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Galaxy Zoo: CANDELS Barred Disks and Bar Fractions*

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ABSTRACT

The formation of bars in disk galaxies is a tracer of the dynamical maturity of the population. Previous studies have found that the incidence of bars in disks decreases from the local Universe to $z \sim 1$; at $z > 1$, simulations predict that bar features in dynamically mature disks should be extremely rare. Here we report the discovery of strong barred structures in massive disk galaxies at $z \sim 1.5$ in deep rest-frame optical images from CANDELS. From within a sample of 876 disk galaxies identified by visual classification in Galaxy Zoo, we identify 123 barred galaxies. Selecting a sub-sample within the same region (brighter than L^*) of the evolving galaxy luminosity function, we find that the bar fraction across the redshift range $0.5 \leqslant z \leqslant 2$ ($f_{bar} = 10.7^{+1.5}_{-1.2}\%$ after correcting for incompleteness) does not significantly evolve. We discuss the implications of this discovery in the context of existing simulations and our current understanding of the way disk galaxies have evolved over the last 11 billion years.

Key words:
galaxies: bars — galaxies: evolution — galaxies: general — galaxies: spiral

1 INTRODUCTION

Large-scale galactic stellar bars form within dynamically cold, rotationally supported disks (Athanassoula 2005; Combes 2009; Athanassoula et al. 2013; Sellwood 2013). Thus the evolution of the fraction of disk galaxies with bar features traces the overall evolution of disk galaxy dynamics. Locally, bars are present in $\sim 25-50\%$ of disk galaxies (e.g. Odewahn 1996; Elmegreen et al. 2004; Aguerri et al. 2009; Nair & Abraham 2010; Masters et al. 2011; Cheung et al. 2013), with their abundance steadily decreasing to $\sim$10% of disk galaxies at $z \sim 1$ (Abraham et al. 1999; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005; Sheth et al. 2008; Melvin et al. 2014).

The lower incidence of bars at higher redshifts may be in part be due to the increased incidence of mergers and galaxy interactions (Conselice et al. 2003; Lotz et al. 2011; Casteels et al. 2013), which disrupt and heat disks, destroying or preventing the formation of bars. It may also be related to the expected increase in disk gas fraction with redshift; this has been observed indirectly via the increase in specific star formation rate to $z \sim 2$ (e.g., Lilly et al. 1996; Madau et al. 1998) and directly via the increased M_{gas}/M_{star} from CO observations (e.g., Tacconi et al. 2010, 2013; for a detailed review, see Carilli & Walter 2013). The presence of a bar in a galaxy is anti-correlated with specific star formation rate (Cheung et al. 2013) and disk gas fraction (Masters et al. 2012), in agreement with theoretical predictions (Friedli & Benz 1993; Berentzen et al. 2007; Villa-Vargas et al. 2010; Athanassoula et al. 2013, though a high gas fraction does not entirely preclude the existence of a bar; Nair & Abraham 2010; Masters et al. 2012). More generally, disk galaxies at $z \sim 1$ tend to be less dynamically "settled" than their more local counterparts, with a lower rotation velocity compared to velocity dispersion as redshift increases (Kassin et al. 2012).

The current theoretical understanding of bar fraction evolution suggests that disk galaxies at $z > 1$ are too dynamically hot to form bars (e.g., Kraljic, Bournaud, & Martig 2012 find no observable bars within a simulated sample of galaxies at $z \sim 1.5$). Other simulations explore the impact of tidal heating and galaxy harassment, which can either inhibit bar formation *or* promote it, depending on mass (with higher-mass galaxies being more likely to form a long-lasting bar due to a minor merger or interaction; Noguchi 1988; Moore et al. 1996; Skibba et al. 2012). Testing this requires high-resolution imaging over a large area of the sky to observe statistically significant samples in multiple redshift bins and adequate spatial resolution to resolve galactic-scale bars in the rest-frame optical (since the detectability of bars decreases rapidly blueward of the 4000 Å break; Sheth et al. 2008).

These observing requirements currently limit studies of disk populations via bar fractions to surveys with the *Hubble Space Telescope (HST)*. Previous studies have used the optical cameras on *HST* to examine bar fractions to $z \sim 1$. In this paper, we present first results from Galaxy Zoo morphological classifications of galaxies imaged by the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011), which uses *HST's* near-infrared Wide-Field Camera 3 (WFC3) to extend the redshift range within which high-resolution rest-frame optical galaxy images are available to $z \gtrsim 2$.

