR $f_{\text{obv+dom}}$ as a function of optical/GZ2 $f_{\text{obv+dom}}$ (**right**) for 502 galaxies which were classified as spiral in both IR and optical images. The colors represent the fraction of galaxies that populate any given bin, and bins which could not represent a possible difference in vote fraction ($\Delta f > f$ or $\Delta f < f - 1$) are colored black. The blue dotted line in both represents a difference in vote fraction of 0, such that galaxies below the line have larger IR vote fractions for the feature represented in each plot, respectively.

compared; on average, GZ infrared morphologies are slightly earlier than the optical, a result of much more prominent bulges. But what of the the optically spiral galaxies whose arms disappear in the IR? Of the 959 optical spirals in the volume and S/N limited sample, 279 (29%) of these were not classified as spirals in the IR. These types will be hereafter referred to as SONIs (Spiral in Optical but Not Infrared) for convenience. The most common morphological classes of galaxies which do not exhibit spiral arms are ellipticals, S0s, and edge-on disks (which may or may not truly have spiral arms, but cannot be discerned due to orientation angle). This section will explore which of these classes SONIs tend to occupy in the IR.

Figure 5.6 shows the different pathways galaxies in the UKIDSS sample follow through the decision tree. The left flow diagram shows the breakdown of morphologies of all galaxies in the volume-limited sample, while the right diagram includes only the SONIs. Galaxies which follow the spiral pathway must first be classified as featured (T00), then not edge-on (T01). At this point the not edge-on featured galaxies can follow the 'spiral' or 'not spiral' path (T03). Those marked as spirals are classified by how tight the arms appear (T09) and how many arms are present (T10). Last, both the spirals and not-spirals are classified by bulge prominence (T04). As a result of this type of decision tree, there are several pathways galaxies may take to ultimately obtain a "not spiral" classification; example images of galaxies following each of these are shown in Figures 5.7-5.10. They may be classified from the beginning as not featured (as ellipticals (Figure 5.7) or star/artifacts (5.10), or they may be featured but edge-on (Figure 6.3), or they may be featured and not edge-on (Figure 5.8), and still show no spiral arms.

The diagram on the right shows which of these paths SONIs tend to take, resulting in their ultimate classification of "not spiral" in the IR. 72% of SONIs follow the elliptical path; that is, the optically-visible spiral arms must become so faint that all that can be seen is the central bulge, which by eye becomes discernible from a full spheroidal galaxy. 19% are classified as both featured and not edge-on. One might hypothesize a majority of these exhibit stellar bars, which drives the "featured" classifications when there are no spiral arms to do so. However, there is no excess of strong bars detected; only 24% of the not edge-on featured SONIs are strongly barred, which is actually lower than that of the full sample (33%). Since the diagram flows are determined by a plurality of votes

for each Task, however, the possibility of weak bars driving the “featured” classification is not accounted for here. Therefore most of the galaxies on this path are likely either weakly barred, and/or retain evidence of both an underlying disk and a bulge, with enough contrast to keep them from being classified as purely elliptical. However it is clear that the bulge is very close to dominating the total light distribution in many of these galaxies; for SONIs, 89% are classified as having an either obvious or dominant bulge, as compared to 82% showing obvious or dominant bulges in the full sample.

5.4 Bar detection

A clean separation of barred and unbarred galaxy populations is required to properly analyze the various effect bars may have on their host galaxies. If a significant portion of bars are better detected in one waveband than another, both classifications should be incorporated to improve the separation of barred and unbarred samples. This section will investigate whether this should be a necessary process for bar population studies by computing the relative numbers of bars detected in optical and infrared imaging. To avoid possible confusion in this portion of the text, two similar quantities are defined explicitly here: the *bar fraction* is defined as the ratio of barred galaxies to total galaxies in a sample, and f_{bar} is the *bar vote fraction*, which is the fraction of users who detected a bar in an image of an *individual galaxy*.

Barred galaxies in the GZ2 and UKIDSS samples are identified using the same prescription described in Chapter 4 (Galloway et al., 2015). Cuts are placed on $f_{\text{features}} \geq 0.35$ and $f_{\text{notedge-on}} \geq 0.6$ to limit the sample to featured, not edge-on galaxies. An additional cut is placed on the number of people to answer the bar question $N_{\text{bar}} \geq 10$ to ensure adequate statistics in calculating the bar vote fraction f_{bar} . Of the galaxies meeting these criteria, bars are then defined as present in galaxies with $f_{\text{bar}} \geq 0.3$.

Figure 5.11 shows the number of barred galaxies in GZ2 and UKIDSS. Of the 1,102 total bars detected, 672 (61%) were detected in UKIDSS, and 899 (82%) were detected in GZ2, with 421 detected in both bands. The optical data recovers a larger portion of the total bars than the IR data, yet still fails to detect 20% of them. Due to the structure of the Galaxy Zoo decision tree, there are two ways in which a galaxy would fail to achieve a bar classification: first, its bar vote fraction f_{bar} can fail to meet the

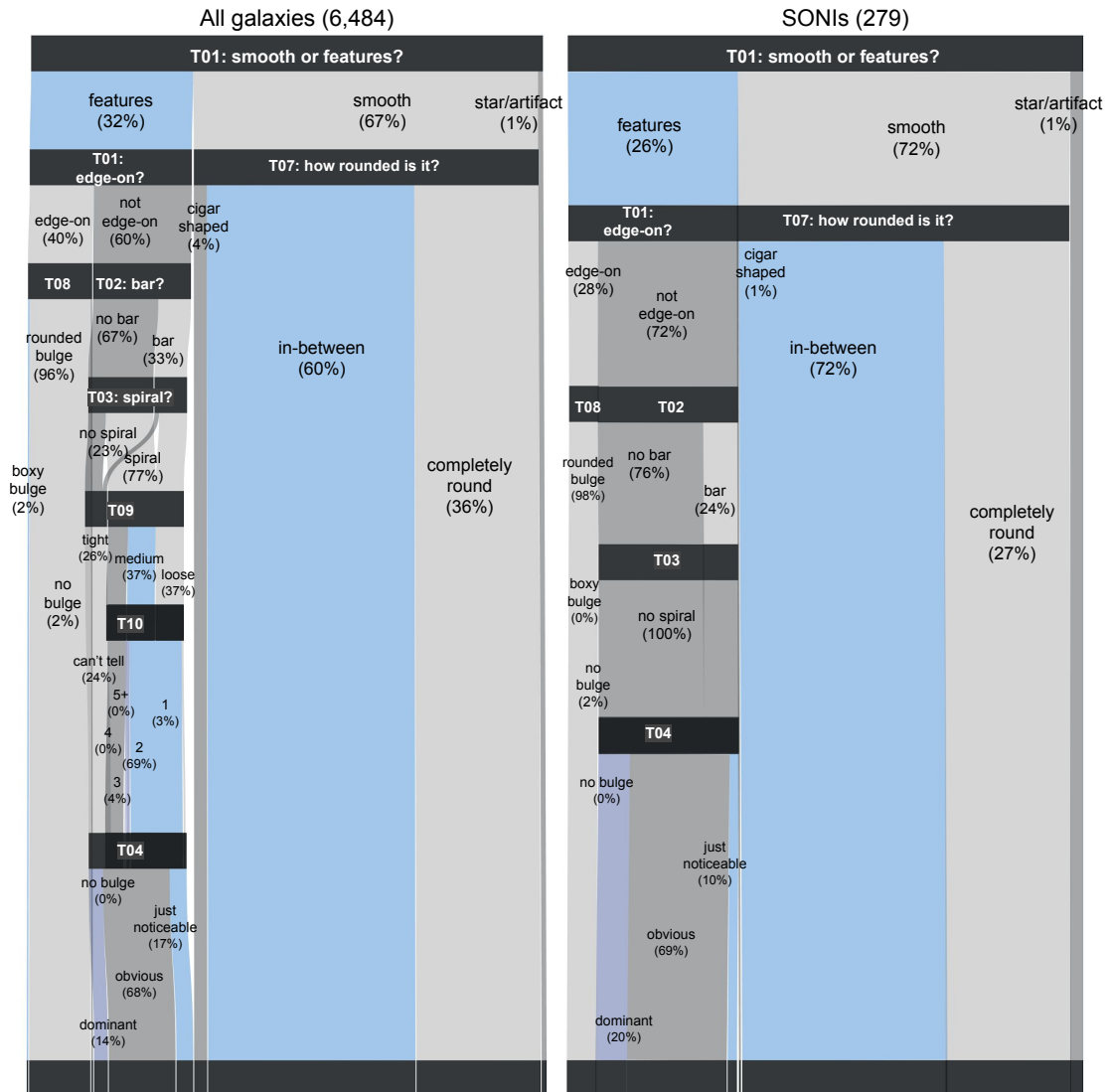


Figure 5.6 Flow diagram showing the breakdown of morphologies in the UKIDSS sample. **Left:** 6,484 galaxies in the volume-limited sample. **Right:** 279 SONIs: galaxies which were classified as spiral in the optical GZ2 classifications but do not follow the spiral path in the UKIDSS classifications.



Figure 5.7 Example images of galaxies which were classified as spiral in optical GZ2 classifications but followed the “smooth” path in the UKIDSS classifications.



Figure 5.8 Example images of galaxies which were classified as spiral in optical GZ2 classifications but followed the “featured, not edge-on, no spiral” path in the UKIDSS classifications.



Figure 5.9 Example images of galaxies which were classified as spiral in optical GZ2 classifications but followed the “featured, edge-on” path in the UKIDSS classifications.

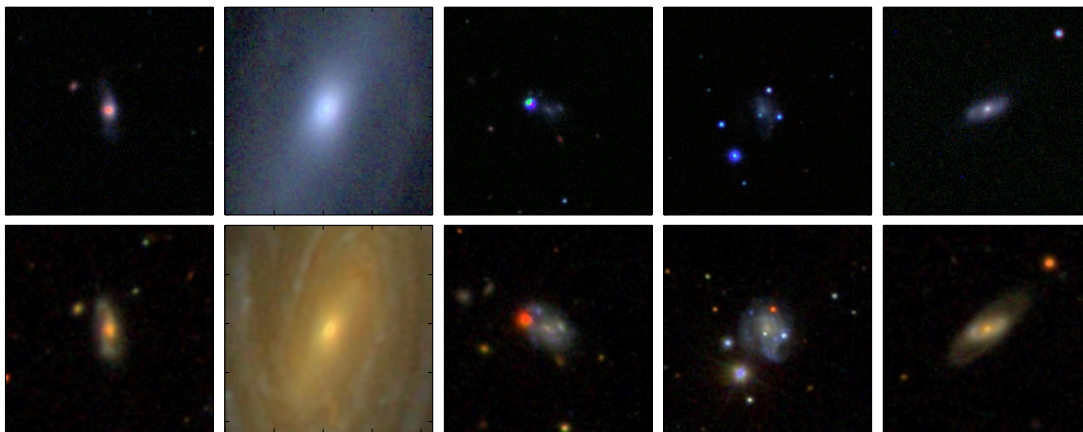


Figure 5.10 Example images of galaxies which were classified as spiral in optical GZ2 classifications but were classified as star/artifact in the UKIDSS classifications.

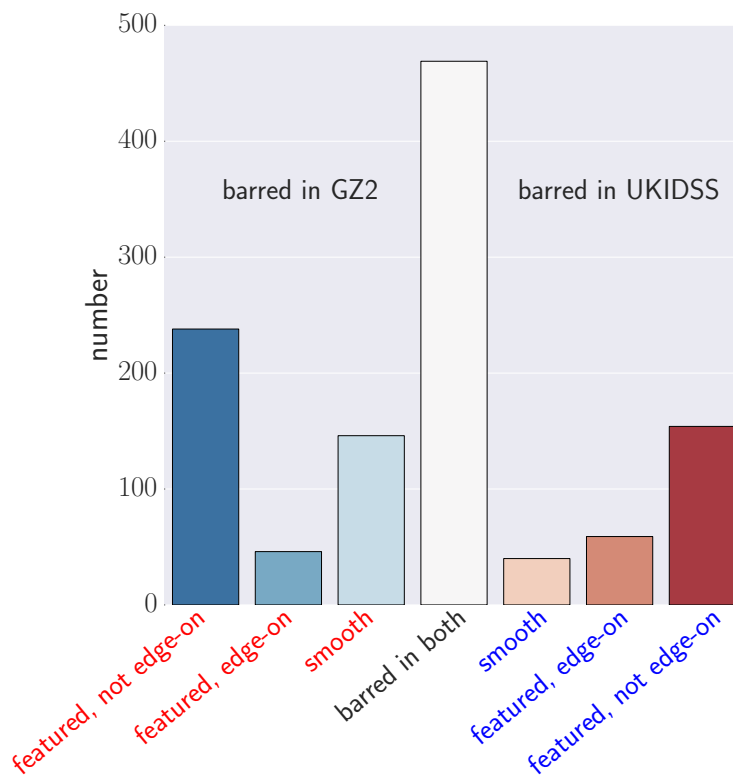


Figure 5.11 The middle bar displays the 421 galaxies which are classified as barred in both GZ2 and UKIDSS. To the left shows the number of galaxies classified as barred in GZ2 but *not* UKIDSS (blue). From left to right, these are broken down by those that changed classifications because they followed the smooth path, featured, edge-on path, and featured, not edge-on path (but with insufficient votes at the bar question to allow a barred classification), respectively. To the right shows the number of galaxies classified as barred in UKIDSS but *not* GZ2 (red). These are broken down in the same way as described for the GZ2-classified bars. The total number of bars detected combining both bands is 1,102.

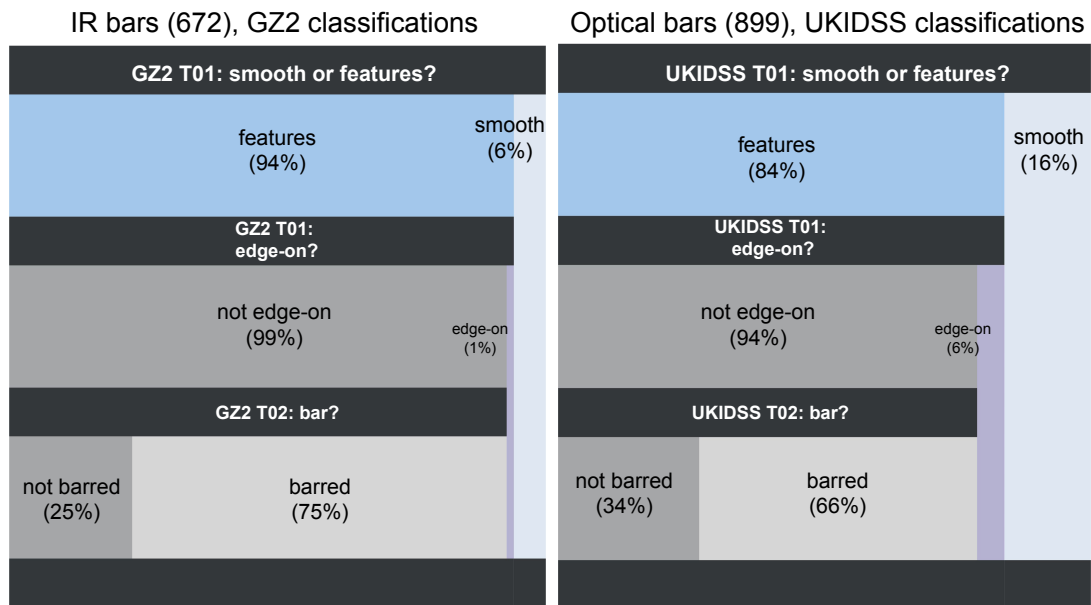


Figure 5.12 **Left:** Flow diagram of UKIDSS-barred galaxies through the first three GZ2 tasks. **Right:** Flow diagram of GZ2-barred galaxies through the first three UKIDSS tasks. Most UKIDSS-barred galaxies are classified as featured, not edge-on galaxies in GZ2. Those which change classifications to unbarred in the optical do so at the bar question; 22% of these have vote fractions lower than the threshold $f_{bar} \geq 0.3$ required for bar classification. Similar is true for GZ2-barred galaxies, although $\sim 20\%$ change classifications to unbarred in the IR because they initially follow the “smooth” path or “featured, edge-on”, without making it to the bar question in the first place. Of those which reach the bar question, 25% do not achieve significant bar votes ($f_{bar} \geq 0.3$) to allow a bar classification.

threshold cut of $f_{\text{bar}} \geq 0.3$; these galaxies have reached the bar question and thus are seen as face-on disks, but no bar is visible. Second, the bar question may never be asked of the galaxy in the first place if it is classified as “smooth” via the first question, or, classified as “featured” but also “edge-on” in the second. For galaxies which are classified as barred in one waveband but not the other, it may be helpful to discern via which scenario they are changing classifications. In the first case, the images would look mostly similar in terms of the overall structure, but the bar would be too weak, or perhaps even be masked, to meet the f_{bar} threshold required. In the second case, the images must transform significantly to follow entirely different paths through the tree.

