

Galaxy Zoo: Detailed Morphological Classifications for 48,000 galaxies from CANDELS*

B. D. Simmons^{1†}, and a *lot* of other people to be named later

¹*Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

8 March 2015

ABSTRACT

To be rewritten, probably last.

Galaxies are sometimes really far away. The distant ones are pretty cool, because they tell us what the Universe was like back when it was just a kid, or maybe a teenager. You really have to look hard to see these galaxies, but once you do, what you do see tells you a whole lot. I mean, it's not exactly a WYSIWYG type of thing: there's a lot of work to figure out what the faint stuff you see really means. We did a bunch of work, and we think we did pretty well. Also, we compared to others who have done different kinds of work to try and answer some of the same questions. But we have a unique way of answering them, so here are those answers, and you can use them to answer other questions about the Universe.

Key words:

galaxies: general — galaxies: evolution — galaxies: morphology — galaxies: structure

1 INTRODUCTION

Outline:

Galaxy morphologies trace physics & dynamics and are therefore important.

They have a long history and there are many types, including those that use proxies [which are useful but not without problems] and those that reduce a galaxy and its billions of stars to a single number [same]. Visual morphologies are in many ways still ideal as they are able to provide incredibly detailed information about galaxies.

Visual morphologies have a scale problem without many eyes, and they're often not quantified. Galaxy Zoo to the rescue.

Galaxy Zoo started in 2007 and has provided robust, quantified visual classifications for more than 1,000,000 galaxies to $z \sim 1$.

Much use has been made of these, including [summarize and include non-GZ papers].

Here we present the visual morphologies of galaxies imaged by the *HST* treasury survey CANDELS.

Section summary and cosmology.

2 OBSERVATIONAL DATA

2.1 Images

The Cosmic Assembly Near-infrared Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) is an *HST* Treasury programme 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, Giavalisco et al. 2004; EGS, Davis et al. 2007; UDS, Lawrence et al. 2007, Cirasuolo et al. 2007; and COSMOS, Scoville et al. 2007) using a two-tiered “deep” and “wide” approach. Each of the wide fields (UDS, COSMOS, EGS and flanking fields to the GOODS-S and GOODS-N deep fields) are imaged over 2 orbits in WFC3/IR, split in a 2:1 ratio between filters F160W and F125W, respectively, with parallel exposures in F606W and F814W using ACS. Each of the deep fields (GOODS-S and GOODS-N) are imaged over at least 4 orbits each in both the F160W and F125W filters and 3 orbits in the F105W filter, with ACS exposures in F606W and F814W in parallel. These are reduced and combined to produce a single mosaic for each field in each band, 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 first set of data to be classified within the Galaxy Zoo interface. Those data cover the COSMOS,

* This publication has been made possible by the participation of more than **COUNT** volunteers in the Galaxy Zoo project. Their contributions are individually acknowledged at <http://authors.galaxyzoo.org/>.

† E-mail: brooke.simmons@astro.ox.ac.uk

GOODS-South, and UDS fields. The 4th release of Galaxy Zoo included all detections with $H \leq 25.5$ from these 3 combined fields, comprising 49,555 unique images. These were shown to visitors to the website galaxyzoo.org¹ starting on the 10th of September, 2012.

The images shown to the public are colour composites of ACS *I* (*F814W*), WFC3 *J* (*F125W*), and WFC3 *H* (*F160W*) filters for the blue, green and red channels, respectively. The angular sizes of the images in different filters are matched, and the native point-spread functions (PSFs) are used. The images are combined with an asinh stretch (described in detail in ?) with a non-linearity value of 3.0.

Sources in the dataset vary greatly in size and surface brightness, and therefore a single set of values for channel scalings is not adequate to capture the variety of features across the images. We therefore use a variable scaling based on the [magnitude and size](#) of each target source. For each image the R, G, and B channels have a fixed ratio of [\[not sure; must get this from Jeyhan\]](#), and the multiplier can vary between [A and B](#). Figure ?? shows examples of these colour composites across a wide range of source fluxes and sizes.