In Section 2 we describe our sample selection, including a summary of Galaxy Zoo classifications of CANDELS galaxies and how disks and bars are selected. We also explore any potential biases that may affect our results. We present our results in Section 3, with a discussion including comparison to simulated predictions in Section 4, and a summary in Section 5. Throughout this paper we use the AB magnitude system, and where necessary we adopt a cosmology consistent with ΛCDM, with $H_0 = 70$ km s^{-1}Mpc^{-1}, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$ (Bennett et al. 2013).

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2 DATA

2.1 CANDELS

The Cosmic Assembly Near-infrared Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) is an *HST* Treasury program combining optical and near-infrared imaging from the Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (infrared channel; WFC3/IR) across five well-studied survey fields (GOODS-North and -South, EGS, UDS and COSMOS) and at two depths, "wide" and "deep". The wide fields are imaged at 2–3-orbit depths, and the deep fields at ∼13-orbit depths, over multiple epochs. These are reduced and combined to produce a single mosaic for each field, with drizzled resolutions of $0.03''$ and $0.06''$ per pixel for ACS and WFC3/IR, respectively (a process described in detail by Koekemoer et al. 2011).

Here we use the CANDELS ACS and WFC3/IR images from within the COSMOS, GOODS-South, and UDS fields for which raw classifications from the Galaxy Zoo project are presently available. The WFC3/IR observations of these fields cover approximately 0.3 square degrees combined. The Galaxy Zoo classifications are based on colour images created using an asinh stretch (Lupton et al. 2004) with WFC3 F160W, F125W, and ACS F814W as red, green and blue channels respectively. Some of the colour images use ACS data that was observed during previous surveys (Giavalisco et al. 2004; Scoville et al. 2007; Koekemoer et al. 2007; Lawrence et al. 2007; Cirasuolo et al. 2007) and re-analysed by the CANDELS pipeline.

2.2 Classifications

Galaxy Zoo provides quantified visual morphologies by obtaining multiple independent classifications for each galaxy. Beginning in 2007, more than 1,000,000 galaxy images in total from the Sloan Digital Sky Survey and the *HST* have each been classified by typically ~ 40 independent volunteers via a web interface[1]. The initial version of the project (Lintott et al. 2008, 2011) asked a single question per galaxy (whether the galaxy was spiral or elliptical). Subsequent versions have collected more detailed morphological information, including finer sub-structures of disk galaxies such as bulge strength and bars, via a tiered classification tree (e.g., Willett et al. 2013; Melvin et al. 2014).

This work uses classifications collected during the fourth release of Galaxy Zoo, specifically of 49,555 images from the COSMOS, GOODS-South, and UDS fields in the CANDELS survey (hereafter GZ-CANDELS). The dataset was initially composed of all sources having $F160W$ (H) apparent magnitude < 25.5; 58% of sources have $25.5 < H < 24.5$, and 31% of sources have $H < 23.5$. We note that this brighter sub-sample includes 95% of galaxies later selected as "featured" galaxies (Section 2.4).

Initial analysis after each source in the full sample had received typically ~ 20 classifications resulted in the early retirement of 1,555 point-like sources and 11,837 faint, low-surface brightness galaxies without resolvable fine features. Although the project is still ongoing, as of the date of this analysis each of the remaining objects has received at least 40 independent classifications.

The classification tree used for GZ-CANDELS (B. Simmons et al., in preparation; see Figure 1 for the portion relevant here) first asks volunteers to choose whether a galaxy is mostly smooth, has features, or is a star/artifact. The bar classification question ("Is there a sign of a bar feature through the centre of the galaxy?") is reached once a volunteer has chosen "Features or Disk" as an answer to the first question and has subsequently said the galaxy does *not* have a mostly clumpy appearance, nor is it an edge-on disk. The bar classification is therefore a fourth-tier task, and the number of volunteers per galaxy who answer the bar question varies depending on responses to the earlier tasks.