Figure 5.12 shows the path followed by the barred galaxies. On the left is the path of the 672 UKIDSS-barred galaxies through the GZ2 classifications, on the right is the path of the 899 GZ2-barred galaxies through the UKIDSS classifications. For the UKIDSS-barred galaxies, the majority (94%) of them maintain the same featured, not edge-on morphologies in both wavebands, but change classifications once they reach the bar question. For the GZ2-barred galaxies, a larger fraction of them change classifications earlier, with 16% of them being classified as smooth from the first question. It is also slightly more common for these galaxies to be re-classified as edge-on in the GZ2 track, but the majority (79%) are consistent in their featured, not edge-on morphologies, and 34% of these change classifications from GZ2-barred to UKIDSS-unbarred at the bar question. The numeric breakdown of these distributions is visualized in Figure 5.11, and example images for each category are shown in Figures 5.13 and 5.14.

Most galaxies which change bar classifications do so *at* the bar question, rather than tending to follow entirely different pathways through the GZ decision tree. Here the change will be analyzed in more detail: Figure 5.15 compares f_{bar} measured in UKIDSS and GZ2 for galaxies which were consistently classified as featured and not edge-on in both samples. White dashed lines mark the threshold value for bar identification, $f_{\text{bar}} \geq 0.3$. Galaxies to the right of the vertical dashed line were classified as barred in the optical images, and those above the horizontal dashed line were classified as barred in the IR images. Four regions can be defined in this way: The top right region of the plot represents galaxies classified as barred in both wavebands, the bottom left shows those which are unbarred in both, the top left shows those which are barred in the IR but not the optical, and the bottom right shows those which are barred in the optical

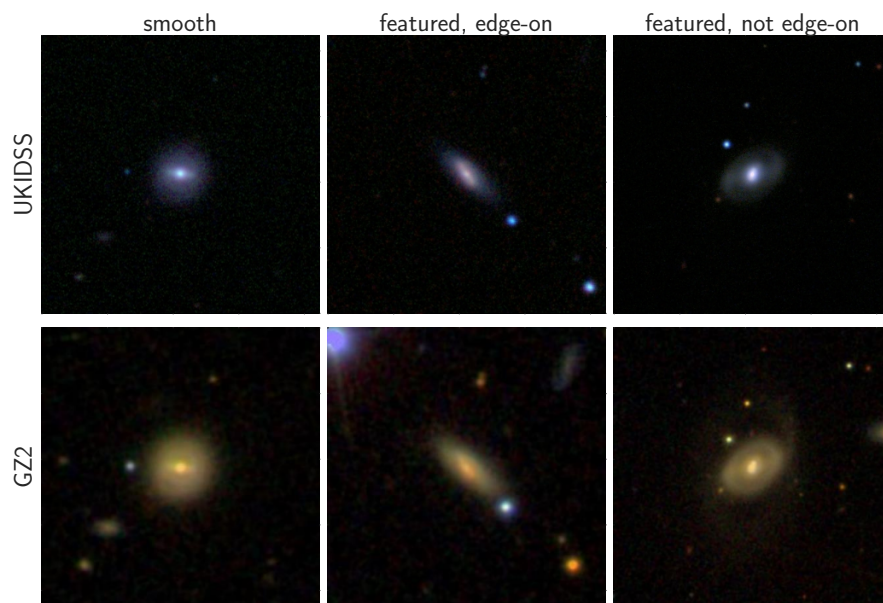


Figure 5.13 Galaxies classified as barred in UKIDSS (top row, IR images) and unbarred GZ2 (bottom row, optical images). The left column is an example of a galaxy which was not classified as barred in GZ2 because it followed the smooth GZ2 path, the middle followed the featured, edge-on path, and the right followed the featured, not edge-on path.

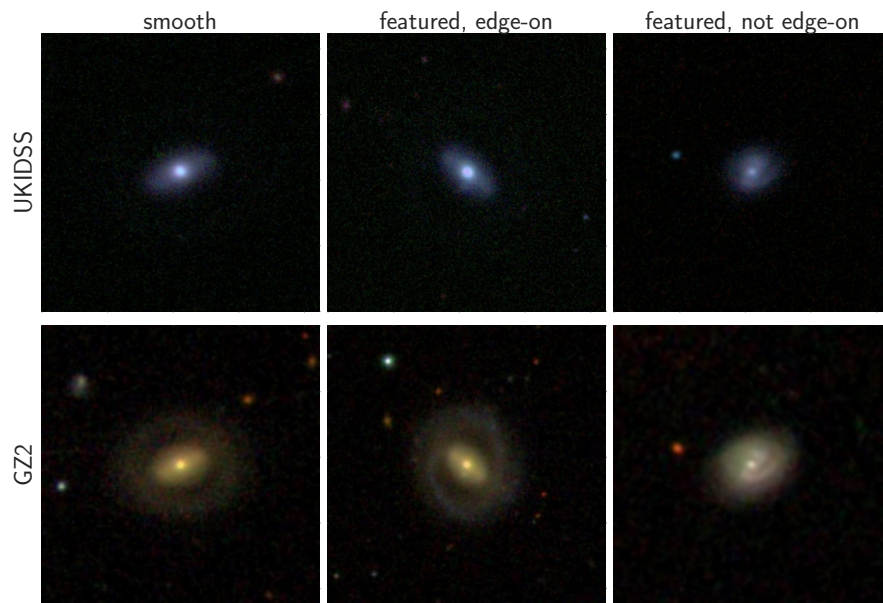


Figure 5.14 Galaxies classified as unbarred in UKIDSS (top row, IR images) and barred GZ2 (bottom row, optical images). The left column is an example of a galaxy which was not classified as barred in UKIDSS because it followed the smooth UKIDSS path, the middle followed the featured, edge-on path, and the right followed the featured, not edge-on path.

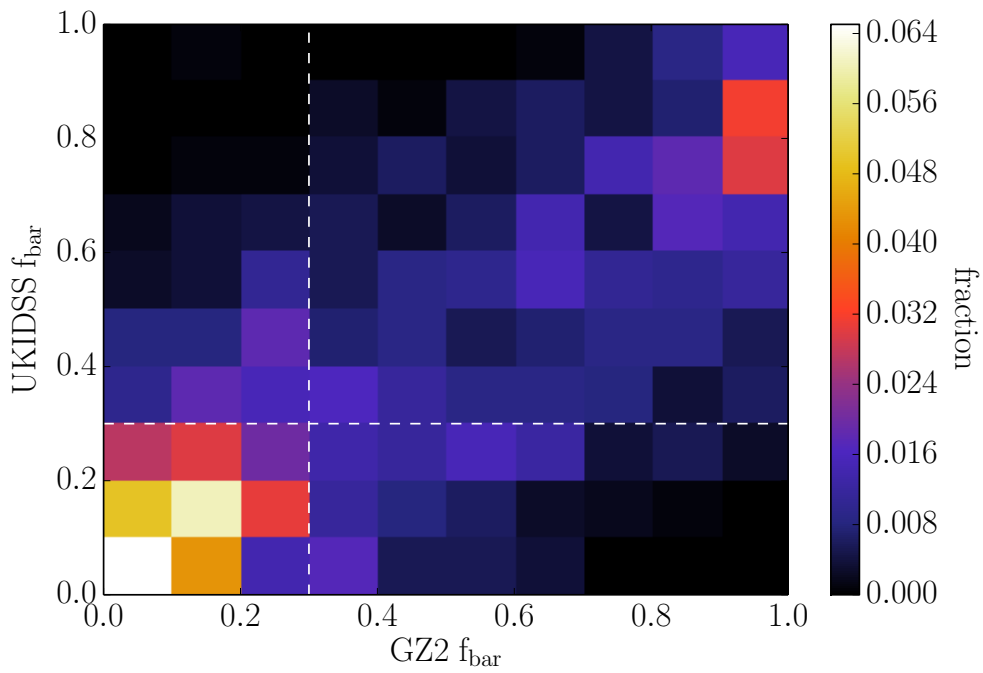


Figure 5.15 GZ2 vs UKIDSS bar strengths of 1,107 featured, not edge-on galaxies measured by f_{bar} . Galaxies shown must have 10 people answer the bar question, $f_{\text{features}} \geq 0.35$ and $f_{\text{not edge-on}} \geq 0.6$ in both samples. The dotted white lines indicate the threshold value for bar classification $f_{\text{bar}} \geq 0.3$; the top-right region therefore displays the fraction of galaxies classified as barred in UKIDSS and GZ2, the bottom left are those classified as unbarred in both, the top-left are UKIDSS-barred and GZ2-unbarred, and the bottom-right are GZ2-barred and UKIDSS-unbarred. Most galaxies have consistent classifications (76% are either barred in both or barred in neither), 11% are barred in UKIDSS but not GZ2 (top left) and 13% are barred in GZ2 but not UKIDSS (bottom right).

but not IR.

The bar vote fraction f_{bar} is well-correlated between both bands. The data follow a mostly 1:1 relationship with an average scatter of $\Delta f_{\text{bar}} = +/ - 0.1$, resulting in consistent classifications for the majority of galaxies, with 42% being barred in both and 23% being unbarred in both. 11% are barred in UKIDSS but not GZ2 (top left). These tend to not be very strongly barred in UKIDSS, with typical bar vote fractions of 0.3-0.6. Since many of these only barely pass the threshold cut, statistical error is likely a partial driver of the different classifications. 13% are barred in GZ2 but not UKIDSS; these have a wider spread of bar vote fractions in GZ2, up to $f_{\text{bar,GZ2}} \sim 0.9$. This change is much more drastic, indicating that the change in classifications in these cases is more driven by a significant difference in the appearance of the images.

5.5 Discussion

This chapter has compared UKIDSS and GZ2 classifications for 6,484 bright, nearby galaxies whose J-band light profiles extended to a significant portion of those in the r-band. UKIDSS galaxies tend to have lower f_{features} and larger $f_{\text{obv+dom bulge}}$ vote fractions, corresponding to slightly earlier-appearing morphologies (or lower T-type). Only 43% of the total bars in the sample were detected in both GZ2 and UKIDSS; the remaining were detected in GZ2 but not UKIDSS (39%) or UKIDSS but not GZ2 (18%).

5.5.1 Changes in spiral structure

Comparisons of optical and infrared morphologies were motivated by the hypothesis that the flocculant appearance of star-forming regions and effects of dust-obscuration may mask the structure of the underlying older stellar populations. This is a reasonable assumption; morphology is a tracer of the light distribution in a galaxy, which may or may not be completely correlated with the baryonic mass distribution. Most of a galaxy's stellar mass is encompassed by older, cooler stars. In optical imaging, the flux may be dominated by light from a smaller contribution of young, hot stars, which could skew the morphology if it differed significantly from the older population;

perhaps even justifying two separate morphological classification systems for the different stellar types. Whether this difference tends to be significant has been difficult to confirm observationally, as even the largest samples for comparison have only consisted of a couple hundred galaxies (Eskridge et al., 2002; Buta et al., 2010). The comparison study reported in this thesis has strong advantages over those previously done, with a sample size over an order of magnitude larger, as well as an advantage in statistical significance for each morphology due to the crowd-consensus nature of the citizen science classifications, whereby each galaxy is seen by many volunteers. Complications are introduced, however, given the structure of the decision tree used in this type of classification (discussed in Section 5.5.3).

Galaxies with identifiable spiral structure in both samples appeared slightly earlier in Hubble type in infrared images than the optical images, which is in agreement with the findings of Eskridge et al. (2002) and Buta et al. (2010). The lack of contrast provided by star-forming regions in the optical gave the infrared image a more smoothed-out appearance, which caused spiral arms present to appear looser, resulting in lower $f_{\text{tight arms}}$ fractions. Additionally, the central bulge of the disk galaxies was much more dominant in the infrared images, as expected due to the older stellar compositions.

In the case of SONIs, these features could not be compared because spiral arms were not identified at all in the infrared images. This problem was mainly driven by the structure of the decision tree - 79% of these optically-classified spirals did not even reach the question that asks to identify spiral arms (Task 03); 72% of which followed the “smooth” path from the beginning. Visual inspection of these cases showed a common contributor to this class: in these spirals, the bulge was often so dominant that the arms appeared extremely faint by comparison. While often still technically visible, they might not have been obvious to the eye unless pointed out (see the center panel of Figure 5.7 for an example). In others, however, it seemed that the contrast provided by star-formation, as in the optical images, is necessary to identify the presence of arms within the disk. Therefore it may seem that, contrary to previously hypothesised, star formation regions aid in rather than hinder visual inspection for morphological classification.

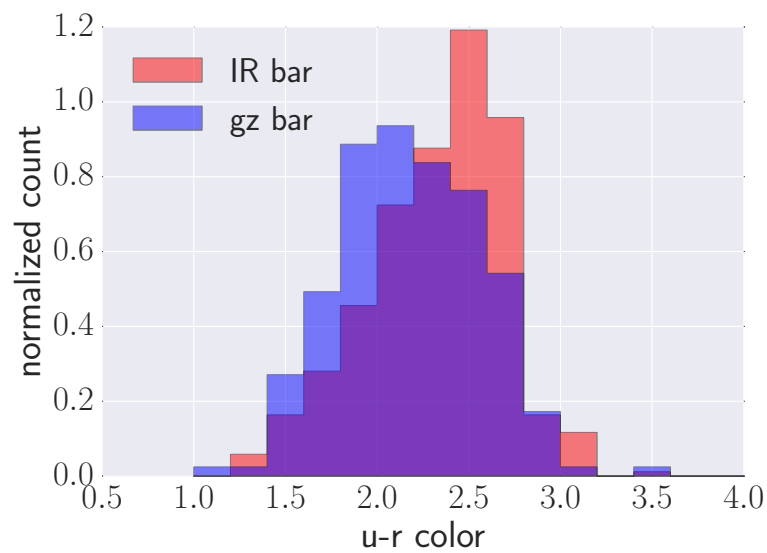


Figure 5.16 u-r colors of 203 galaxies with bars detected in UKIDSS but not GZ2 (red) and 430 galaxies with bars detected in GZ2 but not UKIDSS (blue). The bars detected in the infrared but not optical images have redder colors than those detected in optical, suggesting dust obscuration may play a role in increasing the difficulty in visually identifying bars in optical images. A two-sided KS test yielded a p-value $p < 0.01$ for the color distributions of the two categories, rejecting the null hypothesis that the samples were drawn from the same distribution.

5.5.2 Changes in bar classification

Galaxies classified as featured and not edge-on were consistent in bar vote fractions f_{bar} , with 75% agreement in bar classification. Strong bars detected in one survey were just as easily detected in the other, in agreement with Whyte et al. (2002); Sheth et al. (2008); MenendezDelmestre et al. (2007b). This study however finds many more examples of bars which are only detected in one: of the featured, not edge-on galaxies, these examples tend to be weaker bars that are only just noticeable in the images, and only just meet the threshold $f_{\text{bar}} \geq 0.3$ in the survey in which they are detected, and only just below in that which they are not detected. Therefore these changes of classification tend to only occur in weak bars, and likely are driven partially by minimal contrast in the images and partially by simple statistical error. A small fraction of galaxies (7%) did change morphology from unbarred in UKIDSS to barred in GZ2 via a significant change in vote fraction $\Delta f_{\text{bar}} > 0.3$; in these cases the bars did appear strongly in the infrared images, but their relative appearance with respect to the spiral arms was such that the bar appeared as the dominant structure in the galaxy, rather than just a component (see example in Figure 5.13, right panel). These cases were uncommon, but yet another example of the lack of contrast provided by SF regions creating difficulty in identifying substructures.

43% of the total galaxies which changed bar classifications did so because they did not reach the bar question in one survey or the other. 66% of these were barred in GZ2 and followed alternate paths in UKIDSS, while 34% were barred in UKIDSS and followed alternate paths in GZ2. Both, albeit in different ways, support the hypothesis that bars are more visible in the infrared. The latter case describes galaxies whose bars appear very strong in contrast to the disk, while in the optical the edge is less sharp, possibly due to dust obscuration, suggested by the fact that the galaxies in this category are redder on average (see Figure 5.16). Examples of these are shown in the left and middle panels of Figure 5.13. The former category, in which GZ2-barred galaxies follow the smooth or edge-on path in UKIDSS, is an example of this effect at an extreme level. Here, the bar is still strong and visible in the IR images, but overwhelmingly so, to the point that the rest of the disk and arms are no longer also visible. This produces images of isolated bars, which look like elongated smooth galaxies or edge-on disks; the difference relying on how well-defined the central bulge appears. See the left and middle

panels of Figure 5.14 for examples of this effect.

5.5.3 Task 01: smooth or features

One of the primary complications of this study has been the inability to directly compare vote fractions f_{bar} and f_{spiral} because of the many galaxies which follow alternate paths through the decision tree in each project, beginning with Task 01. This question, which asks, “Is the galaxy smooth and rounded, with no sign of a disk?” was originally placed at the top of the tree to separate spheroidals from galaxies with features. This way, volunteer effort would not be wasted going through the numerous Tasks pertaining to features that are not found in ellipticals. For optical images, this question has performed adequately in separating featured from ellipticals (Willett et al., 2013). For infrared images, however, everything looks “smoother” to an extent, even when features are present. This chapter has presented several examples of UKIDSS galaxies which are clearly not elliptical, but do have a rather smooth appearance. Perhaps this particular wording of the question in Task 01 is inappropriate for infrared image sets, since “smooth” encompasses a broader definition than spheroidal for these in particular. An alternative approach for classifying future infrared datasets would be to first separate the sample in advance by those which were optically classified as smooth and featured, and require that all featured questions be asked for galaxies in the optically-featured sample, even if “smooth” was chosen for Task 01. This would help ensure that higher-tier Task vote fractions could always be properly compared between the two, without completely abandoning the decision-tree format.