Each colour image is 424 pixels square. The angular size of the image varies, such that the colour image encompasses at least [3 times the 80% flux radius of the target source](#), with a minimum screen-to-WFC3 zoom ratio of [1:10](#) and a maximum ratio of [3:1](#). The Galaxy Zoo interface loads the normal colour images by default, and the user may choose to display an inverted colour image, but may not otherwise change the image scaling or size within the software while performing the classification.

2.2 Photometry

Brief description of photometric catalogs. Focus on *IJH* because that's all the images consider. Do mention all the extra stuff available, but note that the classifications themselves don't depend on them.

2.3 Redshifts

Some of them have specz. Lots of them have photz, including CANDELS, 3D-HST and several previous surveys.

Comparison of photoz and specz; might be able to just reference the other papers.

What do we do about those without redshifts? We use them with caution?

2.4 Calibration and Simulated Images

Mention the duplicated images in GDS, which were put in both identically (this was by accident - so we got double each of these and can theoretically check the variance in classifications, but that's kind of a stupid justification and I'm not quite sure how to mention these without saying "oopsies") and at 2-epoch depth (though this has not actually happened yet so I may need to just leave it out). Also it'd be nice to mention the FERENGified images, but ... those aren't in yet either. Basically, the only reason to have this section at the moment is to say "oops".

¹ Archived at zoo4.galaxyzoo.org

3 CLASSIFICATION DATA

3.1 Decision Tree

The goal of Galaxy Zoo CANDELS is to provide detailed quantitative visual morphologies of galaxies observed by the deepest, most complete *HST* multi-wavelength legacy survey to date. There are many morphological features of interest, including both broad questions about a galaxy's overall appearance and more detailed questions about specific features.

We employ a tree-based structure for collecting information on these morphological features, a strategy that has been used successfully in both Galaxy Zoo 2 ([refs here](#)) and Galaxy Zoo: Hubble ([and here](#)). The decision tree, shown visually in Figure 1 and in text in Table 1, first asks the classifier to choose between the broad categories of "smooth and rounded", "features or disk", and "star or artifact". The next question either exits the classification (if the classifier has indicated the image is of a star or artifact) or asks for further details about the galaxy.

If the classifier has indicated in the first question that the galaxy has features or a disk, a series of follow-up questions are asked about features such as clumps, spiral patterns, bulge strength, and the presence of a bar. If the classifier has instead indicated the galaxy is mostly smooth and rounded, the next question asks them to rate the overall roundedness, a question roughly corresponding to an axis ratio measurement. Finally, when the classifier has finished answering all follow-up questions about either the "smooth" or "featured" galaxy, they are then asked whether the galaxy is undergoing a merger, has tidal tails, or has both, or neither.

The tree-based structure has a number of advantages. First, it collects substantially more information on each galaxy than a single question would, and captures a more detailed classification of higher-order structures while minimising the effort required on the part of the classifier by only asking for relevant inputs based on the overall classification in the first question.

Second, it focuses the classifier on a single feature at a time, highlighting each feature. This resets the attention of the classifier with each new question and avoids the issues that may result when a person is presented with a large number of decision tasks at once, including a decrease in optimal decision-making ([references for overchoice](#)) and a reduced ability to recognise the unexpected ([references for inattentive blindness](#)).

Third, the tree-based structure is especially optimal for an interface which may collect classifications from users who have never before seen an image of a galaxy and may seek additional training. Within the interface, the classifier may optionally display training images in a "Help" section that shows different examples of the feature relevant to the current question. Asking single-topic questions in turn permits a full set of training images to be available throughout the classification without placing an unnecessary cognitive load on the classifier.

Other advantages we should mention?