2.3 Redshifts

Each of the fields covered by CANDELS data has considerable ancillary data from previous and ongoing work. In addition to newly-calculated photometric redshifts in CANDELS (T. Dahlen et al., submitted), we assemble photometric and spectroscopic redshifts from the available literature. For galaxies in the COSMOS field, we combine spectroscopic redshifts from the zCOSMOS project (Lilly et al. 2007) with photometric redshifts from COSMOS (Ilbert et al. 2009) and from the NEWFIRM medium-band survey (Whitaker et al. 2011). In the GOODS-South field, we use the catalog of Cardamone et al. (2010), who added photometric redshifts based on deep broad- and medium-band data from MuSYC (Gawiser et al. 2006) to available spectroscopic redshifts compiled from multiple sources (Balestra et al. 2010; Vanzella et al. 2008; Le Fèvre et al. 2004; Cimatti et al. 2002). In the UDS field, we use available spectroscopic and photometric redshifts (Mortlock et al. 2013), the latter of which make use of deep multi-wavelength coverage from UKIDSS as well as J and H-band magnitudes from CANDELS. Of the 49,555 galaxies originally included in Galaxy Zoo: CANDELS, 46,234 currently have spectroscopic (2,886) or photometric (43,348) redshifts. Where available, agreement between spectroscopic and photometric redshift is generally very good, with $\sigma_z/(1+z_{spec}) = 0.017$.

2.4 Sample Selection

A full reduction of the GZ-CANDELS classifications, resulting in a catalog of morphological votes for each galaxy, is ongoing. Here we use the raw vote percentages, which have been neither weighted nor debiased. The effects of using raw versus the reduced classifications are twofold. First, the unweighted votes are likely biased in the first question toward an excess of votes for "Star or Artifact" (see Willett et al. 2013 for a discussion of how inconsistent votes are down-weighted in Galaxy Zoo 2, which has a similar decision tree). Second, the effects of surface brightness dimming and loss of spatial resolution are not accounted for in the vote percentages, which is potentially a significant effect in a sample extending to $z \sim 2$ in the rest-frame optical.

To favour completeness in the final disk galaxy sample and to minimize the impact of the lack of user weighting, we employ a lower vote percentage threshold when selecting "featured" galaxies than is typical when using weighted

[1] zoo4.galaxyzoo.org

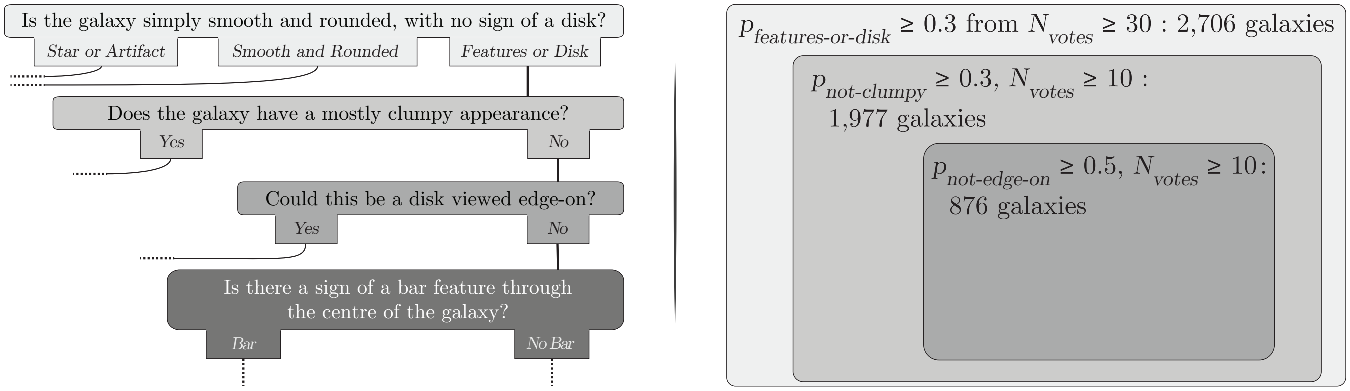

Figure 1. *Left:* Partial Galaxy Zoo: CANDELS classification tree, starting with the first question (top) and leading to the bar feature question. There are 17 questions total in the tree; the bar question is a 4th-tier task. *Right:* Selection of the featured, not-edge-on disk galaxy sample (876 galaxies) in GZ-CANDELS; relative box areas are scaled to the sample sizes. This selection was made independently of restrictions on redshift or luminosity (a full description of the sample selection is given in Section 2.4). Eight independent classifiers subsequently examined each of the 876 disk galaxies for evidence of a bar.