The strong correlation between vote fractions of the optical GZ2 and infrared UKIDSS morphologies indicate that older stellar populations trace mostly the same light distributions as their younger counterparts; this negates the notion (Block & Puerari, 1999) that separate classification schemes are necessary when considering galaxy morphology. As to whether IR images aid in revealing the “stellar backbone” structure, this analysis suggests this is true, albeit with some caveats. While SF regions can dominate the flux in optical images and affect the overall appearance, a similar effect seems to take place in the IR. UKIDSS images were often so dominated by the flux from older populations in the bars and the bulge that the rest of the disk became hidden as a result; in these cases, the utilization of IR to find bars can be countereffective. Deeper imaging is thus

crucial for future comparisons. However, there were sufficient examples in which the infrared images detected a bar where the optical images did not, but mostly for weak bars. Based on these results, it is strongly recommended that both wavebands are utilized in studies for which detecting bars of all strength is required.

5.6 Conclusions

The main findings of this analysis are as follows:

- For galaxies whose spiral arms are detected in both optical and IR images, the IR classifications are slightly earlier than the optical, driven mostly by a stronger appearance of the bulge.
- A significant fraction (29%) of galaxies were classified as having spiral arms in the optical images but not the infrared images. The majority of these (72%) instead appeared smooth in the IR, 7% appeared featured but edge-on, and 19% appeared featured and face-on.
- For galaxies which can be identified as featured and not edge-on, a majority 76% of galaxies have consistent barred or unbarred classification in optical and infrared classifications. Galaxies which were barred in UKIDSS but not GZ2 tended to be weakly so, such that statistical error is likely the driving factor between the mismatched classifications. It is more common for bars to be detected in GZ2 but not UKIDSS due to genuine differences in the images, where separation between features were more distinct in the optical and smoothed-over in the IR.
- 57% of the total bars in the sample were found in one project but not the other; therefore it is suggested that studies analyzing the effect of bars use both wavebands for detection when possible.

Chapter 6

Galaxy Zoo Hubble: the evolution of red disc galaxies since $z = 1$

This chapter is in preparation for submission in the Monthly Notices of the Royal Astronomical Society.

Passive, red disks are an unconventional class of galaxies. They do not adhere to the standard bimodality of the color-morphology relationship, whereby most galaxies tend to exist in one of two populations: blue, late-type disks exhibiting active star formation, and red, early-type ellipticals showing little to no signs of recent star formation (Strateva et al., 2001; Baldry et al., 2004; Correa et al., 2017). The division between the two populations is particularly apparent when represented visually on a color-magnitude or color color diagram. Galaxies tend to populate in two distinct regions: the “red sequence” in the upper band, which contains predominantly early-type galaxies, and the “blue cloud” in the lower, containing mostly late-type spirals. This relationship has been shown to hold for $\sim > 85\%$ of galaxies out to $z \sim 1$ (Bell et al., 2004; Cirasuolo et al., 2007; Mignoli et al., 2009) and possibly beyond (Giallongo et al., 2005; van Dokkum et al., 2006; Franzetti et al., 2007; Cassata et al., 2008).

The relatively tight correlation between galaxy color (which traces the stellar content) and morphology (which traces dynamical history) suggests an evolutionary link between the two. In the simplest interpretation, it could be deduced that galaxies tend to begin their lives as young, star-forming disks, until some mechanism (secular or external) causes star formation to cease while the galaxy simultaneously undergoes a morphological transformation from disk to spheroidal. The growing evidence for a significant population of galaxies which breaks this relationship, however, insists on more nuanced interpretations of this model.

Since their initial discovery, the passive disk population has been a matter of interest for understanding the mechanisms driving the evolutionary link between color and morphology. In one of the earliest documented reports of this class, van den Bergh (1976) identified a set of spirals in the Virgo cluster which were forming stars “much less vigorously” than the other galaxies of the same type, which were dubbed “anemic spirals”. Analysis of this population suggested the possibility of “gentle” quenching mechanisms which could shut off star formation without disrupting the morphology (in contrast to violent processes such as mergers, which are capable of destroying the disk (Bell et al., 2004; Negroponte & White, 1983; De Lucia et al., 2006; Springel et al., 2005)). The low gas content in the anemic spirals suggested that subtle environmental factors played a role in stripping the gas required to continue star formation, a process commonly known now as ram-pressure stripping (Gunn & Gott, 1972; Steinhauser et al., 2016).

Other studies have since investigated other possible mechanisms could lead to the formation of passive disks, and how significant of a contribution this population makes to understanding the full picture of galaxy evolution. Environment is believed to play a strong role in thier formation; many studies for instance find passive spirals preferentially in high-density environments (Dressler et al., 1999; Poggianti et al., 1999; Goto et al., 2003; Deng et al., 2009; Hughes & Cortese, 2009). Moran et al. (2006) model the star formation histories of passive spirals at $z \sim 0.4$ and find them to be consistent with models for spirals affected by gas-starvation (Larson et al., 1980; Quilis et al., 2000; Bekki et al., 2002). Environment plays a significant factor in this scenario, whereby the interaction of the galaxy with the intra-cluster medium halts the accretion of gas onto the galaxy, inhibiting star formation and causing a quench without disrupting the morphology significantly. Their results did not argue that starvation was the only

mechanism responsible for building up the population of disks in the red sequence, but do conclude that passive disks are indeed an important transition population.

Masters et al. (2010) is one of the few studies which finds no strong correlation of passive disks with environment, but do not rule out environment playing a significant contribution in their creation. They also find strong evidence for quenching via completely secular processes; given by their sample of passive disks being more massive and having a higher bar fraction than their star-forming counterparts. Massive galaxies are more likely to have been assembling for very long times, allowing sufficient time to use up all of their gas, without environment being a direct factor. This option could explain the observed correlations with density and passivity, given that higher-density regions were more likely to have been assembled at earlier times. Secondly, Masters et al. (2010) observed a significantly higher bar fraction in passive spirals (67%) than star-forming spirals (27%). Bars are known for their ability to efficiently drive gas to the centers of galaxies via a redistribution of angular momentum throughout the disk (Sellwood & Wilkinson, 1993; Shlosman et al., 1989; Ann & Thakur, 2005), which could increase central star formation (Hawarden et al., 1986; Ho et al., 1997) or feed the central supermassive black hole (Athanasoula, 1992; Friedli & Benz, 1993). The excess of bars in passive disks then suggests that bars were responsible for quickly using up the gas in the galaxy, resulting in subsequent quenching.

Passive disks have thus far been proposed as both a final stage of galactic evolution, driven by secular and external processes capable of exhausting gas required for star formation, and as a transition phase of galaxies toward a final evolution to red spheroidal, driven by processes which quench and morphologically transform on different timescales, or multiple separate processes acting independently. Understanding the significance of the passive disk population is therefore unquestionably an important key to understanding galaxy evolution as a whole. Bundy et al. (2010) investigates this subject by measuring the different morphological contributions to the red sequence since $z = 1$, and estimate as high as 60% of all galaxies go through a passive disk phase. It was not quantified which of these further evolve to spheroidal and which stay disks for the remainder of their lifetimes, but the decaying contribution of passive disks to $z = 0.3$ was evidence that some fraction of these did indeed transform to elliptical.

This paper will investigate the evolution of the passive disk population from $z = 1$ to $z = 0.3$ using galaxies identified in the COSMOS field with morphological classifications from Galaxy Zoo: Hubble (Willett et al., 2017). We will measure the fraction of disks which are passive and the fraction of the red sequence occupied by disks as functions of mass and redshift, and argue that three factors drive the evolution of these fractions: 1) the rate of blue disks quenching to form passive disks, 2) the rate of blue disks quenching and simultaneously transforming to elliptical, 3) the rate of red disks transforming to red ellipticals, and 4) the net merger rate of ellipticals. We will implement a simple toy model to simulate the evolution of the relative abundances of red disks, blue disks, and red ellipticals, in order to quantify these rate parameters. We will use the results to estimate the fraction of galaxies that enter a red disk phase, and discuss the likelihoods of the red disk phase being a transitory stage or an end-point of a typical galaxy’s evolutionary path.

Section ?? will describe our methods for selecting disk galaxies and separating the sample into active / passive populations using a color-color diagnostic. In Section 6.2 we describe a new method of correcting for redshift bias in the detection of disk galaxies with Galaxy Zoo classifications using an artificially-redshifted set of images. In Section 6.3 we present our results of the fraction of disk galaxies which are red, and the fraction of red sequence galaxies that are disks, as functions of mass and redshift. Here we also explain our toy-model for measuring the dominant evolutionary pathways taken by galaxies in different bins of mass. We compare our findings with results from the literature and discuss their implications in Section 4.3. Our main conclusions are outlined in Section 6.5. We adopt a Λ CDM cosmology throughout this paper of $\Omega_m = 0.31$ and $H_0 = 68 \text{ km s}^{-1}\text{Mpc}^{-1}$ (Planck Collaboration et al., 2015).

6.0.1 Quenching Mechanisms

An isolated galaxy will eventually cease to form new stars as it naturally exhausts its limited supply of gas. The time-scale for complete consumption can be estimated from the amount of gas in a typical galaxy and the rate at which it is consumed through star formation: $\tau \sim M_{gas}/\dot{M}_{gas}$ (Larson et al., 1980), and is expected to range from 1-3 Gyr. Most galaxies do not exist in such isolation; the exchange of matter in the galaxy due to its surroundings can disrupt and often accelerate the depletion of a galaxy’s gas reservoir.

Quenching is defined as any process which drives the shutting-down of star formation in this way. This section will introduce different proposed quenching mechanisms, some of which are internal (driven by the galaxy’s structure or components), or external (driven by direct influence of the surrounding environment).

Ram Pressure Stripping

As a galaxy moves through the intracluster medium (ICM), it experiences ram pressure $P_{ram} = \rho_e v^2$, where ρ_e is the density of the ICM and v is the velocity of the galaxy (Gunn & Gott, 1972). The force per area required to hold gas onto the traveling galaxy is $F/A = 2\pi G\sigma_s\sigma_g$, where σ_s and σ_g are the star and gas surface densities, respectively. If a galaxy is moving fast enough, or the ICM density is large enough, the ram pressure can exceed this force and consequently rip the gas from the galaxy; this process is known as ram pressure stripping. Evidence of this effect is seen observationally in asymmetries of the disk in spirals (a common example is NGC 4402, which has a bowed appearance and a one-sided concentration of dust, believed to be the effects of the galaxy struggling to hold onto gas on the outer regions of the disk) and truncated radial density profiles. Simulations (Steinhauser et al., 2016) show that extreme cases of ram pressure stripping can completely strip a galaxy of its cold gas, causing a rapid quenching on timescales of a few hundred Myr. More mild cases, on the other hand, can actually temporarily increase star formation, which quickly uses up the available cold gas, and eventually quenches the galaxy on timescales similar to natural isolation, ~ 1 Gyr. Fillingham et al. (2016) find a mass dependence on the efficiency of this process: they find RPS to be very efficient and rapid for galaxies $M_* = 10^{8-9}M_\odot$ for a range of halo host properties, suggesting RPS may be the dominant quenching mechanism for low-mass galaxies.

Strangulation and Harassment

Even if the ram pressure exerted by the ICM is not strong enough to completely remove all of the gas from a galaxy, it may be just strong enough to strip the outer hot gas which would have otherwise cooled and replenished the cold gas reservoir. This process is appropriately defined as strangulation, where star formation ceases after the initial cold gas is used up (Larson et al., 1980). More frequent and violent encounters can

increase star formation in a similar process known as harassment (Moore et al., 1996). These can lead to a compression of the cold gas causing a temporary and intense burst of star formation, depleting it completely on a time scale of $\sim 1\text{-}2\text{Gyr}$ (Kawata & Mulchaey, 2007). Moore et al. (1999) show through simulations that harassment can be powerful enough to alter the morphology of low-mass, low-surface brightness galaxies.

AGN feedback

AGN are believed to play a strong role in the regulation of star formation in their host galaxies via AGN *feedback*, whereby accretion onto the central SMBH generates strong outflows of energetic material and hard radiation; these AGN-driven winds may then terminate star formation by heating the gas or expelling it completely from the galaxy. This effect was first proposed as an important quenching mechanism through the development of theoretical models aiming to reproduce the observed local-Universe luminosity function. The bright end, where there is a sharp break in the observed number density of highly luminous galaxies, tends to only be reproducible in models which incorporate AGN feedback to suppress star formation as galaxies build up their mass (Benson et al., 2003; Di Matteo et al., 2005; Bower et al., 2006; Croton et al., 2006; Somerville et al., 2008). One of the leading observational arguments for this effect is the high fraction of AGN in the green valley (Martin et al., 2007b; Schawinski et al., 2010), suggesting that AGN may be responsible in part for transitioning galaxies from the blue cloud to the red sequence. Smethurst et al. (2016) found strong evidence for rapid and recent quenching through an analysis of star formation histories of a large population of AGN hosts, indicating that AGN-feedback can play a strong role in the quenching process.

Mergers

Mergers are a well-known driver of quenching (Peng et al., 2010), and are perhaps the dominant mechanism in particular for central galaxies (Smethurst et al., 2017) whose dense environments give an increased probability of galaxy-galaxy interaction. Simulations demonstrate that these events cause a mechanical disruption of the merging disks (Pontzen et al., 2017) which triggers powerful, brief starbursts (Barnes & Hernquist, 1996; Hopkins et al., 2006), yielding star formation rates up to twice that observed

for their isolated counterparts (Mihos & Hernquist, 1994), resulting in a quench after the gas required for star formation is rapidly depleted. Major (1:1 mass ratio) events have been shown to strongly disrupt the morphology of the interacting galaxies. It is hypothesized modern-day ellipticals were primarily formed from the mergers of disk galaxies (Toomre, 1977; Schweizer, 1982; Schweizer et al., 1990), which has been supported both by simulations (Mihos & Hernquist, 1996; Pontzen et al., 2017) and observations (Schweizer, 1982; Wright et al., 1990; Stanford & Bushouse, 1991), whereby recently-quenched galaxies were shown to follow $r^{1/4}$ light profiles.

6.1 Data

The parent sample of galaxies in this paper is drawn from the Galaxy Zoo: Hubble (GZH) catalogue (Willett et al., 2017), which provides morphological classifications for galaxies sourced from the HST Legacy Surveys. From the main catalog we select galaxies with imaging from the Cosmic Evolution Survey (COSMOS, Scoville et al. (2007)) in the redshift range $0.2 < z < 1$. Stellar masses and rest frame NUV- r and r -J colours are taken from the UltraVISTA catalog (McCracken et al., 2012; Ilbert et al., 2013).

6.1.1 Sample Selection

We identify a mass-limited sample of 20,811 galaxies within $0.2 < z < 1.1$ and $10.1 < \log(M/M_{\odot}) < 11.3$, indicated by the dashed lines in Figure 6.1. We categorise the galaxies as disc-like or elliptical using the morphological classifications provided by GZH. In the Galaxy Zoo project, volunteers classify galaxy images by answering simple questions prompted via an online interface. We use the question, “Is the galaxy simply smooth and rounded, with no sign of features or a disk” to classify a galaxy as disc-like by applying a threshold on the fraction of users to answer “features or disk”, $f_{\text{features}} \geq 0.3$. For a thorough discussion of the full set of questions and corresponding morphological classifications available in GZH, see Willett et al. (2017). We also exclude mergers and irregulars from the analysis by applying cuts of $f_{\text{irregular}} > 0.3$ and $f_{\text{merger}} > 0.5$ for galaxies which have at least 20 “yes” votes for the question, “Is there anything odd?”.

To classify the galaxies as passive or star-forming, a method similar to that described by Ilbert et al. (2013) (hereafter I13) was used, implementing a rest-frame NUV- r versus

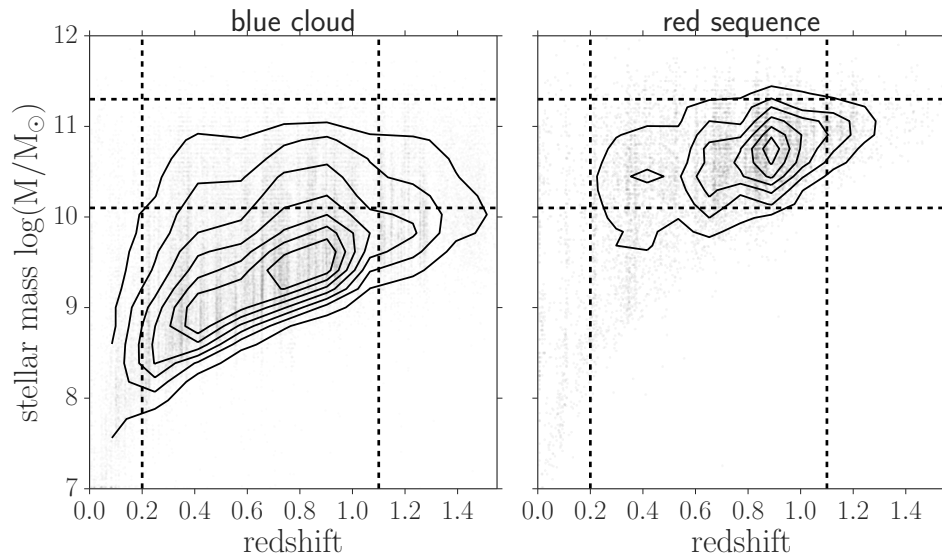


Figure 6.1 The box enclosed by the dotted lines displays our mass-limited sample, defined as $0.2 < z < 1.1$ and $10.1 < \log(M/M_{\odot}) < 11.3$. Blue cloud (left-panel) and red sequence (right-panel) galaxies are plotted separately to illustrate the difference in limiting magnitudes for galaxies whose fluxes are dominated by I-band vs. V-band light respectively. The redshift cut was chosen to ensure morphological classifications are reliable, and the stellar mass cut was chosen to ensure a complete sample of both red sequence and blue cloud galaxies out to $z = 1$. **Left:** Black contours show counts for the blue cloud sample, with the outermost contour starting at $N=200$ and separated by intervals of 200. **Right:** Black contours show counts for the red sequence sample, with the outermost contour starting at $N=50$ and separated by intervals of 50.