The disadvantage of a tree-based classification structure concerns the dependencies introduced into the vote fractions by such a structure. A classifier cannot, for example, answer that the same galaxy has both a mostly smooth appear-

GZ-CANDELS

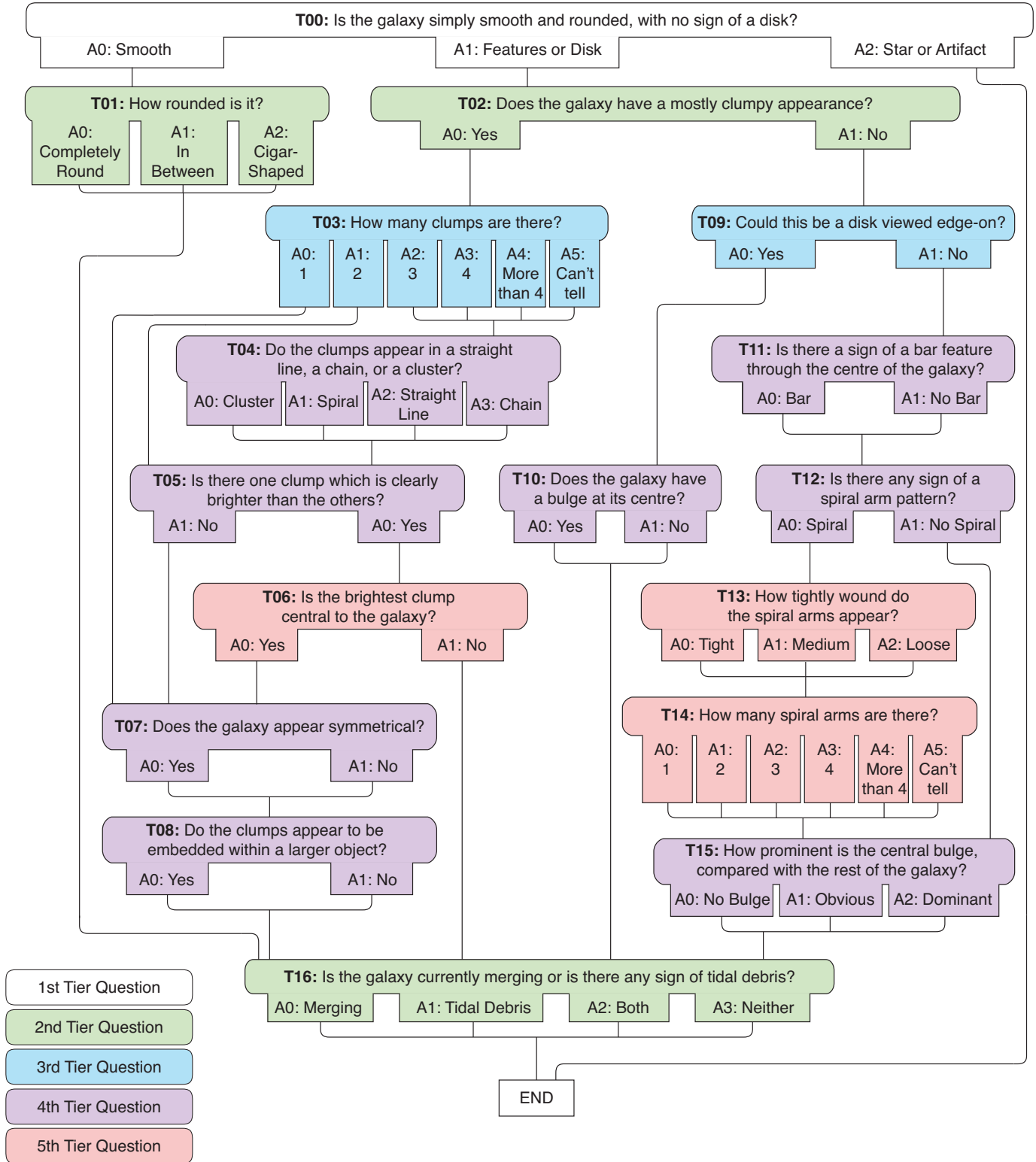


Figure 1. The Decision Tree for Galaxy Zoo: CANDELS in visual format. There are 16 tasks, with one question per task and up to 6 answers per question. Questions are coloured according to the minimum number of branches prior to that question. All users are asked the first question (task T00), and there are 4 subsequent levels of branching. The tree is also shown in text in Table 1.