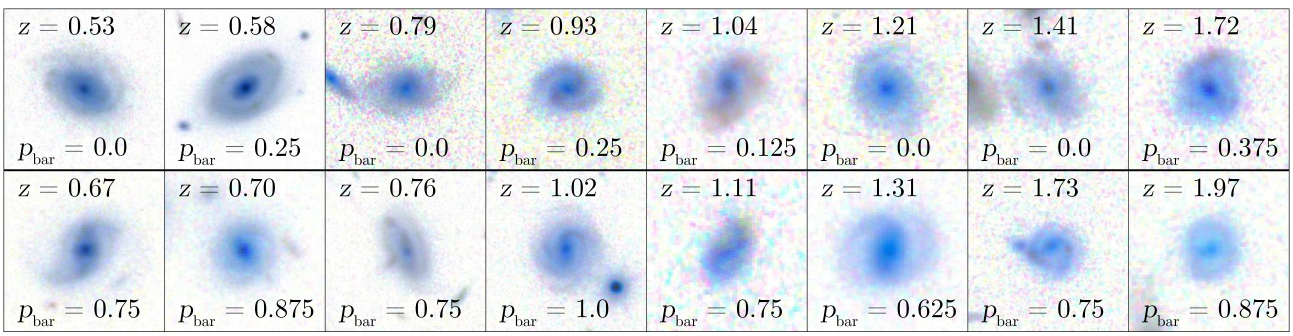

Figure 2. Examples of disk galaxies in GZ-CANDELS whose bar vote percentage (p_{bar}) places them in the unbarred (top row) and barred (bottom row) sub-samples.

data. We select as "featured" galaxies those where at least 30% of votes (out of at least 30 volunteers total) were registered for "Features or Disk". This selects 2,706 featured galaxies. After the first question, the user weighting used by previous Galaxy Zoo data reductions affects vote percentages by typically no more than a few percent; we therefore expect the lack of weighting to have little to no systematic effect on additional vote percentages.

Subsequent to the featured galaxy selection, we select a sub-sample where at least 30% of volunteers (where a minimum of 10 answered the question) registered a vote for "no" to the question "Does the galaxy have a mostly clumpy appearance?" in order to remove galaxies whose features do not clearly include a disk; this selection removes 729 clumpy galaxies in total. We include this selection in order to consider each branch of the classification tree that leads to the bar-feature question; however, we note that were we to ignore the clump-threshold criterion completely, this would only cause contamination of the final "featured" sample at the 1% level, due to the subsequent inclination and luminosity selection criteria. Our qualitative results are thus not sensitive to the specific choice of clumpy threshold between $0.1 \leqslant p_{not-clumpy} \leqslant 0.6$.

Further, we also require that 50% of volunteers (of at least 10) registered a vote for a disk galaxy that is "not-edge-on". This is a deliberately conservative choice to reflect the fact that bars would be invisible in edge on systems (the thresholds used to select disk features are less strict to favour completeness).[2] This selects a sample of 876 featured disk galaxies from which a bar may be identified, if it exists. Figure 1 shows a visual representation of this sample selection, from which a further sub-sample of barred galaxies may be identified. However, approximately 20% of these 876 galaxies received less than 10 raw votes *total* for the question "Is there any sign of a bar feature through the centre of the galaxy?", a consequence of the broad initial selection of featured galaxies and the multiply-branched nature of the classification tree. Because of the lower number of votes per galaxy in the 4$^{\rm th}$ tier of the classification tree (the position of the bar question), within the featured sample the raw bar fractional vote is statistically useful, but uncertain for these individual galaxies.

We therefore elected to supplement the volunteer data with visual classifications from the Galaxy Zoo science team to select the sub-sample of barred disk galaxies. Eight of the authors[3] inspected each of the 876 featured disk galaxies for

[2] The discussion in Section 3 assumes the bar fraction is the same in edge-on galaxies as face-on galaxies; we also note that an application of the results to include clump-dominated galaxies requires a similar assumption.
[3] BDS, TM, KWW, WCK, MR, KLM, RS, EC