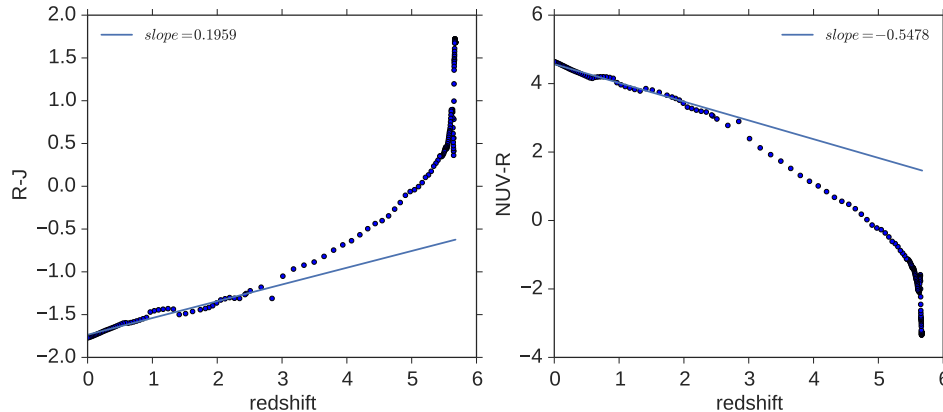


Figure 6.2 Evolution of colors using stellar population synthesis models. Galaxy was assumed to have formed at $z = 6$ for plotting purposes.

r - J diagnostic. NUV- r colors perform better than pure optical colors (like u - r) in separating the blue cloud from the red sequence, due to NUV bands exhibiting a greater sensitivity to low levels of star formation (Martin et al., 2007a; Wyder et al., 2007). This makes an excellent probe for stellar populations with light-weighted age of 10^8 year, while r is primarily sensitive to those of 10^9 year (Arnouts et al., 2007). NUV - r has thus been shown to be very well correlated with, and an excellent indicator of, current vs. past star formation activity (Martin et al., 2005; Salim et al., 2005).

The demarcation line to separate the passive and star-forming populations at $z = 1$ is adopted from I13, which defines the red sequence galaxies as those which satisfy: $M_{NUV} - M_r > 3(M_r - M_J) + 1$ and $M_{NUV} - M_r > 3.1$. I13 applies this criteria to all galaxies in a range of $0.2 < z < 3$, although it performs best at separating the two populations in the redshift bin $0.7 < z < 1.2$, where $> 98\%$ of galaxies identified as quiescent exhibited specific star formation rates less than $\log(\text{sSFR}) = -11$ (see Figure 3 of I13). This performance justifies our use of the I13 separation criteria for galaxies at $z = 1$, but we compute the evolution of the demarcation lines as a function of redshift to $z = 0$.

The evolution of $r - J$ and $NUV - r$ colours was derived using a stellar population synthesis model from Bruzual & Charlot (2003). An instantaneous-burst model was chosen from the Padova 1994 track to represent the colour evolution of a passively

evolving galaxy, with a metallicity $Z = 0.008 = 0.4Z_{\odot}$. A linear fit was generated for each colour within the range $0 < z < 2$, and the slopes for each were used to redefine the population separators in five redshift bins with widths $\Delta z = 0.2$ (Figure 6.2). We explicitly define one bin bracketing a central redshift $z = 0.007$ in order to coincide with the sample of SDSS galaxies used to identify completeness in disc detection (FERENGI2, Section 6.2). The remaining four bins coincide with the HST sample, with central values $z = [0.30, 0.50, 0.70, 0.90]$. The red sequence galaxies are thus defined in these bins as those that satisfy:

$$M_{NUV} - M_r > 3.1 + a_1(z) \quad (6.1)$$

$$M_{NUV} - M_r > 3(M_r - M_J + a_2(z)) + a_1(z) + 1 \quad (6.2)$$

where $a_1(z) = [0.54, 0.38, 0.27, 0.16, 0.05]$ and $a_2(z) = [0.19, 0.14, 0.10, 0.06, 0.02]$. We note that the evolution of the demarcation lines from $z = 1$ to $z \sim 0$ is very minimal, and our final results do not change if we perform the separation using the $z = 1$ definition.

After separating the sample by colour, it was observed that the red sequence region of the sample was dominated by highly-inclined galaxies, shown in Figure 6.3. Given that spectral colour of a galaxy’s combined stellar population should be independent of the angle in which it is observed, it is clear that the inclined galaxy colours are strongly affected by dust reddening. Although we are not using dust-corrected colours in our colour-colour separation, inclination has shown to have an affect on colours even in those for which dust-correction has been attempted (Morselli et al., 2016; Devour & Bell, 2017). We therefore remove highly inclined discs from the sample using an inclination limit defined by GZH vote fractions: $f_{\text{not edge-on}} > 0.3$ and $N_{\text{not edge-on}} > 10$ (right panel of Figure 6.3).

For clarity, the preceding discussion has rigorously enforced the convention that the terms “blue” and “red” refer exclusively to observed spectral colours. Similarly, “active” and “passive” were reserved to describe galaxies with ongoing or quenched star formation. Hereafter, we relax this strict terminology and conflate “red” and “blue” with “passive” and “active”, respectively.

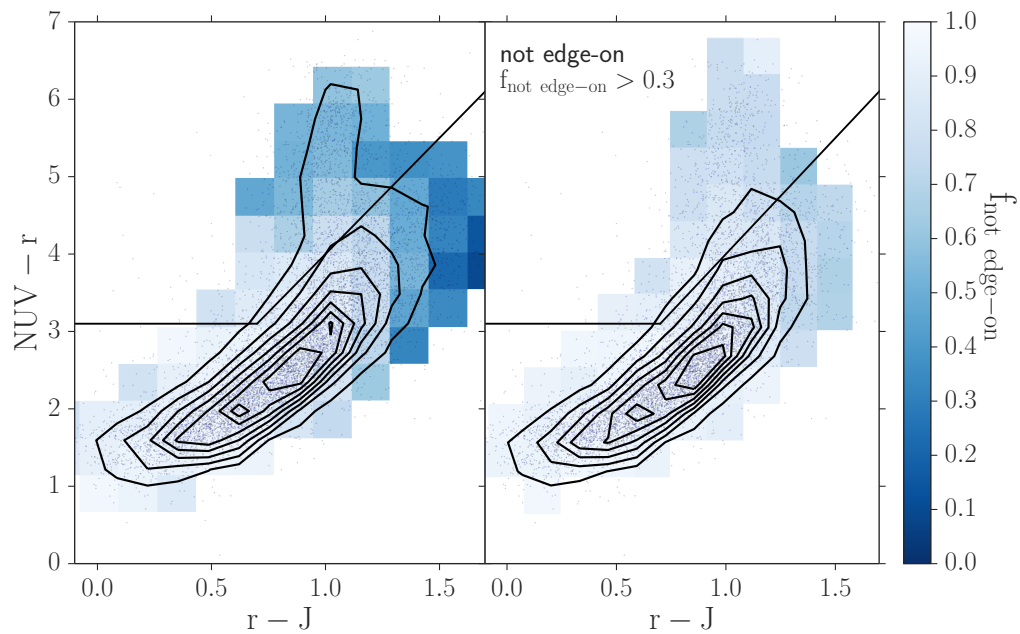


Figure 6.3 The effect of reddening for highly inclined galaxies. On the left panel is the distribution of $f_{\text{edge-on,no}}$, which is the fraction of Galaxy Zoo users who voted “no” in response to the question “Could this be a galaxy viewed edge-on?”. This vote correlates with inclination angle, such that low values represent highly inclined galaxies, and high values represent face-on galaxies. The bins are colored such that darker blue bins have a higher fraction of highly inclined galaxies, and white bins have high fractions of face-on galaxies. There is an obvious bias towards redder colours for galaxies with high inclination angles (low votes for $f_{\text{edge-on,no}}$). We therefore implement a cut of $f_{\text{edge-on,no}} > 0.3$ to ensure that observed red colours are an indicator of a lack of star formation, and not dust-reddening (right panel).

6.2 Correcting for Incompleteness in Disk Detection

In this work, we identify disc galaxies in our sample using a cut of $f_{\text{features}} \geq 0.3$, such that galaxies meeting this criterion are considered to have distinguishable features or disc structure (additional cuts are also placed to eliminate highly inclined, irregular, and merging galaxies; see Section 6.1.1), and galaxies which do not are considered to be elliptical. However, it has been empirically established that distinguishing disc structure from spheroidal becomes increasingly challenging in high redshift galaxies (for both experts and novice classifiers alike), for which features are less resolved and more difficult to identify. Willett et al. (2017) show using a set of artificially-redshifted simulated galaxy images classified in Galaxy Zoo that vote fractions for a nominally featured galaxy at $z = 0$ can differ sufficiently from those for the same galaxy at $z = 1$ to change its morphological classification to elliptical (we will show the same in Section 6.2.1). This result implies that applying a redshift-independent f_{features} cut to identify discs will increasingly underestimate their true number at increasing redshift intervals. A set of artificially redshifted images was used to quantify and correct for this incompleteness in disc and elliptical detection. We describe this dataset in the next section.

6.2.1 FERENGI2 set of artificially redshifted galaxy images

FERENGI2 is a set of simulated galaxy images created using the FERENGI code (Barden et al., 2008). These were created from a parent sample of 936 nearby ($z < 0.01$) SDSS galaxies, all of which had been previously classified in Galaxy Zoo 2 and were cross-matched against 2MASS (Skrutskie et al., 2006) to obtain J magnitudes and GALEX (Martin et al., 2005) to obtain NUV magnitudes, which were necessary to define a colour-colour separation using as similar as possible a criterion to that applied to the COSMOS sample. An “evolution factor” of $e = -1$ was applied, which brightens each galaxy linearly with redshift: $M' = M + ez$, where M' is the corrected magnitude. This correction is performed to mimic the known physical increase of galaxy magnitude with redshift (Lilly et al., 1998; Loveday et al., 2011), and the value $e = -1$ was chosen based on an analysis of spectra template models provided by Brinchmann et al. (2004), which showed that typical galaxies tend to evolve in brightness by one magnitude per unit redshift. Each galaxy was artificially redshifted to appear at 8 different distances

between $z = 0.3$ and $z = 1$ in intervals of $\Delta z = 0.1$ and processed to mimic *HST* imaging parameters, giving a total of 7,488 images (3 examples are shown in Figure 6.5). The set was then classified in Galaxy Zoo using the same decision tree as used for GZH. Highly inclined disc galaxies were removed from the sample by excluding any with $N_{\text{edgeon}} > 20$ and $f_{\text{not edge-on}} > 0.3$, using the vote fraction associated with the real galaxy image measured in GZ2. This was to exclude those which may be mis-classified due to dust reddening. Using the NUV-J-R selection method described in section 6.1.1, the remaining sample was divided into subsets of red sequence galaxies (259 per redshift bin) and blue cloud galaxies (543 per each redshift bin) (see Figure 6.4).

6.2.2 Measuring the completeness in disc and elliptical detection, ξ

The FERENGI2 dataset was used to measure the completeness/contamination in visual disc/elliptical detection, from which correction factors ξ_D and ξ_E were derived. These are defined as the number of discs/ellipticals detected divided by the true number of discs/ellipticals expected to exist in a given redshift interval: $\xi_D(z) = N_{\text{discs detected}} / N_{\text{discs true}}$, and $\xi_E(z) = N_{\text{ellipticals detected}} / N_{\text{ellipticals true}}$.

The completeness values $\xi_D(z)$ and contamination values $\xi_E(z)$ were computed for each of the 8 redshifts represented in the FERENGI2 dataset. An example calculation of ξ_D in the $z = 0.7$ bin is shown in Figure 6.6. Each point represents a FERENGI2 galaxy, where the y-axis indicates values of f_{features} measured in the image redshifted to $z = 0.7$, and the x-axis indicates values of f_{features} measured in the same galaxy redshifted to $z = 0.3$. Disk galaxies are identified as those for which $f_{\text{features}} \geq 0.3$. Since, on average, f_{features} decreases for the same galaxy when it is viewed at higher redshifts, the number of galaxies meeting this threshold is always lower at higher redshifts than at $z = 0.3$. This is indicated by the dotted lines: galaxies to the right of the vertical dashed line at $f_{\text{features},z=0.3} = 0.3$ are identified as discs at $z = 0.3$; their sum is considered the “true” number of discs, N_{true} . Similarly, the galaxies above the horizontal line at $f_{\text{features},z=0.7} = 0.3$ are identified as discs at $z = 0.7$; their sum is the “detected” number of discs at $z = 0.7$, or $N_{\text{discs detected}}$. The figure makes it obvious that $N_{\text{discs detected}}$ is much lower than $N_{\text{discs true}}$, emphasizing the increasing difficulty in detecting features at higher redshifts. Their ratio is the completeness ξ_D ; in this example $\xi_D(z = 0.7) = 0.61$, meaning only 61% of discs were detected at this redshift. This process was repeated for

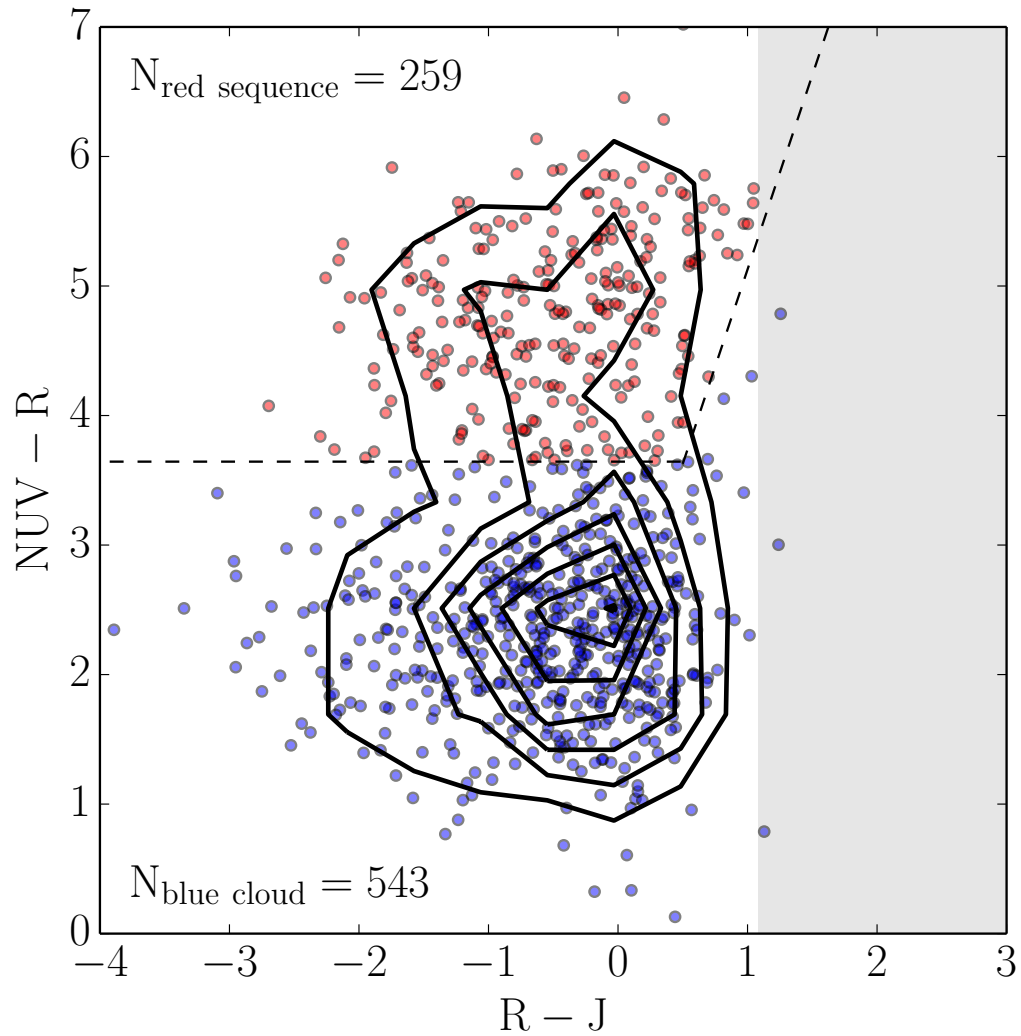


Figure 6.4 Separation of the passive population (red sequence) and active population (blue cloud) of the FERENGI2 sample. The gray shaded region represents the $R - J$ limit of the sample. Combining the limit of $r < 17$ that was adopted for the GZ2 dataset (of which the FERENGI2 galaxies are a subset), with the 2MASS magnitude limit of $J < 15.91$, yields a limiting colour for the FERENGI2 sample $R - J < 1.1$.