ance and also has a spiral feature. This is in some ways an advantage, as it prevents contradictory and unphysical classifications, but it also means that an analysis of morphological vote fractions with the goal of examining spiral galaxies must account for the fact that whether a given classifier reached the spiral branch of the decision tree depends on their answer to the questions preceding it.

Accounting for dependencies of questions in deeper branches of the decision tree on higher-level questions is, however, a manageable task which has been undertaken successfully in many previous studies of specific galaxy structural features (for specific examples, see [citation bomb here]).

The Galaxy Zoo CANDELS decision tree is shown in visual form in Figure 1 and in text form in Table 1. We note that this tree is most similar to the tree used in the Galaxy Zoo: Hubble project (shown in ?) (note to self to check that the full tree is actually shown there), which also has an additional branch identifying clumpy galaxies and focusing on the detailed structure of galaxy clumps. There are small differences, however: for example, Task 10, the question about a bulge in an edge-on disk, is a Yes/No question here, whereas in previous iterations of the decision tree this question also asked whether the bulge shape was rounded or boxy. Additionally, the final question in the tree (Task 16) is substantially different from previous versions and is here only concerned with galaxy mergers and tidal features.

After the classification of each image is finished, the classifier is asked "Do you want to discuss this galaxy?" If the classifier selects "No", a new image is shown for classification. If the classifier selects yes, a new window opens with a discussion page focused on the image they have just classified. Within this part of the Galaxy Zoo software, called Talk, users may ask questions and make comments on specific images, or engage in more general discussions. Users may also "tag" images and discussions using a format identical to Twitter's hashtag system. Some of these tags were used in the pre-analysis of Galaxy Zoo CANDELS data, on which more details are given in Section ?? below.

3.2 Raw classifications

The first classification of an image from CANDELS was registered on the Galaxy Zoo interface² on the 10th of September 2012. The final classification considered here, in the first phase of Galaxy Zoo CANDELS, was registered on the 30th of November 2013. Between these times, the site collected 2,149,206 classifications of 52,076 CANDELS subjects from 41,552 registered volunteers and 53,714 web browser sessions where the user did not log in. For all analysis presented here we have assumed that each unregistered browser session contains classifications from a single, unique volunteer.

Subjects within a given Galaxy Zoo sample are chosen randomly for classification, so that the number of independent classifications per galaxy builds up uniformly through the full sample. Once a pre-set classification limit has been reached, the subject is retired from the active classification pool. The initial goal for Galaxy Zoo CANDELS was to obtain at least 40 independent classifications for each galaxy.

Task	Question	Responses	Next
00	<i>Is the galaxy simply smooth and rounded, with no sign of a disk?</i>	smooth features or disk star or artifact	01 02 end
01	<i>How rounded is it?</i>	completely round in between cigar-shaped	16 16 16
02	<i>Does the galaxy have a mostly clumpy appearance?</i>	yes no	03 09
03	<i>How many clumps are there?</i>	1 2 3 4 more than four can't tell	07 05 04 04 04 04
04	<i>Do the clumps appear in a straight line, a chain or a cluster?</i>	cluster spiral straight line chain	05 05 05 05
05	<i>Is there one clump which is clearly brighter than the others?</i>	yes no	06 07
06	<i>Is the brightest clump central to the galaxy?</i>	yes no	07 16
07	<i>Does the galaxy appear symmetrical?</i>	yes no	08 08
08	<i>Do the clumps appear to be embedded within a larger object?</i>	yes no	16 16
09	<i>Could this be a disk viewed edge-on?</i>	yes no	10 11
10	<i>Does the galaxy have a bulge at its centre?</i>	yes no	16 16
11	<i>Is there a sign of a bar feature through the centre of the galaxy?</i>	bar no bar	12 12
12	<i>Is there any sign of a spiral arm pattern?</i>	spiral no spiral	13 15
13	<i>How tightly wound do the spiral arms appear?</i>	tight medium loose	14 14 14
14	<i>How many spiral arms are there?</i>	1 2 3 4 more than four can't tell	15 15 15 15 15 15
15	<i>How prominent is the central bulge, compared with the rest of the galaxy?</i>	no bulge just noticeable obvious dominant	16 16 16 16
16	<i>Is the galaxy currently merging or is there any sign of tidal debris?</i>	merging tidal debris both neither	end end end end