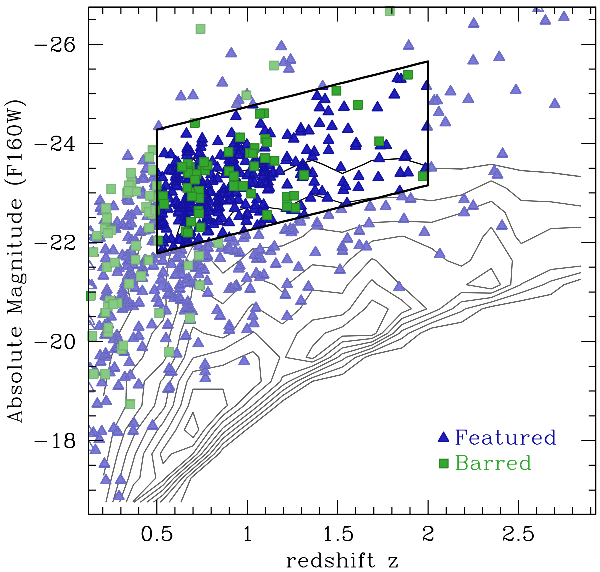

Figure 3. Absolute H-band magnitude versus redshift for all sources with $H < 25.5$ (contours in steps of 10%) and 876 "Featured" not-edge-on disks (blue triangles), of which 123 galaxies show clear evidence of a bar (green squares). To facilitate comparison between lookback times, avoid biases due to surface-brightness dimming when calculating bar fractions, and ensure all observed H-band flux is redward of the 4000 Å break, we select sub-samples within the same region of the evolving galaxy luminosity function (Marchesini et al. 2012) and $0.5 \leqslant z \leqslant 2$ (parallelogram). Within this region there are 370 not-edge-on disk galaxies, 56 of which have clear evidence of bars.

evidence of a bar; these votes were unanimous approximately 60% of the time, either for a bar feature (23 galaxies) or no bar (512 galaxies). Among galaxies where the science team voted unanimously that a bar is present, the mean volunteer bar vote percentage is 0.65 ± 0.15. Among galaxies where the science team was unanimous that a bar is *not* present, the mean volunteer bar vote percentage is 0.11 ± 0.11. The science team and volunteer bar vote percentages generally correlate, although the low number of volunteer votes for many objects means the dispersion in the correlation is high. Following vote percentage thresholds used in previous studies (this method has been shown to select strong bars; Masters et al. 2011; Willett et al. 2013; Melvin et al. 2014), we mark a galaxy as barred if at least half of the science-team classifiers indicated the presence of a bar ($p_{bar} \geqslant 0.5$).

The absolute H-band magnitudes in the sample are plotted as a function of redshift in Figure 3. Of the featured not-edge-on (and barred) galaxies, 525 (61) have redshifts between $0.5 \leqslant z \leqslant 2.0$. Within this redshift range, all flux collected by the WFC3 H band is redward of the 4000 Å break. Examples of barred and unbarred galaxies are shown in Figure 2.

To minimize any bias caused by surface-brightness dimming at higher redshifts, we additionally employ a conservative luminosity cut when examining bar fractions, choosing a minimum H absolute magnitude of -23.15 at $z = 2$ (or approximately an apparent $H = 23.5$). This ensures that featured galaxies can be detected within the sub-sample at all $z < 2$. We note that this is brighter than the knee of the rest-frame-V-band luminosity function at this redshift (Marchesini et al. 2012). In order to examine similar populations across our entire redshift range, we use a redshift-dependent luminosity cut based on selecting the same region of the evolving luminosity function (corrected to observed H band; Blanton & Roweis 2007; Marchesini et al. 2012): this selection is shown as a parallelogram shape in Figure 3. This final cut produces 370 featured, not-edge-on disk galaxies, of which 56 have strong bar signatures. We note that our results are robust to small variations in the redshift and luminosity thresholds chosen for the sample. For example, our qualitative result does not change if we use a fixed luminosity/stellar mass range.

2.4.1 Completeness corrections

Given the depth of the CANDELS images (even those in the shallower "wide" fields) and the luminosity ranges considered here, the completeness of the final sample of featured, not-edge-on disk galaxies is unlikely to be affected by surface brightness dimming. Using Galaxy Zoo classifications is demonstrably reliable for selection of specific features (Darg et al. 2010a,b; Masters et al. 2011; Skibba et al. 2012; Casteels et al. 2013; Willett et al. 2013; Melvin et al. 2014), and all analysis here is concerned with large-scale strong galactic bars, which are less affected by surface brightness dimming or diminished resolution effects than smaller-scale or weaker features. Overall, the selection is conservative with respect to detection of features, in the sense that both strong bars in particular and featured disks in general are unlikely to be missed.

However, it is possible that the selection described above could omit rotationally-supported disk galaxies with completely smooth light distributions (i.e., completely lacking in "features"). As such galaxies would not contain bar features, they would preferentially bias the bar fractions discussed in Section 3 below to higher-than-actual values. This possible source of bias is not addressed by the conservative selection with respect to inclusiveness of features described above.