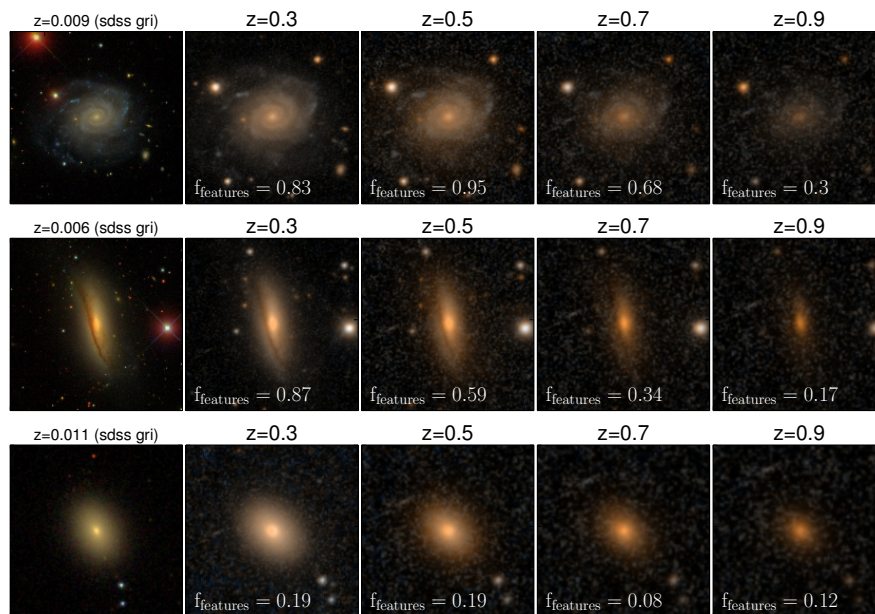


Figure 6.5 Example images of three galaxies artificially redshifted with the FERENGI code. The left image in each row is a real SDSS gri-composite image; the four to the right are images generated by FERENGI at varying redshifts, processed to mimic *HST/COSMOS* imaging. The f_{features} vote fraction for each simulated image is given; this value tends to decrease for each galaxy as it is processed to be viewed at higher redshifts.

the elliptical galaxies in each bin, defined as those with $f_{\text{features}} < 0.3$. Conversely for the ellipticals, $N_{\text{ellipticals,detected}}$ is always lower than $N_{\text{ellipticals,true}}$, yielding contamination factors $\xi_E > 1$ in each redshift bin. Measurements of ξ_D and ξ_E for each redshift interval are shown in the right panels of Figure 6.7.

It was possible that completeness/contamination in disc/elliptical detection may be a function of other parameters in addition to redshift. For example, at fixed redshift, it is a reasonable supposition that features could be easier to detect in galaxies that have higher mass, radius, or surface brightness. To test whether these parameters also impact the number of discs/ellipticals detected, ξ_D and ξ_E were measured in fixed redshift bins as functions of surface brightness, effective radius, and mass. The surface brightness was calculated as $\mu = m + 2.5 \times \log_{10}(2 \times (b/a) \times \pi R_e^2)$, using `MAG_AUTO`, b/a and R_e , derived by the `SEXTRACTOR` (Bertin & Arnouts, 1996) utility using the I_{814W} band images. The effective radius used was the 50% `FLUX_RADIUS` converted to kpc, and the masses used were the `MEDIAN` values in the MPA-JHU DR7 catalog (Kauffmann et al., 2003b).

Figure 6.9 shows completeness as a function of redshift and surface brightness, for the red sequence and blue cloud galaxies. 8 redshift bins were further divided into bins of surface brightness with varying widths, where the sizes were chosen to satisfy that $N_{\text{detected}} + N_{\text{true}} \geq 10$ in each bin. This was chosen as a compromise between having a sufficient number of galaxies in each bin to compute the completeness fraction $\xi = N_{\text{detected}}/N_{\text{true}}$, and having enough bins of surface brightness to measure a trend with confidence of completeness as a function of μ . Visual inspection of the data did not suggest any relationship between the two. To be sure, the data were fit to a linear function in each redshift bin (Figure 6.8). For each fit, a p-value representing a hypothesis test whose null hypothesis is that the slope is zero was computed. Only one reached the criteria $p < 0.05$, but with a low R^2 value of 0.28 which is not considered large enough to represent a good fit. This process was repeated using effective radius and mass as parameters. Similar to Willett et al. (2017), who found no effect on f_{features} with surface brightness, we did not detect any effect on ξ_D or ξ_E with any of the above parameters. Therefore only redshift was used as a parameter which impacted completeness value with confidence. As a final check, we computed ξ_D and ξ_E as functions of redshift for the blue cloud and the red sequence separately, to detect any color-dependence on

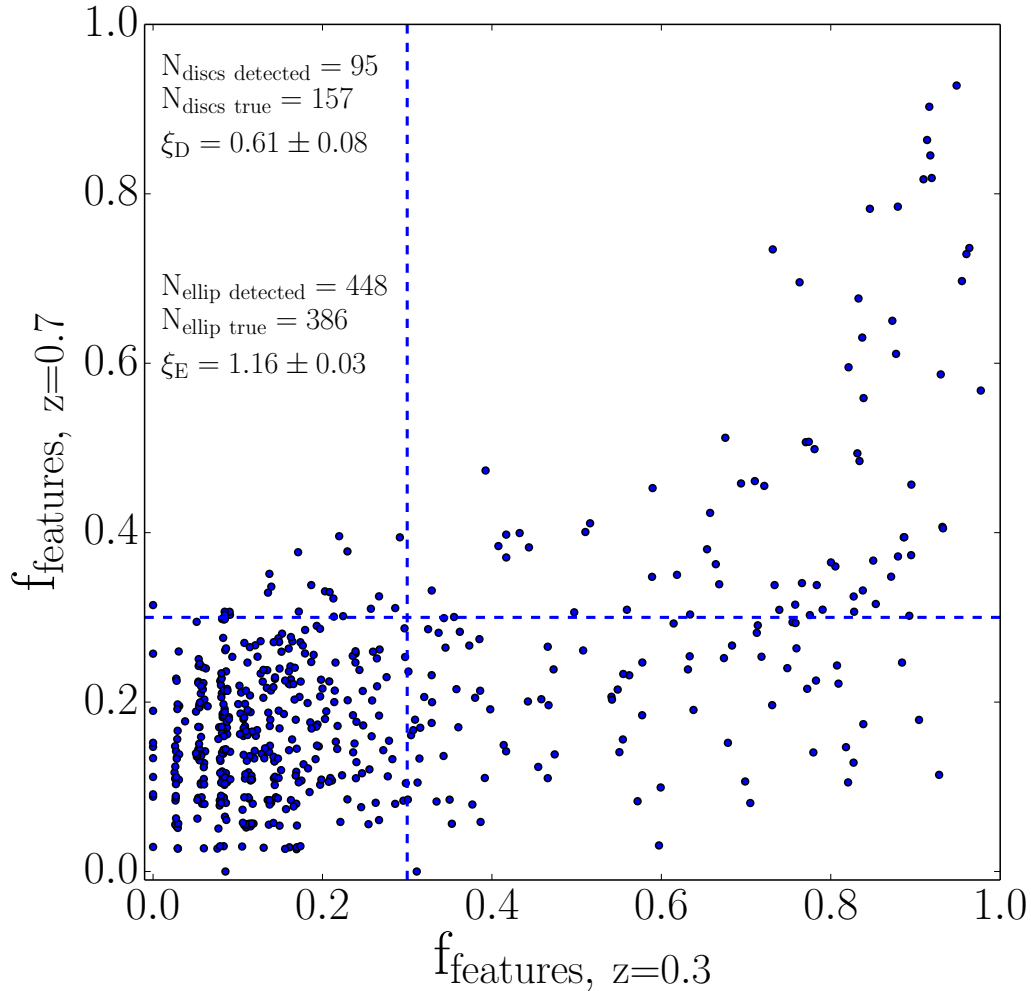


Figure 6.6 Example calculation of completeness/contamination ξ_D/ξ_E at redshift $z = 0.7$. Points represent GZ classifications of FERENGI2 images. The y-axis corresponds to the value of f_{features} measured at the galaxy redshifted to $z = 0.7$, and the x-axis corresponds to the value of f_{features} measured at the galaxy redshifted to $z = 0.3$. On average, the f_{features} is lower at the higher redshift, indicating classifiers on average have more difficulty identifying features in images modelling higher redshifts. The dotted lines correspond to the threshold $f_{\text{features}}=0.3$, above which a galaxy is considered to have a disc. Galaxies to the right of the vertical dashed line were identified as discs at the lowest redshift $z = 0.3$. The total number of such galaxies is denoted $N_{\text{discs true}}$, and is defined to represent the true number of disc-like galaxies. Galaxies above the horizontal dash line were identified as discs at the higher redshift $z = 0.7$, and their total number is denoted $N_{\text{discs detected}}$. The ratio $\xi_D = N_{\text{discs detected}}/N_{\text{discs true}}$ is the completeness value; in this example, only 61% of discs were detected at $z = 0.7$. Conversely, a contamination of 1.16% of ellipticals were detected. Errors on the displayed ξ_D and ξ_E are 95% Bayesian binomial confidence intervals (Cameron, 2013)

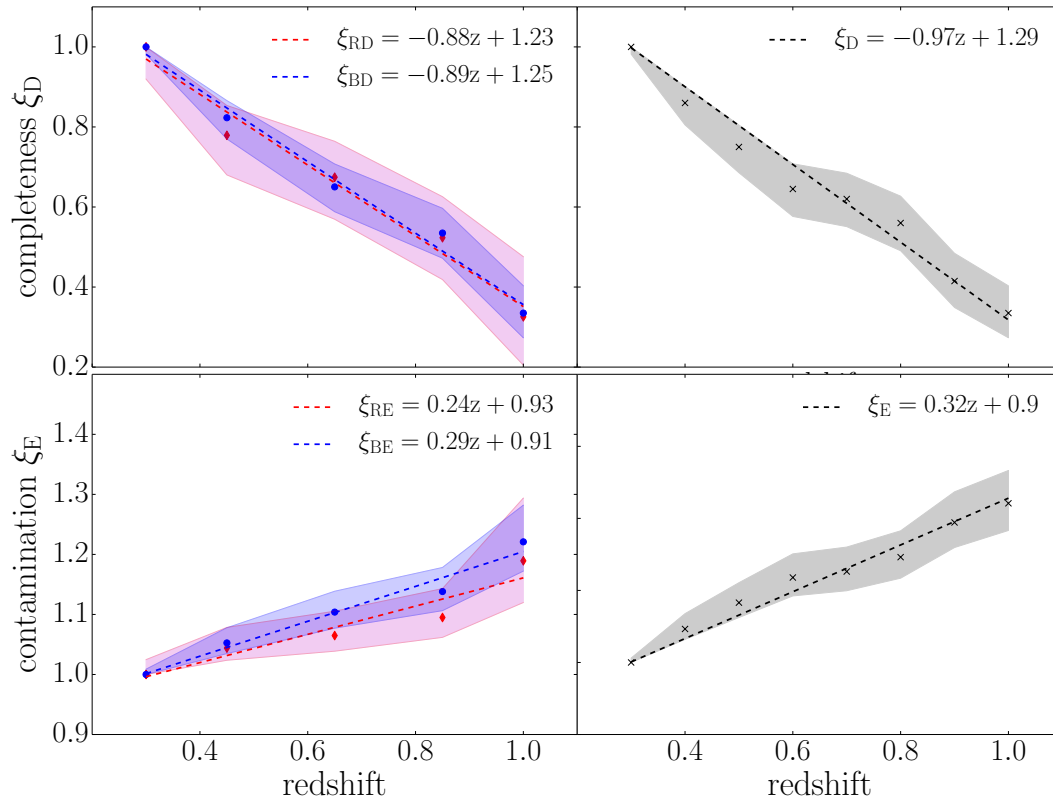


Figure 6.7 **Left:** Completeness ξ_{RD} and ξ_{BD} (top) and contamination ξ_{RE} and ξ_{BE} (bottom) as functions of redshift for red sequence and blue cloud FERENGI2 galaxies separately. All show a clear dependence on ξ with redshift, but there is no strong difference in completeness for the red and blue populations. **Right:** Completeness ξ_D (top) and ξ_E (bottom) as a function of redshift for all FERENGI2 galaxies (red and blue combined). The equation representing the linear fit for each is displayed. Shaded regions represent the 95% Bayesian binomial confidence intervals around each point (Cameron, 2013).

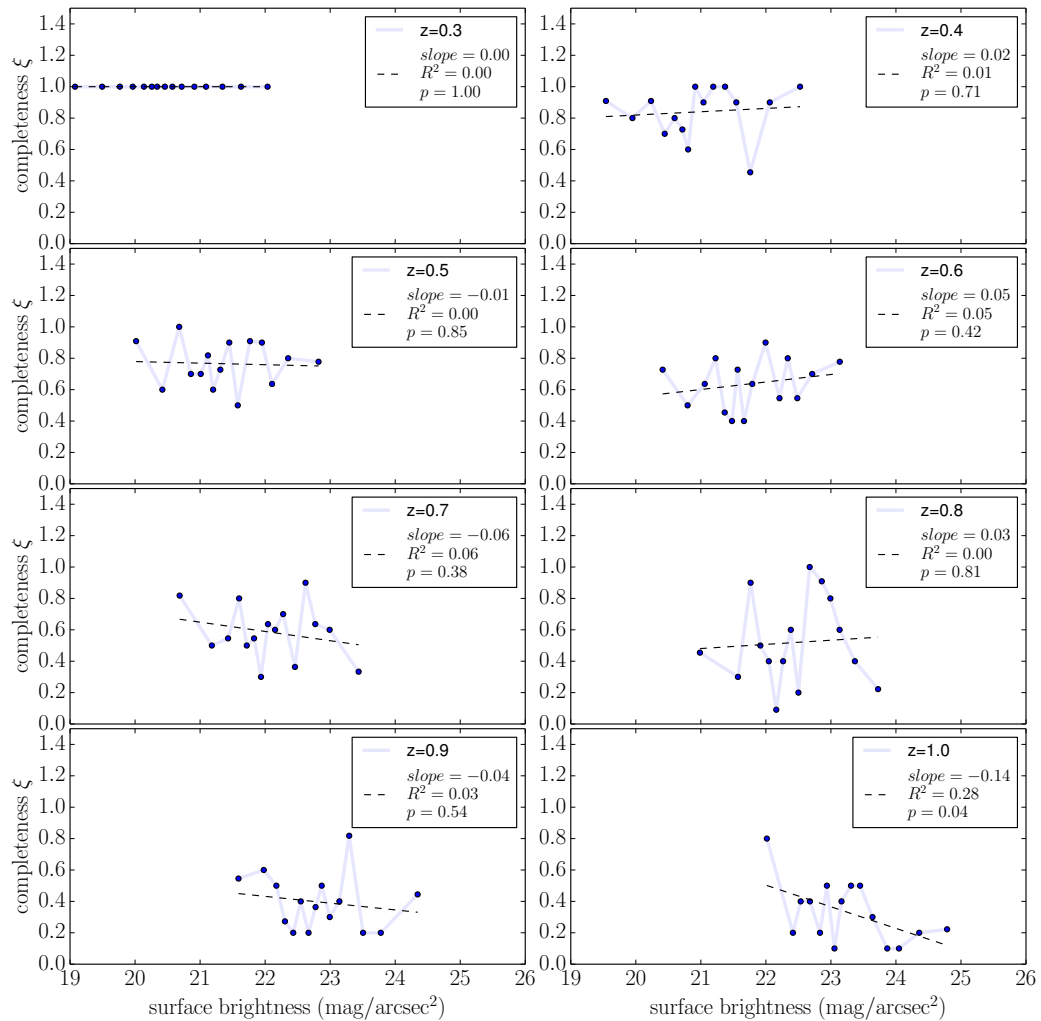


Figure 6.8 No observed dependence on completeness ξ with surface brightness at fixed redshift. Shown is ξ vs μ in bins of redshift for blue cloud galaxies (average values of ξ in each redshift bin are shown in Figure 6.9, right panel). Linear fits were computed in each bin, shown as the dashed black lines. Low overall R^2 values and large p values, displayed in the legends of each panel, suggest surface brightness does not have a strong effect on completeness. The final calculation for ξ was therefore only a function of redshift.