Table 1. The Galaxy Zoo CANDELS decision tree, comprising 16 tasks and 51 responses. Each task is comprised of a single question and up to 6 possible responses. The first question is Task 00, and a classification is completed by responding to all subsequent questions until the end of the tree is reached. The 'Next' column indicates the subsequent task the classifier is directed to upon choosing a specific response. Although a classifier will flow through the tree from top to bottom, there is no path through the tree that includes all tasks.

² zoo4.galaxyzoo.org

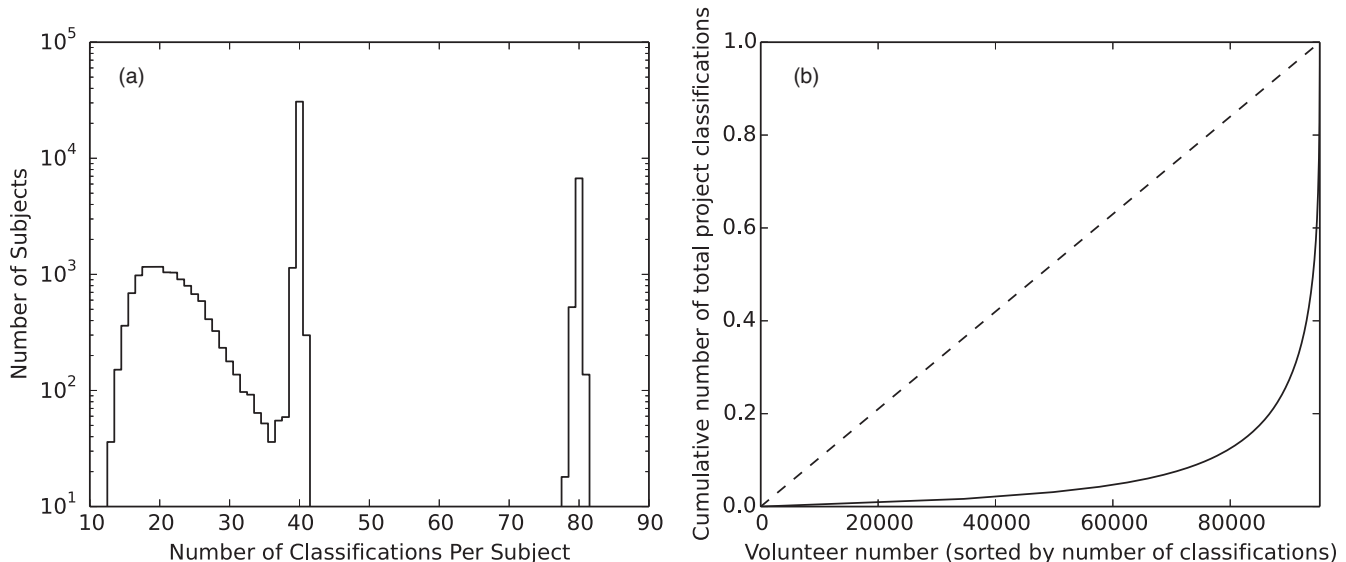


Figure 2. Basic information on classifications and volunteers. *Left:* Distribution of number of classifications per subject in Galaxy Zoo CANDELS. The majority of images have 40 independent classifications each; a subset of 13,392 were retired early after being identified as too faint and low-surface-brightness for additional classifications to be useful (11,837) or as stars or artifacts (1,555). Subsequently, 7,402 subjects where at least 20% of classifiers registered a vote for “Features or Disk” in the first task were re-activated with a retirement limit of 80 classifications, in order to ensure a complete sampling of the deepest branches of the question tree. *Right:* Cumulative distribution of classifications by volunteers, where the volunteers are sorted in order of least to most classifications contributed (Lorenz curve for classifiers). The dashed line indicates the even line, i.e., what the curve would look like if every volunteer had contributed the same number of classifications. The top 9% of users contributed 80% of the classifications (Gini coefficient = 0.86).

This uniform retirement limit was modified twice during the project. In the first instance, a pre-analysis of the dataset performed when the average number of classifications per galaxy had reached approximately 20 revealed 11,837 subjects where further classification was unlikely to provide any additional information. These subjects were identified using a set of subjects tagged in the Galaxy Zoo Talk software as “#toofainttoclassify” and “#FHB” (which stands for “Faint Hubble Blob”). Tags in Galaxy Zoo Talk are generally highly incomplete; thus the 204 tagged subjects were used as tracers during a further examination of all subjects in magnitude-surface brightness parameter space. The selection, made from initial photometry, was deliberately conservative, retiring only those subjects where it was clear that the classification vote fractions had converged at all tiers of the classification tree. During this analysis, an additional 1,555 subjects were identified as highly likely to be stars or artifacts and were also retired.