To correct for this possible bias, we examine the population of "smooth" galaxies (that is, those where fewer than 30% of votes from at least 30 total were registered for "Features or Disk" and fewer than 30% of volunteers selected "Star or Artifact") within the luminosity and redshift selections described above. We assume this set of featureless galaxies contains a population of rotationally supported circular disk galaxies which are randomly oriented on the sky. We constrain the maximum possible fraction of disks within the featureless sample by assessing the highest fraction of the observed axis ratios within the featureless galaxies that is consistent with this population of randomly oriented disks (Binney & Merrifield 1998; Lambas, Maddox, & Loveday 1992), normalizing this fraction by assuming that *all* featureless galaxies with axis ratios $b/a \leqslant 0.4$ are disks. This fraction is $\approx 19\%$ for the full sample, and generally increases with redshift between 15% and 25%.

In the following analysis, we correct for this incompleteness factor by adding the maximum number of featureless, not-edge-on galaxies that may be disks to the total number of featured, not-edge-on disk galaxies in each redshift bin. Given the inclusive sample selection, the maximal correc-

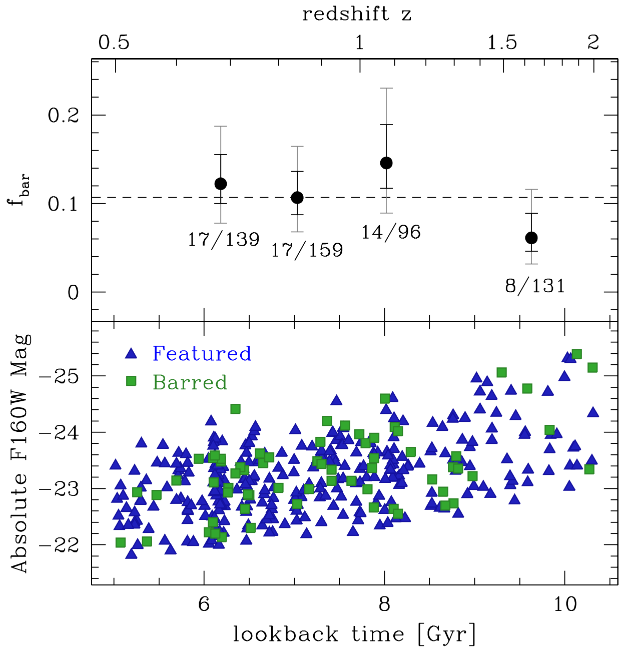

Figure 4. *Top panel:* Bar fraction versus lookback time. Error bars are 68% (black) and 95% (gray) Bayesian binomial confidence intervals (Cameron 2011); within these confidence intervals, the bar fraction is consistent with no evolution from $0.5 \leqslant z \leqslant 2$. Bins were chosen to enclose similar lookback time intervals; the bar fraction across all bins ($10.7^{+1.5}_{-1.2}$%) is shown as a dashed line. Black points include correction for incompleteness described in Section 2.4.1; purple diamonds are the uncorrected fractions. *Bottom panel:* absolute H-band magnitudes of the featured disk sample from which the fractions are drawn.