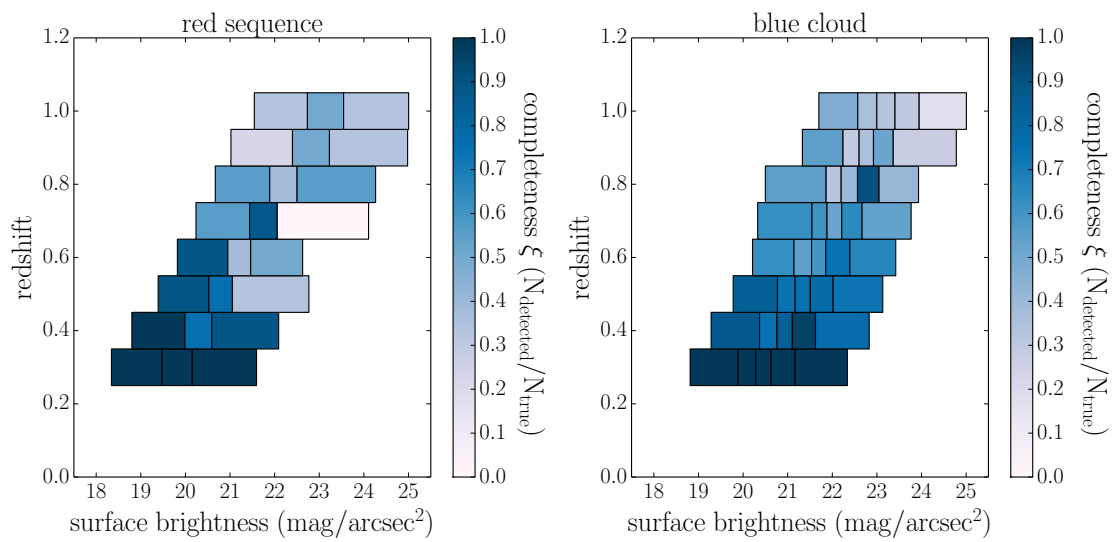


Figure 6.9 Completeness ξ as a function of redshift and surface brightness for red sequence (left) and blue cloud galaxies (right). In each redshift bin, galaxies were binned by surface brightness in varying widths such that $N_{\text{detected}} + N_{\text{true}} \geq 10$ in each bin. The completeness ξ was computed in each z, μ bin, represented by the colors. Darker colors represent a completeness of 1, such that all disks were detected, while fainter colors represent a completeness near 0, representing a failure to detect disks. ξ tends to decrease with redshift, but no correlation of ξ with surface brightness is observed at fixed redshift.

disc or elliptical detection; results are shown in the left panel of Figure 6.7. ξ_{RD} and ξ_{BD} refer to the completeness of red and blue disc galaxies, and ξ_{RE} and ξ_{BE} refer to the contamination of red and blue ellipticals. No significant difference was detected between the two populations, which is apparent from the overlapping 1σ errors on the plot. ξ_D and ξ_E were computed for the combined red and blue populations in bins of redshift between 0.3 and 1.0 with widths $\Delta z = 0.1$. Linear relationships for ξ_D and ξ_E as functions of redshift were derived:

$$\begin{aligned}\xi_D(z) &= (-0.97 \pm 0.04)(z) + 1.29 \pm 0.02 \\ \xi_E(z) &= (0.32 \pm 0.02)(z) + 0.90 \pm 0.01\end{aligned}\tag{6.3}$$

where the errors represent the 1σ deviations on the fit of the slope and intercept for each equation. These corrections were used to calculate the corrected number of each color-morphological type as follows:

$$\begin{aligned}N'_{BD}(z) &= N_{BD}(z) \times \xi_D^{-1}(z) \\ N'_{RD}(z) &= N_{RD}(z) \times \xi_D^{-1}(z) \\ N'_{BE}(z) &= N_{BE}(z) \times \xi_E^{-1}(z) \\ N'_{RE}(z) &= N_{RE}(z) \times \xi_E^{-1}(z)\end{aligned}\tag{6.4}$$

where unprimed numbers refer to the raw number counts of blue disks (BD), red disks (RD), blue ellipticals (BE), and red ellipticals (RE) in a given redshift interval in the GZH sample, and primed numbers represent the completeness/contamination-corrected values. Tables of all raw and corrected counts in bins of stellar mass and redshift are given in Section 6.7.

6.3 Results

In this section we present our results for the evolution of the fraction of blue disc, blue elliptical, red disc, and red elliptical galaxies from $z = 1$ to $z = 0.3$ in a sample of 20,811 *COSMOS* galaxies morphologically classified in GZH. In Figure 6.10, we

divide our sample into four bins of galaxy stellar mass and show how the fractional contributions of all four permutations of colour and morphology vary as a function of redshift, using the corrected number counts (Equation 6.4). In discussing these results, we refer to increases or decreases in these fractions with respect to *increasing* cosmic time; that is, from right to left in the plots shown in Figures 6.10 and 6.11.

In Figure 6.10 we find blue discs are the most common population at each redshift for all mass bins. At fixed redshift, red discs are most common in the highest mass bin, and their contribution decreases monotonically towards lower masses. Red ellipticals tend to significantly outnumber red discs except in the highest mass/redshift bin, where the population sizes are almost equal. Blue ellipticals represent an insignificant fraction for galaxies with mass $\log(M/M_\odot) > 10.7$, but begin to outnumber the red disc population at lower masses.

Red disc galaxies are presumed to form primarily from blue disc galaxies which have quenched without undergoing a morphological transformation. If this is true, and if the resulting quenched discs do not later become red ellipticals, one would expect a “pile up” of red discs at later times, resulting in an increasing fraction at lower redshift. This trend is observed in the two lowest mass bins, however there is no large change in the fractional contribution of red disks to the total population in the $\log(M/M_\odot) \sim 10.85$ bin, and even a small decrease in the highest mass bin. If we assume that red discs are continuously produced from blue discs, even at a small rate, then a constant or decreasing fraction can only be explained if their numbers are simultaneously being depleted, presumably by a morphological transformation to red ellipticals.

To better assess the evolution of the red disk population with respect to all discs and to the red sequence, we define two fractional quantities: the red disc fraction $f_{R|D}$, and the red sequence disc fraction, $f_{D|R}$, defined explicitly:

$$f_{R|D} = \frac{N'_{RD}}{N'_{RD} + N'_{BD}} \quad (6.5)$$

$$f_{D|R} = \frac{N'_{RD}}{N'_{RD} + N'_{RE}} \quad (6.6)$$

Maintaining an identical subdivision of our parent sample in $M_* - z$ space, equations 6.5 (left-panel) and 6.6 (right-panel) were evaluated for each subsample to yield

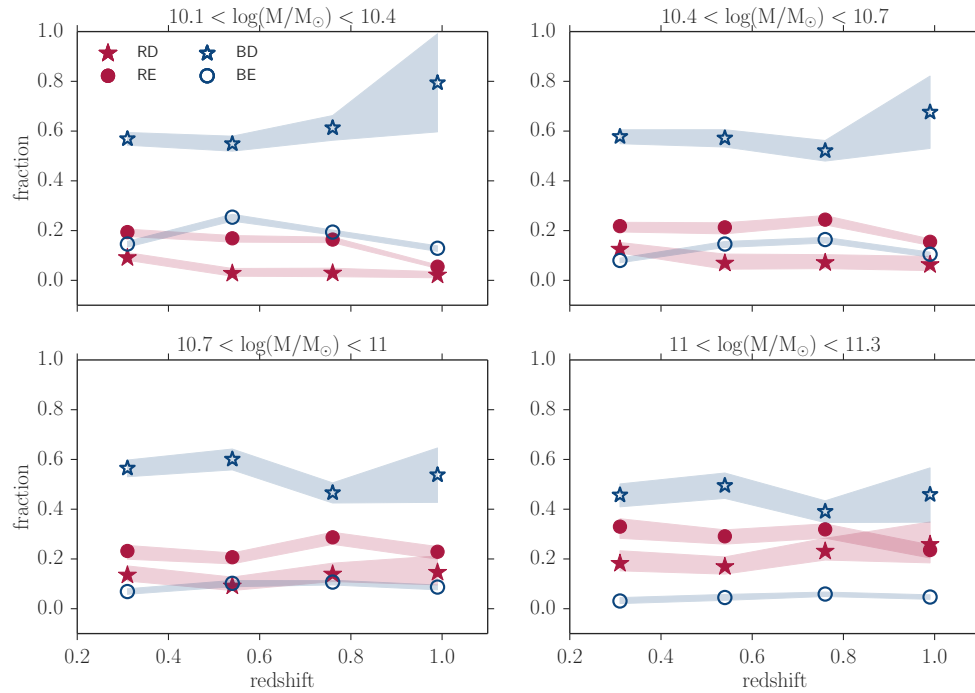


Figure 6.10 Evolution of four types of galaxy populations since $z = 1$: blue discs (blue open stars), red discs (red closed stars), blue ellipticals (blue open circles), and red ellipticals (red closed circles). Each point represents the fraction of the indicated type with respect to the total population, such that all points in a given redshift, mass bin sum to 1. Statistical errors were calculated as propagations of multinomial counting errors and the errors associated with the functional fits to the correction terms ξ_D and ξ_E . Systematic errors were calculated by bootstrapping the classifier votes for each galaxy and re-calculating the fractional contributions of each type; errors were taken as the 1σ dispersion in the fractions. The total error, represented by the shaded regions, is the statistical and systematic errors added in quadrature.

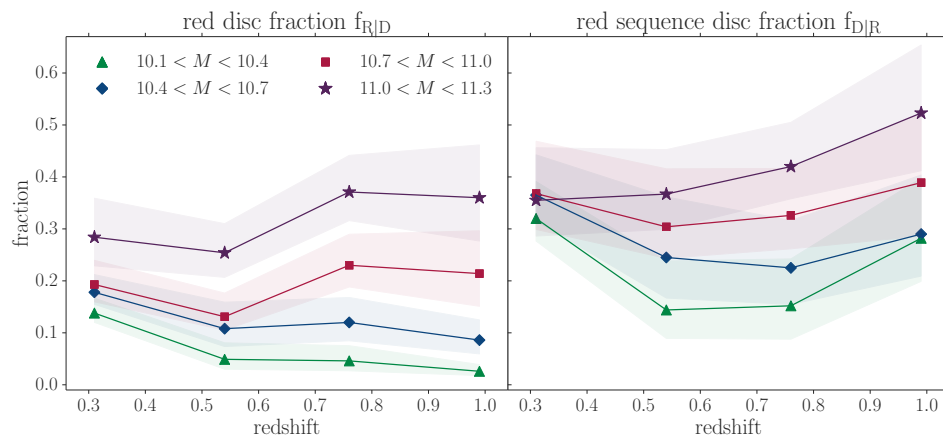


Figure 6.11 **Left:** Red disc fraction ($f_{R|D} = N'_{RD}/(N'_{RD} + N'_{BD})$, equation 6.5) vs redshift in four mass bins. **Right:** Red sequence disc fraction ($f_{D|R} = N'_{RD}/(N'_{RD} + N'_{RE})$, equation 6.6) vs redshift in four mass bins. Statistical errors were calculated as propagations of multinomial counting errors and the errors associated with the functional fits to the correction terms ξ_D and ξ_E . Systematic errors were calculated by bootstrapping the classifier votes for each galaxy and re-calculating the fractional contributions of each type; errors were taken as the 1σ dispersion in the fractions. The total error, represented by the shaded regions, is the statistical and systematic errors added in quadrature.

the curves plotted in Figure 6.11. We observe a mass dependence in both fractions. At fixed redshift, both $f_{R|D}$ and $f_{D|R}$ tend to increase with increasing mass; this is a consequence of the higher abundance of red discs observed at high masses, as seen in Figure 6.10.

Given the large errors on some of the fractions (particularly for $f_{D|R}$), we check whether $f_{R|D}$ and $f_{D|R}$ increase, decrease, or remain constant between $0.3 < z < 1.0$ in each mass bin by fitting the data to a linear function and evaluating if their slope is consistent with zero within the 1σ errors on the slope. We find that the red disc fraction $f_{R|D}$ decreases for the highest mass bin, is constant for $\log(M/M_\odot) \sim 10.85$, and increases for the two lower mass bins $\log(M/M_\odot) < 0.7$. An increase in $f_{R|D}$ could be driven by the increase of red discs or a depletion of blue discs; Figure 6.10 shows the increase may be driven more by the latter at $z \sim 1$, and the former at lower redshift. On the right, we find a decrease in the red sequence disc fraction $f_{D|R}$ for all masses in the interval from $z \sim 1$ to $z \sim 0.8$. Figure 6.10 shows that this is mainly driven by the increase in red ellipticals during this time, which is consistent with higher merger rates at this epoch (Molina et al., 2016). From $z \sim 0.8$ to $z \sim 0.3$, $f_{D|R}$ continues to decrease for galaxies $\log(M/M_\odot) > 11$, becomes constant for galaxies $\log(M/M_\odot) \sim 10.85$, and increases for the lower mass bins. Figure 6.10 reveals that the enhancement of $f_{D|R}$ among the low mass population is driven more by increases in the proportion of red discs, rather than a depletion of red ellipticals. The increase of $f_{R|D}$ and $f_{D|R}$ with redshift observed at low masses, coupled with the constant or decreasing trends for high masses, suggests that low mass red disc galaxies may be more likely to remain unchanged, while more massive red disc galaxies are more likely to evolve further via a morphological transformation. We explore the potential drivers of these trends in terms of different evolutionary quenching pathways in detail in Section 6.4.

The downward trend we observe in the red sequence disc fraction $f_{D|R}$ for massive galaxies is in agreement with Bundy et al. (2010) (hereafter B10) who perform a similar analysis of the morphological makeup of the red sequence. The trend we see at low masses, however, is in disagreement with B10. At the lowest redshift bin ($z \sim 0.3$), we measure similar absolute fractions of discs occupying the red sequence for all masses. However, B10 find the contribution of low mass red disc galaxies to increase at higher lookback time to $z = 1$, while we find a decreasing contribution.

The fact that our results agree for the highest mass at all redshifts, but only at the lowest redshift for lower masses, suggests the differences may be attributed to biases in morphological classification. B10 segregates early and late-type disc galaxies using ZEST (Scarlata et al., 2007) morphologies, which they acknowledge are biased towards classifying faint galaxies as discs. These tend to be associated with the lowest mass, highest redshift objects. This bias could influence their observed increase in red sequence discs toward $z = 1$ for low masses. Conversely, GZ classifications tend to be biased towards elliptical morphologies at fainter magnitudes. Our attempt to quantify and correct for this effect is described in Section 6.2.1, but if our calculation of the correction function was underestimated, this may have driven the apparently decreasing abundance of disc galaxies observed at increasing redshift for low masses. However, it has been shown that red disc galaxies in the local Universe tend to be more massive, as in Masters et al. (2010). If this is true at all epochs, we would not expect such a significant contribution by red discs to the low-mass galaxy population as found in B10.

6.4 Discussion

We have examined the evolution of red disc galaxies since $z = 1$ in Figures 6.10 and 6.11. Different trends in the abundance of red discs for distinct stellar mass bins are observed, which are consistent with a physical scenario in which 1) more massive galaxies undergo morphological transformations to elliptical at a higher rate than their less massive counterparts (implied by the decrease/increase of $f_{D|R}$ from $z = 1$ to $z = 0.3$ for high/low mass bins), and 2) more massive galaxies are more likely to enter a red disc phase to begin with (implied by the higher proportion of red discs in the high mass bin of Figure 6.10).

Figure 6.12 is a simple schematic of dominant quenching pathways for typical galaxies. Path A represents the creation of red discs via a quenching mechanism which does not transform the morphology of a blue star-forming disc. Path B represents a morphological transformation of a red disc to a red elliptical galaxy. Path C represents the quenching of blue discs via a mechanism which simultaneously invokes a morphological transformation. If all galaxies adhered to the standard color-morphology relationship,

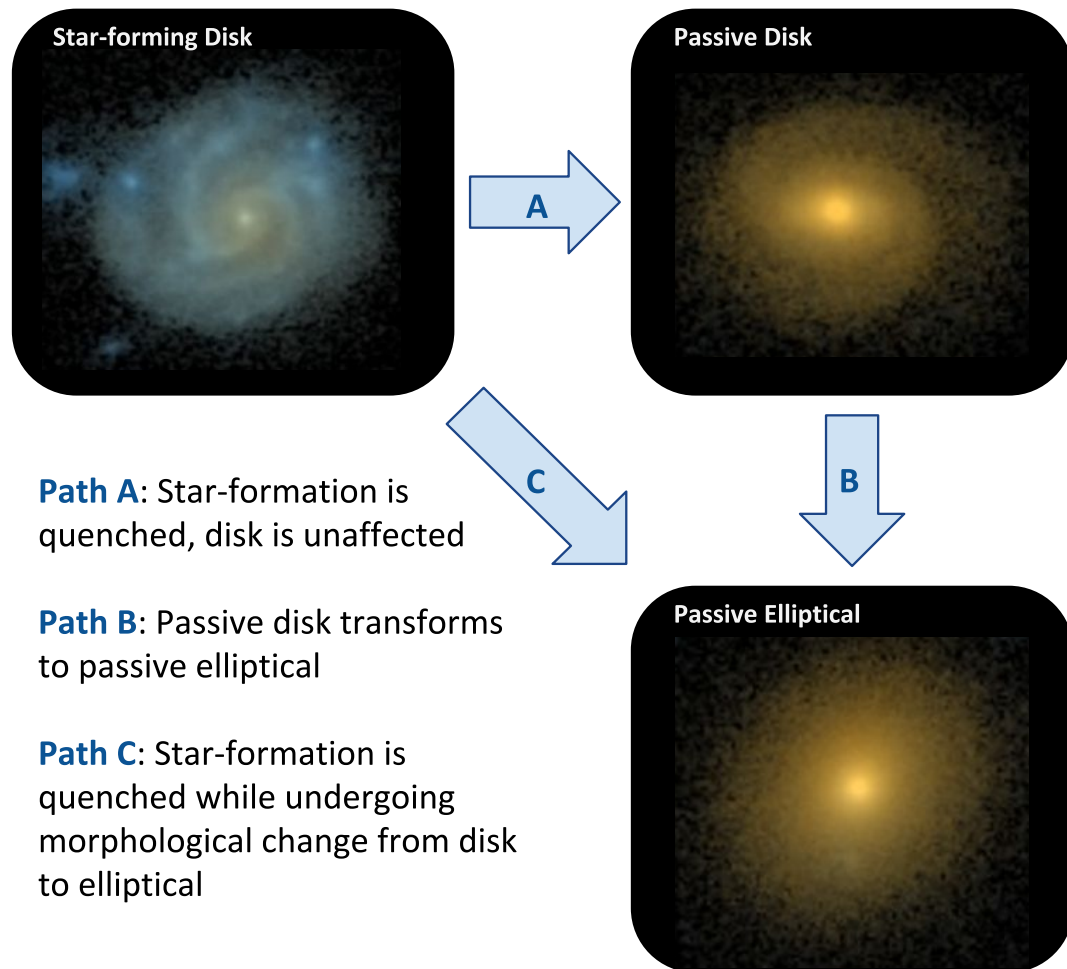


Figure 6.12 Cartoon representing three common evolutionary pathways of star-forming disc galaxies. Path A represents an active star-forming galaxy which quenches without destroying the disc, becoming a red disc. Path B represents a red disc morphologically transition to red elliptical. Path C represents a blue discs simultaneously quenching and morphologically transforming to become a red elliptical.

one could deduce that all galaxies follow this path. The existence of the red disc population asserts that Path A is also a viable channel. If these were the only two channels, we would expect pile ups of red discs at all masses as the Universe evolves. We observed such pile ups for low mass red disc galaxies (Figures 6.10 and 6.11), but not for massive galaxies. This suggests that Path B, the depletion of red discs via a later morphological transformation, is necessary to deplete the pool and counteract the pile up effect, and has increasing significance in higher mass galaxies.