The second modification of the retirement limit was implemented 1 year after the project start. At this time, the retirement limit was raised to 80 classifications for all galaxies where at least 20% of volunteers had answered “Features or disk” to the first question (task T00 in Figure 1 and Table 1. This is a higher retirement limit than in previous Galaxy Zoo projects, and it is justified by the increased complexity of the question tree compared to, e.g., Galaxy Zoo 2 (?). The Galaxy Zoo CANDELS question tree has an additional branch level, and the number of volunteers answering a question is typically reduced at each branch point. Thus, 40 classifications at the first question may not be enough to ensure convergence in, for example, task 14, “How many spiral arms are there?”, a 5th-tier question with 6 possible

answers. The increased retirement limit affected 7,402 subjects.

Figure 2 shows the distribution of total classification counts within the sample. There are peaks at ~ 20 , 40, and 80, consistent with the description above.

How many users participated, and the distribution of classifications (typical number per person, number signed in and not, maybe that square diagram Old Weather uses).

3.3 User Weighting

Note: we may discuss other weighting if that proves useful.

3.3.1 Consensus Weighting

3.3.2 IBCC

4 COMPARISON TO OTHER CLASSIFICATIONS

Kartaltepe et al. 2014

Distribution of Sersic indices for different galaxy types

5 SOME KIND OF INITIAL RESULT

Clumpy galaxies as a function of redshift? Not too difficult to show this.

6 SUMMARY

Galaxies! We have galaxies!

ACKNOWLEDGMENTS

The development of Galaxy Zoo was supported in part by the Alfred P. Sloan Foundation. Galaxy Zoo was supported by The Leverhulme Trust.

This work is based on observations taken by the CANDELS Multi-Cycle Treasury Program with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

- Cirasuolo M. et al., 2007, MNRAS, 380, 585
- Davis M. et al., 2007, ApJ, 660, L1
- Giavalisco M. et al., 2004, ApJ, 600, L93
- Grogin N. A. et al., 2011, ApJS, 197, 35
- Koekemoer A. M. et al., 2011, ApJS, 197, 36
- Lawrence A. et al., 2007, MNRAS, 379, 1599
- Scoville N. et al., 2007, ApJS, 172, 1