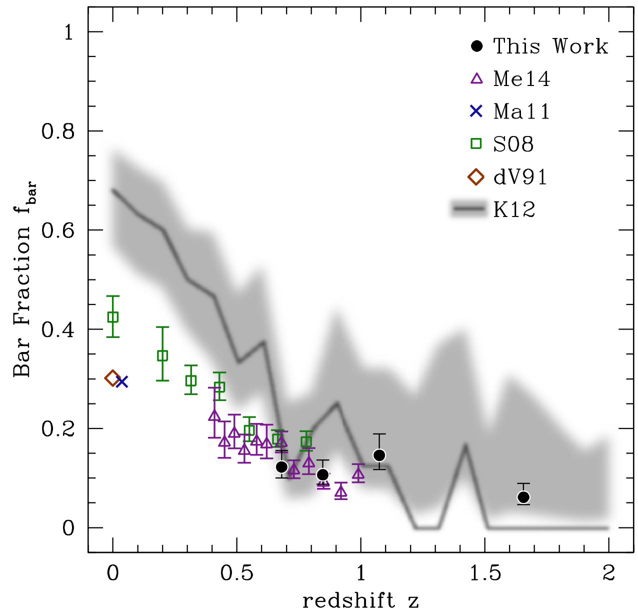

Figure 5. Fraction of disk galaxies having a strong bar feature versus redshift, in the context of other work assessing visual strong bar fraction. All shading and error bars indicate Bayesian binomial confidence intervals (Cameron 2011); the 1σ error bars for the Masters et al. (2011, Ma11, blue cross) and de Vaucouleurs et al. (1991, dV91, red diamond) fractions are smaller than the size of the points and are omitted. At higher redshift, bar fractions in this work (black circles) at $z < 1$ are consistent with those of Sheth et al. (2008, S08, green squares) and Melvin et al. (2014, Me14, purple triangles) despite differences in selection methods. Kraljic et al. (2012, K12) computed the fraction of strong bars to $z = 2$ among disk galaxies that evolved to stellar masses $M_* \approx 10^{10-11}\,\mathrm{M}_\odot$ (shaded region); the predicted bar fraction is consistent with that observed here within the uncertainties, although we note that differences between simulated and observed mass/luminosity ranges make direct quantitative comparisons more difficult.

tion for missed disk galaxies, and the lack of correction for possible contamination of non-disks in the sample, the bar fractions discussed below may be taken to be conservative lower limits.

3 RESULTS: BAR FRACTIONS

The fraction of disk galaxies with visually identified strong bars between $0.5 \leqslant z \leqslant 2$ is $\sim 10\%$, a figure that is robust to moderate changes in luminosity ranges or vote fractions for detected features, lack of clumpiness, disk inclination angle, and strong bar features. Figure 4 shows the bar fraction with lookback time, from $t_{lb} = 5.0$ Gyr ($z = 0.5$) to 10.2 Gyr ($z = 2.0$). The sample encompasses the same subset of the galaxy luminosity function relative to the evolving L^*; the conservative selection to ensure detectability of features (or lack thereof) to $z = 2$ means the galaxies examined here are all brighter than L^* at their epoch.

Figure 5 shows the visually identified strong bar fraction versus redshift in the context of other work, both observational and theoretical. Within the redshift range where we overlap with other observational studies, the bar fraction is consistent. However, the bar fraction with redshift appears to flatten at $z > 1$.

Within this sample, and given the uncertainties, the bar fraction is consistent with zero evolution between $1 < z < 2$. Many studies of the bar fraction at $z \lesssim 1$ find that the bar fraction does evolve, though these findings are not unanimous (Abraham et al. 1996, 1999; Jogee et al. 2004; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005; Sheth et al. 2008; Cameron et al. 2010; Melvin et al. 2014). Two independent studies of the full COSMOS-ACS sample (Sheth et al. 2008; Melvin et al. 2014) show that the fraction of visually identified strong bars decreases with redshift, from approximately 35% at $z = 0.2$ to 15% at $z = 1$.

Using zoom-in cosmological simulations of 33 field and loose group galaxies, Kraljic et al. (2012) find that disk galaxies at $z \gtrsim 1$ are generally too dynamically hot to become unstable to bar formation; this manifests itself as a decreasing bar fraction with increasing redshift. Although the quantitative bar fractions in their simulations depend on the threshold used to define a bar feature, the fraction of disk galaxies hosting bars drops to zero, or near zero, by any definition they use (Figure 5 shows their standard "strong bar" definition, which is the closest to observational samples defined by visual classifications such as those here and in previous work; Masters et al. 2011; Willett et al. 2013; Melvin et al. 2014). This initially appears inconsistent with our results showing a low, but non-zero, bar fraction. However, due to the very small number of simulated galaxies in Kraljic et al. that are disk galaxies at $z > 1$, a complete lack of bar feature detection within the subset of their sample identified as disk galaxies does not directly predict a 0% bar fraction. As the normal approximation (used in that study) systematically underestimates proportional confidence errors when the true population fraction approaches 0 or 1, especially for small sample sizes, we have re-calculated the uncertainties quoted in Kraljic et al., using a Bayesian approach to compute binomial confidence intervals (Cameron 2011). Given this approach, the lack of detection of bars at $z > 1.5$ in the simulations is consistent with a bar fraction of up to $\approx 30\%$ at these redshifts, within the 68% confidence intervals.