6.4.1 Red disc fraction ($f_{R|D}$) and red sequence disc fraction ($f_{D|R}$): limiting cases

To help understand the influences of the different quenching mechanisms Paths A, B, and C (Figure 6.12), we explore limiting cases of the relative rates of these pathways and their influence on the red disc and red sequence disc fractions. A summary of these effects are displayed in Table 6.1. As in the previous section, we only discuss increases or decreases in fractions with *increasing* cosmic time; that is, from right to left in the plots shown in Figure 6.11.

Limiting case 1: Path A only

In this scenario, blue discs may quench and retain their disc structure, but no morphological transformation occurs for either type. This results a depletion in the number of blue discs at the same rate as the build-up of red discs. A decrease in blue discs and increase in red discs both result in increases in $f_{R|D}$, so we would observe only increasing values of $f_{R|D}$ in Figure 6.11. Similarly, an increase in red discs coupled with no change in red ellipticals would result in a pure increase of the fraction of discs on the red sequence, $f_{D|R}$.

The creation of red discs via Path A requires quenching mechanisms which do not significantly alter the disc’s morphology. Possible mechanisms include mass-quenching or AGN-feedback, which both induce quenching by cutting off the galaxy’s gas reservoir required for ongoing star formation. Mass-quenching occurs when a galaxy halo grows to a critical mass that induces virial shocks which heat the gas (Schawinski et al., 2007; Birnboim & Dekel, 2003; Cattaneo et al., 2006). Since this type occurs in high mass

galaxies, this could explain the observed increasing abundance of red discs as a function of mass (Figure 6.10). Dilution of gas in massive galaxies due to such shock-induced heating can cause it to become more vulnerable to AGN feedback (Dekel & Birnboim, 2006), whereby accretion onto the galaxy’s supermassive black hole generates strong outflows of energetic material and hard, non-thermal radiation. These AGN-driven winds may then terminate star formation by heating the gas or expelling it completely from the galaxy, causing a quench. Such a process is not likely to induce a morphological transformation, and therefore could be another valid mechanism for creating a quenched disc.

Red discs can also be the product of merger events. Simulations have shown cases of rotationally supported discs surviving or reforming after a major merger. This seems to be possible under conditions such that the progenitor discs are gas-dominated (Governato et al., 2009; Springel & Hernquist, 2005); for Robertson et al. (2006) discs were only re-formed if the gas fractions exceeded $f_{gas} > 0.5$. Under these conditions, it would be more likely to form low-mass discs, given that gas fraction tends to anti-correlate with stellar mass (Kannappan, 2004; Bell & De Jong, 2000). Perhaps this mechanism could explain some portion of the low-mass red disc population. However, regrown discs in these simulations tend to exhibit star formation activity. If the merger-disc regrowth event enhances star formation only briefly, then perhaps the remaining gas is used up on a shorter time-scale, leading to a low-mass red disc. Sparre & Springel (2017) find that although most of the new discs were star-forming, some were immediately quenched in simulations which incorporated particularly strong AGN feedback.

Limiting case 2: Path B only

Path B represents the depletion of red discs as they morphologically evolve to build up the population of red ellipticals. If blue discs are no longer quenching to build up the population of red discs, then we would only observe decreases in both $f_{R|D}$ and $f_{D|R}$ as the number of red discs drops, blue discs remain constant, and red ellipticals increase.

Our results suggest that Path B, the morphological transformation of red discs, is more common for high mass red discs than their low mass counterparts. It has been long suggested that major mergers are the dominant mechanism for transforming the majority disc-like galaxies to an elliptical morphology (Toomre, 1977; Schweizer,

1982; Schweizer et al., 1990), with multiple minor mergers being the second-most dominant (Bundy et al., 2009; Hopkins et al., 2010a). Studies using observations of close pairs have shown the galaxy merger rate increases with mass, both in the local Universe (Xu et al., 2004; Patton & Atfield, 2008; Domingue et al., 2009; Robotham et al., 2014; Casteels et al., 2014) and out to $z \sim 1$ (Xu et al., 2012; Bundy et al., 2009), which agrees with predictions from both empirical models and dynamical simulations (Hopkins et al., 2010b,a; Maller et al., 2006). Casteels et al. (2014) find the merger rate is as much as three times higher for massive ($\log(M/M_\odot) \sim 11.25$) than for lower mass ($\log(M/M_\odot) \sim 8.25$) galaxies, using a similar mass range probed in our study. The increasing merger rate with mass may explain why massive red disc galaxies do not tend to stay in this phase long before merging, while low mass galaxies which become red discs are more persistent in that phase.

Limiting case 3: Path C only

We now consider the scenario in which blue disc galaxies only quench via processes which simultaneously destroy their discs. The most extreme consequence of this scenario is of course a complete absence of red disc galaxies, which would give $f_{R|D} = f_{D|R} = 0$ for all redshifts. Allowing for an initial population of red discs, we can explore how $f_{R|D}$ and $f_{D|R}$ would evolve if Path C were to suddenly become the only option.

The evolution of $f_{R|D}$ is dependent on the growth/depletion of red and blue discs. In this scenario red discs are not building up, nor are they transforming morphologically; therefore their number remains constant, and the evolution of $f_{R|D}$ is solely dependent on the blue discs. If blue discs only evolve via path C, their number could only decrease, leading to an overall increase of $f_{R|D}$. $f_{D|R}$ in this scenario is only affected by the net change of red ellipticals, whose numbers are increasing via Path C. Therefore this scenario would give a decrease of $f_{D|R}$.

Limiting case 4: No quenching pathways, only mass growth via star formation

Even in the limiting scenario in which there are no quenching mechanisms or morphological transformations, the fractions in Figures 6.10 and 6.11 would evolve due to star formation in the blue discs. In a given mass bin, blue discs may enter from a lower mass

net effect on:	$f_{R D}$	$f_{D R}$
Path A only	↑	↑
Path B only	↓	↓
Path C only	↑	↓
star formation only	↓	no effect

Table 6.1 Net effects on the red disc fraction $f_{R|D}$ and red sequence disc fraction $f_{D|R}$ for limiting single-scenario cases of transformative pathways A, B, C (Figure 6.12) and mass growth via star formation. ↑ represents an increase in respective fractions with increasing cosmic time / decreasing redshift (right to left in Figure 6.11). This information can be used to find the dominant effects driving the trends in Figure 6.11.

bin or exit to enter a higher mass bin as they continuously increase their mass via star formation. The net rate of blue galaxies entering/leaving a mass bin via star formation can be estimated by the mass derivative of the mass function of blue galaxies times the specific star formation rate $d\phi_{blue}/dm \times sSFR(m, t)$ (Peng et al., 2010). Using a Schechter (1976) mass function, $d\phi_{blue}/dm = (1 + \alpha_s) - m/M^*$ with $\alpha_s = -1.4$ and $M^* = 10.28 (\log(M/M_\odot))$ (Ichikawa & Matsuoka, 2017) and specific star formation rate given by Peng et al. (2010) $sSFR(t) = 2.5(\frac{t}{3.5Gyr})^{-2.2} Gyr^{-1}$, we find the net rate of change of blue discs *due to star formation only* is always positive for the masses and redshifts considered in Figure 6.11.

Therefore, in the absence of quenching, we would observe a steady increase of the fraction of blue discs in Figure 6.10. The flatness observed suggests that their numbers are depleting via Paths B or C at similar rates as their numbers are replenishing each bin via star formation. In $f_{R|D}$ we would only observe a decrease as the number of blue discs increased, and $f_{D|R}$ would remain constant as the number of blue discs do not enter the equation.

6.4.2 Identifying the dominant transformative pathways as a function of mass

In the context of the above discussion outlining the net effects of Paths A, B, C, and mass growth via star formation, we will summarize the trends observed in Figure 6.11 for each stellar mass bin and identify the most probable drivers of the trends.

$$11.0 < \log(M/M_{\odot}) < 11.3$$

For galaxies in the highest mass bin, $f_{R|D}$ decreases from 0.36 to 0.28 since $z = 1$. This suggests that the rate of occurrence of Path B, the morphological transformation of red discs to elliptical, is strong with respect to paths A or C. Via Table 6.1 it is possible that star formation has an impact in this trend, however it is not expected to be the dominant driver given the flatness of the fraction of blue discs observed in Figure 6.10.

$f_{D|R}$ decreases from 0.52 to 0.36, which could be driven by Path B or C. Given that a dominant Path C would cause an increase in $f_{R|D}$ (opposite of what we observe), it is more likely that Path B is the primary driver of this decrease.

$$10.7 < \log(M/M_{\odot}) < 11.0$$

For galaxies in the second highest mass bin, $f_{R|D}$ is consistent with a slope of zero. Via Table 6.1, Paths A and C both cause an increase in $f_{R|D}$, while Path B causes a decrease. This suggests that the combined rates of Paths A and C must be near equal to the rate of Path B, in order to give a net change of zero. As with the highest mass, star formation is not expected to be a dominant contribution due to the flatness of the blue disc fraction in Figure 6.10.

$f_{D|R}$ is also consistent with a slope of zero. This suggests Path A is significantly strong to balance the decreasing effects of Paths B and C.

$$10.4 < \log(M/M_{\odot}) < 10.7$$

For galaxies in the second lowest mass bin, $f_{R|D}$ increases from 0.09 to 0.12. Table 6.1 shows paths A and C cause $f_{R|D}$ to increase, while Path B would cause a decrease. This indicates that paths A and C are dominating, meaning path B is less dominant as compared to the higher masses.

$f_{D|R}$ increases from 0.29 to 0.37. This indicates that Path A dominates over both B and C.

$$10.1 < \log(M/M_{\odot}) < 10.4$$

$f_{R|D}$ increases from 0.03 to 0.14, indicating path B is not significant compared to A and C.

$f_{D|R}$ is consistent with a slope of zero, indicating the rate of Path A is comparable to the combined effect of B and C.

A summary of the above breakdown is as follows: Path B, the depletion of red discs via a morphological transformation to elliptical, operates at a higher frequency for more massive galaxies than the lower mass galaxies. In other words, lower mass galaxies are more likely to remain in a red disc phase, while high mass red discs are more likely to merge and transition to elliptical. Path A, the creation of red discs, is strongest for high masses, given by the trends of $f_{R|D}$, $f_{D|R}$ and the larger abundance of red discs in the higher mass bins.

6.4.3 Looking forward: developing a model to reproduce observations

Through observations of the evolution of the red disc population since $z = 1$, we have deduced that massive galaxies are more likely to both enter a red disc phase and subsequently exit the stage via a morphological transformation, while low mass discs which enter a passive stage are more likely to remain in that phase than continue their evolution. To quantify and verify this interpretation would require further work, such as a semi-analytical model which could reproduce these observations given parameters describing the rate of occurrences of the different evolutionary pathways shown in Figure 6.12. A complete model is beyond the scope of this work, but an example of a simple toy-model approach is given in Section 6.6. Our simple model found that the rate at which blue discs transform into red discs (Path A) increases with increasing stellar mass, which agrees with our interpretations thus far. However it was unable to constrain values for the rates of Paths B or C due to degeneracies in the results; constraining all such parameters is the subject of future work.

6.5 Conclusions

We have investigated the population of passive disc galaxies across a range of stellar masses and redshifts from $z=1$ to the present epoch. We used morphological classifications from Galaxy Zoo: Hubble and rest-frame colours from UltraVISTA. Using data from artificially-redshifted FERENGI2 images to quantify the known redshift bias in the GZ classifications, we derived expressions to correct the incompleteness in the number

of discs and ellipticals detected as a function of redshift. The relative population statistics were described in terms of the fraction of disc galaxies that are red $f_{R|D}$ and the fraction of disc galaxies on the red sequence $f_{D|R}$. Our main conclusions are as follows:

- The fraction of disc galaxies that are red $f_{R|D}$ and the fraction of red sequence galaxies that are discs $f_{D|R}$ decrease from $z = 1$ to $z = 0.3$ for massive galaxies, and increase for the least massive galaxies.
- Low mass galaxies which experience a passive disc phase are more likely than massive galaxies to remain discs, while massive galaxies are more likely to continue their evolution by transforming to passive ellipticals. Additional data are required to properly constrain semi-analytic models that might further elucidate the physical processes that generate the observed population trends.

6.6 Toy Model

Our observations of the evolution of different morphological and activity types of galaxies since $z = 1$ are well-suited for the implementation of a model to constrain the frequencies of different evolutionary pathways. Here we present a toy model designed to reproduce our observations, given different sets of input parameters. This pilot study is expected to initiate further development of a sophisticated, semi-analytic model to describe and constrain potential rates of quenching and morphological evolution.

We implement a model to track the change in $f_{R|D}$ and $f_{D|R}$, given a range of parameters representing the quenching and morphological transformation rates for galaxies at fixed stellar mass. We begin by considering the rate of change in the number of blue discs (dN_{BD}/dt), red discs (dN_{RD}/dt), and red ellipticals (dN_{RE}/dt). In a given mass bin, the change in numbers for each population will depend on several parameters, illustrated visually in Figure 6.12.

6.6.1 Blue Disks

Galaxies in a blue bin may transition into a red disc bin via a quenching process that does not destroy its disc; we define this rate as $r_{BD \rightarrow RD}$, representing the fraction of blue galaxies to transition to red discs per Gyr (path A in Figure 6.12). Blue galaxies

may also exit a bin via a quenching process which *does* destroy the disc; this fraction per Gyr we define as $r_{BD \rightarrow RE}$ (path C in Figure 6.12).

The number of galaxies in a blue disc bin will also change due to star formation, which brings active galaxies from a lower mass bin into the current mass bin. To account for this term we use the formalism outlined by Peng et al. (2010), in which this rate of change is given by $(\alpha + \beta)sSFR$. Here $\alpha = d\phi_{blue}/dm$ is the derivative of the mass function for blue galaxies, which equates to $\alpha = (1 + \alpha_s) - m/M^*$ for a mass function described by the Schechter (1976) function. We use best-fit parameters for blue galaxies measured by Ichikawa & Matsuoka (2017), which give $\alpha_s = -1.4$ and $M^* = 10.28$ ($\log(M/M_\odot)$). Following the method of Peng et al. (2010), we let $\beta = 0$, both for simplicity, and because their conclusions found not to be strongly dependent on β . Finally, the specific star formation rate is given by $sSFR(t) = 2.5(\frac{t}{3.5Gyr})^{-2.2}Gyr^{-1}$ (Peng et al., 2010).

Accounting for all sources and sinks of blue discs entering or exiting a bin of given mass, the rate of change of blue discs can be written fully as:

$$\left. \frac{dN_{BD}}{dt} \right|_m = \left(-r_{BD \rightarrow RD} - r_{BD \rightarrow RE} - \alpha(m)sSFR(t) \right) N_{BD} \quad (6.7)$$

Red Disks

Galaxies exiting a blue bin as they quenched without disrupting their discs enter the pool of red discs, increasing N_{RD} for a given mass bin. Red discs also may undergo a morphological transformation, depleting the pool of red discs as they enter the red elliptical bin (path B in Figure 6.12). The fraction of galaxies to undergo this pathway per Gyr is denoted as $r_{RD \rightarrow RE}$. Combining these factors gives the expression:

$$\left. \frac{dN_{RD}}{dt} \right|_m = +r_{BD \rightarrow RD}N_{BD} - r_{RD \rightarrow RE}N_{RD} \quad (6.8)$$

6.6.2 Red Ellipticals

In this simple model, it is assumed that red, passive ellipticals are the final state in a typical galaxy's evolution. Therefore N_{RE} will always be increasing from the transformation from blue discs and red discs to red ellipticals ($r_{BD \rightarrow RE}$, $r_{RD \rightarrow RE}$). However,

the number of red ellipticals *in a single mass bin* may still decrease due to ellipticals at the given mass merging to enter a bin of red ellipticals at a higher mass. Similarly, their number can increase as ellipticals from a lower mass bin merge to enter the current mass bin. A complete model would consider this full range of possibilities and couple the resulting equations appropriately amongst all mass bins. For the purposes of simplicity, we opted to represent the total, net rate of change of the number of red ellipticals as a single parameter, κ_{RE} , which we note may be positive or negative, depending on whether more ellipticals are entering or leaving the given mass bin.

$$\left. \frac{dN_{RE}}{dt} \right|_m = \kappa_{RE} N_{RE} \quad (6.9)$$

We exclude the contribution from blue ellipticals from the model for maximum simplicity, and because they represent only a small fraction of the total population, particularly at higher masses (Figure 6.10). A complete version of the model would include this population.