We also note that the galaxy masses and luminosities used in the simulations were on average lower than those examined in this work, making a direct comparison to this work more difficult, as bar fraction also depends on stellar mass (Sheth et al. 2008; Melvin et al. 2014). Kraljic et al. predict that massive disk galaxies will be more likely to form bars at higher redshift than lower mass disk galaxies due to higher-mass galaxies reaching dynamical maturity at earlier epochs. This is qualitatively consistent with our finding that the bar fraction at $z \sim 2$ may be as high as 11% within 2σ binomial uncertainties, but a direct and quantitative theoretical comparison to our observational result is currently not possible given available simulations. Expanded simulations encompassing galaxies with higher stellar masses would help to advance this field further.

Our results agree with previous work that the main epoch of disk settling (and thus bar formation) in the disk galaxy population begins at $z < 1$. However, bars are not completely absent even at $z \sim 2$: some disks at the masses probed by our sample are mature enough even by this epoch ($\sim 3-4$ Gyr after the Big Bang) to host a bar.

Whether the bar features are analogous to long-lived bars in dynamically cold disks at lower redshift or are shorter-lived features triggered within dynamically warmer disks is unclear from examination of bar fractions alone. Examination of individual simulated galaxies by Kraljic et al. indicates that bars formed at $z > 1.5$ tend to undergo shorter cycles of formation and destruction., and there is some evidence that short-lived grand design spiral features more commonly associated with mature disks can be triggered by interactions at $z > 2$ (Law et al. 2012).

Thus the incidence of bars in massive high-redshift disks may be due at least in part to galaxy interactions and mergers, combined with shorter bar lifetimes due to dynamically warmer disks. Minor galaxy mergers may dynamically heat a disk and destroy a bar, or they may trigger the formation of a bar, depending on the particulars of the interaction (Noguchi 1988; Gerin et al. 1990; Berentzen et al. 2003, 2004). The relative likelihood of these contrasting end results, combined with the incidence of minor mergers among this population at $z \sim 2$, may combine to produce a net effect that stabilizes the bar fraction at $f_{\rm bar} \sim 10\%$ during this epoch of galaxy assembly.

Among the galaxies in the highest-redshift bin of the sample, 2 of the 8 barred galaxies appear to be undergoing an interaction or merger, and another 2 appear tidally disturbed, possibly by a nearby companion. This may suggest these bar features are merger-induced; on the other hand, mergers and interactions are not particularly rare during this epoch of galaxy assembly, so their appearance in the same galaxy during the same epoch does not necessarily indicate a causal link.

To investigate this further, we examined the distributions of Galaxy Zoo vote fractions for the question "Is the galaxy currently merging or is there any sign of tidal debris?", a second-tier question in the decision tree to which the possible responses are "Merger", "Tidal features", "Both", or "Neither". Kolmogorov-Smirnov tests between the barred and unbarred disk galaxy samples in any redshift bin for vote fractions for responses $f_{\rm merger}$, $f_{\rm tidal}$, $f_{\rm both}$, and the sum of these fractions, are inconclusive. Resolving the question of whether shorter-lived bars are triggered by interactions and/or mergers may be possible in the future, upon the full reduction of Galaxy Zoo: CANDELS data and the addition of galaxy images from the remaining CANDELS fields to the Galaxy Zoo sample.

4 SUMMARY

Using visual classifications of rest-frame optical *HST* galaxy images from the ongoing Galaxy Zoo: CANDELS project, we examined for the first time the fraction of disk galaxies hosting a bar feature to $z \sim 2$ in order to trace the dynamical state of disks as early as ~ 3 Gyr after the Big Bang. We find that the bar fraction to $z \sim 1$ is consistent with previous studies using similar analysis methods.

At $z > 1$, the bar fraction is approximately 10% and consistent with no evolution to $z \sim 2$. This is qualitatively consistent with the predictions of zoom-in cosmological simulations, although further work is needed to determine whether simulations of disk galaxies with $L > L^*$ predict the same quantitative strong bar fraction at $z < 2$.

That the bar fraction from $0.5 < z < 2$ appears to be small but constant among massive disk galaxies implies that massive disk dynamics do not rapidly change on average over this period. Further clarification may come in the future when additional detailed morphological classifications of deep $z \sim 2$ rest-frame optical galaxy images are available; future comparison with independent morphologies of the same galaxies (Kartaltepe et al. 2014) as well as additional simulations will help provide a more nuanced understanding of the underlying physical causes of this apparently stable bar fraction.

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