We initialize our model using the observed relative numbers of blue discs, red discs, and red ellipticals measured at $z = 1$, then use the model to compute their evolution to $z = 0.3$ using a range of values for each of the four parameters in four mass bins. For $r_{BD \rightarrow RD}$, $r_{BD \rightarrow RE}$, and $r_{RD \rightarrow RE}$, we test 25 values between 0 and 1, and 25 values between -1 and 1 for κ_{RE} . We note that a complete model would explore time-varying rates, but we only experiment with static parameters. For each mass bin, the model was evaluated for each permutation of the four rate parameters. The success of each run was evaluated using a χ^2 metric; these results are shown for each mass bin in the corner-plot in Figure 6.13. The bins are weighted by $1/\chi^2$, such that white regions represent the rate parameters that yield the lowest χ^2 , and black representing the largest.

We find a strong mass dependence on the fraction of blue galaxies to quench to red discs ($r_{BD \rightarrow RD}$), or Path A in Figure 6.12. Our observations of $f_{R|D}$ and $f_{D|R}$ are most closely reproduced when $r_{BD \rightarrow RD} = [0.05, 0.07, 0.1, 0.2] \text{ Gyr}^{-1}$ for masses $\log(M/M_\odot) = [10.25, 10.55, 10.85, 11.0]$. These values for $r_{BD \rightarrow RD}$ correspond to the peaks of the 1-D histograms shown in Figure 6.13. This increase of $r_{BD \rightarrow RD}$ with mass could suggest either: 1) more massive galaxies are more likely to undergo quenching processes which do not destroy their discs, or 2) less massive galaxies simply quench less frequently overall, via any pathway.

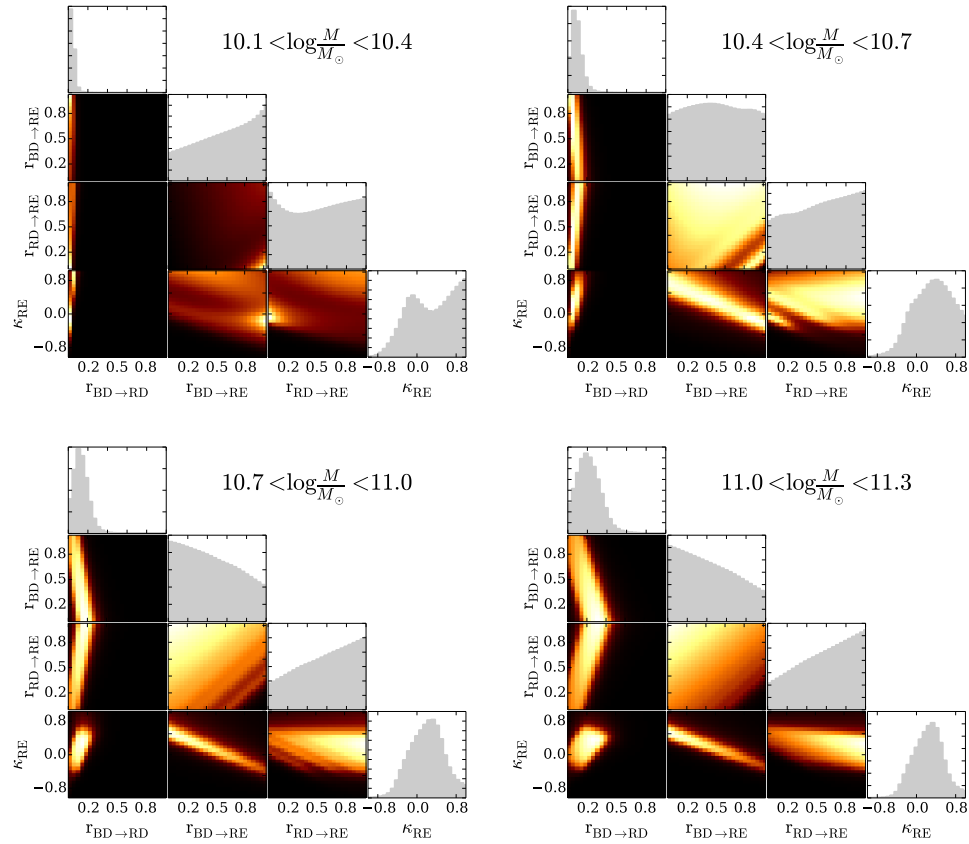


Figure 6.13 Results of the grid-search for the best-fit rate parameters $r_{BD \rightarrow RD}$, $r_{BD \rightarrow RE}$, $r_{RD \rightarrow RE}$, and κ_{RE} for four mass bins. The units for all rate parameters is Gyr^{-1} . 25 equally-spaced values were tested between (0,1) for each parameter, with the exception of κ_{RE} which was tested for 25 values between (-1,1); these are represented by the 25 bins on each axis. Each bin is weighted by $1/\chi^2$, such that white regions correspond to parameters which produced the lowest χ^2 , and black representing the highest. There is a strong result in the dependence of $r_{BD \rightarrow RD}$ with mass, such that the fraction of blue discs which transition to red discs (ie, quench without disrupting the disc), increases for more massive galaxies. The other parameters are less constrained by this model; therefore a more complex semi-analytic model will be necessary for obtaining the precise values of these rates, and is the subject of future work.

Analysis of the next parameter in the low mass bin, $r_{BD \rightarrow RE}$, suggests that the former is more likely, given the peak of $r_{BD \rightarrow RE}$ at $> 0.9 \text{ Gyr}^{-1}$. The high rate of low-mass blue discs quenching to red ellipticals is evidence that they do not quench any less frequently than high mass galaxies, and the increase of $r_{BD \rightarrow RD}$ with mass is indeed consistent with quenching processes less likely to destroy the disc of massive galaxies. However, this result is not nearly as constrained, given the broad distribution of similarly likely values for this parameter. $r_{BD \rightarrow RE}$ is even less constrained for all higher masses. The degeneracies evident in this rate and $r_{RD \rightarrow RE}$ make it clear that our model is not sufficient to constrain the relative frequencies of the processes involved in quenching and morphological transformations; a larger dataset or a full semi-analytic treatment with the adjustments we have described thus far would be necessary to paint the full picture.

6.7 Data Tables

Here we provide the raw and corrected counts of four morphology/colour types of galaxies: red discs, blue discs, red ellipticals, and blue ellipticals. Counts are divided into four tables representing data for the four mass bins used in Figures 6.10 and 6.11. In each table, the counts are further subdivided into four redshift bins corresponding to the bins used in the same figures, and the redshift displayed is the central redshift value of the bins. Corrected counts are derived for each redshift interval using $\xi_D(z)$ for discs and $\xi_E(z)$ for ellipticals, as explained in Section 6.2. Errors for the raw numbers represent multinomial counting errors, while errors on the corrected numbers are multinomial counting errors propagated with the errors associated with the fits for ξ_D and ξ_E .

10.1 < log(M/M _⊙) < 10.4				
redshift	0.31	0.54	0.76	0.99
N _{RD}	66 ± 8	23 ± 5	36 ± 6	17 ± 4
N' _{RD}	66 ± 8	30 ± 6	65 ± 11	51 ± 14
N _{BD}	411 ± 14	445 ± 16	754 ± 22	629 ± 18
N' _{BD}	416 ± 17	582 ± 30	1368 ± 96	1920 ± 266
N _{RE}	197 ± 12	262 ± 14	561 ± 20	213 ± 13
N' _{RE}	141 ± 9	178 ± 10	365 ± 13	132 ± 8
N _{BE}	148 ± 11	394 ± 16	665 ± 21	504 ± 18
N' _{BE}	106 ± 8	269 ± 11	433 ± 14	312 ± 12
N _{total}	822 ± 23	1124 ± 27	2016 ± 37	1363 ± 29
N' _{total}	731 ± 22	1060 ± 34	2232 ± 99	2418 ± 266

Table 6.2 Raw (unprimed) and corrected (primed) number counts of four morphology/colour categories in four redshift bins for galaxies with stellar masses within $10.1 < \log(M/M_{\odot}) < 10.4$.

10.4 < log(M/M _⊙) < 10.7				
redshift	0.31	0.54	0.76	0.99
N _{RD}	76 ± 8	46 ± 7	83 ± 9	44 ± 7
N' _{RD}	76 ± 8	60 ± 9	150 ± 19	134 ± 27
N _{BD}	351 ± 13	381 ± 15	611 ± 21	470 ± 18
N' _{BD}	355 ± 15	498 ± 26	1109 ± 81	1434 ± 201
N _{RE}	186 ± 12	272 ± 14	799 ± 22	530 ± 18
N' _{RE}	133 ± 8	185 ± 9	520 ± 15	329 ± 12
N _{BE}	68 ± 12	186 ± 12	537 ± 20	359 ± 16
N' _{BE}	48 ± 6	127 ± 8	349 ± 13	222 ± 10
N _{total}	681 ± 21	885 ± 24	2030 ± 37	1403 ± 31
N' _{total}	615 ± 20	871 ± 31	2130 ± 85	2121 ± 204

Table 6.3 Raw (unprimed) and corrected (primed) number counts of four morphology/colour categories in four redshift bins for galaxies with stellar masses within $10.4 < \log(M/M_{\odot}) < 10.7$.

10.7 < log(M/M _⊙) < 11.0				
redshift	0.31	0.54	0.76	0.99
N _{RD}	53 ±7	40 ±6	118 ±10	78 ±9
N' _{RD}	53 ±7	52 ±8	214 ±23	238 ±41
N _{BD}	222 ±10	265 ±12	396 ±17	287 ±15
N' _{BD}	224 ±12	346 ±20	718 ±56	876 ±127
N _{RE}	128 ±10	175 ±11	680 ±19	602 ±17
N' _{RE}	92 ±7	119 ±8	442 ±13	373 ±11
N _{BE}	38 ±6	86 ±9	254 ±14	228 ±14
N' _{BE}	27 ±4	58 ±6	165 ±10	141 ±9
N _{total}	441 ±17	566 ±19	1448 ±31	1195 ±28
N' _{total}	398 ±16	577 ±24	1541 ±62	1630 ±134

Table 6.4 Raw (unprimed) and corrected (primed) number counts of four morphology/colour categories in four redshift bins for galaxies with stellar masses within $10.7 < \log(M/M_{\odot}) < 11.0$.

11.0 < log(M/M _⊙) < 11.3				
redshift	0.31	0.54	0.76	0.99
N _{RD}	29 ±5	33 ±5	89 ±9	71 ±8
N' _{RD}	29 ±5	43 ±7	161 ±19	216 ±38
N _{BD}	73 ±7	97 ±8	151 ±11	126 ±10
N' _{BD}	73 ±7	126 ±11	274 ±26	384 ±60
N _{RE}	74 ±7	109 ±8	343 ±13	319 ±12
N' _{RE}	53 ±5	74 ±5	223 ±8	198 ±8
N _{BE}	7 ±3	17 ±4	64 ±8	63 ±7
N' _{BE}	5 ±2	11 ±3	41 ±5	39 ±5
N _{total}	183 ±11	256 ±13	647 ±20	579 ±19
N' _{total}	162 ±10	256 ±15	701 ±34	839 ±72

Table 6.5 Raw (unprimed) and corrected (primed) number counts of four morphology/colour categories in four redshift bins for galaxies with stellar masses within $11.0 < \log(M/M_{\odot}) < 11.3$.

Chapter 7

Looking Forward

Morphology has been, and continues to be, one of the strongest tools available for unravelling the fundamental aspects of the evolution of galaxies. Understanding the myriad secular and environmental processes which give rise to the multitude of morphological types observed contributes to our growing knowledge of the past, present, and future of our Universe.

Using morphology as such a tool, however, is not without its own challenges. Most of these stem from the difficulty in obtaining accurate morphological classifications on a sufficiently large scale. For example, while the SDSS has imaged the largest number of galaxies in a single survey to date ($N \sim 900,000$), only a small fraction of these are nearby enough, large enough, and bright enough to accurately classify their morphologies. Figure 7.1 shows side-by-side images of a galaxy at $z = 0.1$ imaged by SDSS (left) and HST (right). The ground-based image at $0.4''/\text{pixel}$ is not resolved enough to even make out the strong bar or spiral arms, which are very easy to identify in the HST image at $0.04''/\text{pixel}$.

The solution to this problem has typically been to limit one's sample to only include the most bright galaxies, via a magnitude or volume-limit, to ensure all morphologies in the study are accurate. However a statistical price is paid, particularly in population studies which seek to identify dominant trends in large samples of galaxies. Such studies tend to require extensive binning of the parent sample to remove inter-dependencies in the variables, which as a consequence increases the statistical error in the results as the number of subjects per bin decreases. This type of limitation amplifies as one extends

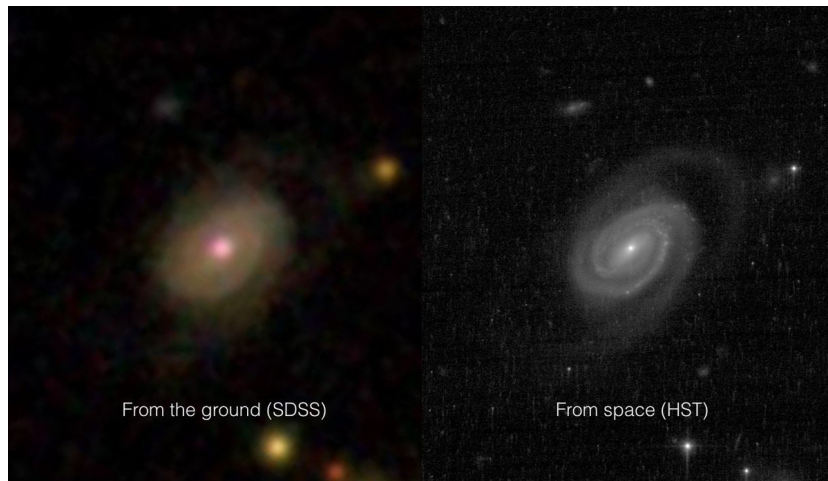


Figure 7.1 Resolution of the instrument has a strong impact on the physical appearance of a galaxy, and large differences could change a morphological classification drastically, even for nearby galaxies. Shown is a spiral galaxy at $z = 0.1$, imaged by SDSS at $\sim 4''/\text{pixel}$ (left), and HST at $\sim 0.04''/\text{pixel}$ (right) (HST Program ID 14606, PI: Simmons). The strong bar and distinct spiral arms in the HST imaging are mostly lost in the low-resolution ground-based image.

to higher redshift; even the high-resolution capability of HST is insufficient in capturing consistent detailed morphological substructures for galaxies beyond $z \sim 0.5$, except for the very largest and brightest objects.

The future of the field is incredibly promising, as technological advances in instrumentation continue to improve on these limitations. Noteworthy examples include the Giant Magellan Telescope (GMT), Extremely Large Telescope (ELT), and the Thirty Meter Telescope (TMT) which will provide images 10-16 times sharper than HST, due to their improved light-collecting areas via large mirrors and implementation of sophisticated adaptive optics technology.

Perhaps the most notable upcoming advances in this field involve the Large Synoptic Space Telescope (LSST) and the Euclid mission, which will be imaging galaxies on scales previously unattainable. Producing data on the order of terabytes per night, the surveys are ultimately expected to produce detailed images of more than a billion galaxies. While samples on this scale may certainly solve the aforementioned statistical challenges of morphological population studies, this inflow of data presents an entirely

new challenge: how can we possibly obtain accurate morphologies on such a large scale in a reasonable timeframe? On these scales, even crowdsourced visual inspection via Galaxy Zoo is nowhere near fast enough.

The next stage of Galaxy Zoo is tackling this issue by combining human and machine effort, beginning with an innovative system dubbed Galaxy Zoo Express (GZX) (Beck et al. 2017, submitted). GZX improves on the speed and accuracy of human classifications in two ways. First, it maximizes the information that can be obtained from human effort via the algorithm SWAP (Space Warps Analysis Pipeline) (Marshall et al., 2016). SWAP continuously tracks and updates the probability that a galaxy has a given feature, given the history of the volunteers' classifications and their performance classifying known galaxies as part of a training set. Using this technique, human effort is greatly reduced as most galaxies would not require 40 volunteers all classifying each galaxy, which was the retirement threshold in all previous GZ projects. Second, GZX incorporates a machine-learning algorithm which works together with the human classifications to increase the classification time even further. With all of these improvements combined, Beck et al. 2017 showed that GZX could classify 70% of the GZ2 catalog in *32 days*, a feat that took a full year using the current approach.

This thesis began with the observation that all data available for studying the evolution of the Universe is contained in a single snapshot of the present cosmos. Methods of imaging galaxies in this snapshot are continuously advancing, as are methods for fast and efficient morphological classification. These advancements undoubtedly point to a promising new era of discovery, which should unveil a whole new wealth of information to further our understanding of the life and fate of galaxies in the Universe.

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