DRAFT VERSION JANUARY 14, 2016
Preprint typeset using LaTeX style emulateapj v. 05/12/14

GALAXY ZOO 2: BIVARIATE SIZE-MASS FUNCTION

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Draft version January 14, 2016

ABSTRACT

Super duper bivariate size-mass function – joint probability y'all.

Subject headings: galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. INTRODUCTION

Galaxy size and total luminosity (closely related to mass) are among the most basic model-independent measurements that can be performed on a galaxy. The study of these quantities has unveiled the existence of both luminosity-dependent and mass-size relations that hold, with different slopes, for both disk (star-forming) and bulge-dominated (passive) galaxies. Recently it has been possible to push these studies out to z 2 thanks to the new WFC3-IR camera on HST. Observations show that the mass-size relation for bulge-dominated galaxies evolves significantly faster than for star-forming disk-dominated galaxies. Similarly, the size functions of star-forming and passive galaxies evolve differently, remaining relatively unchanged for disk galaxies (out to z 1.5) while changing substantially for bulge-dominated objects; i.e. bulge-dominated galaxies have grown by a factor of five in size since z 2 with minimal change in mass.

These results prompted a large number of theoretical works aiming to understand which physical processes are responsible for these trends and their change with time. Simulations suggest disks should grow due to efficient filamentary accretion. Moreover, because different feedback mechanisms are important on different mass scales, the growth rate is predicted to depend on galaxy mass with larger massive galaxies growing in size at a higher rate than small massive ones. To reproduce the slow evolution of the mass-size relation of disk galaxies these models require galaxies to grow in such a way as to evolve along the relation with time. Thus, the rate at which galaxies move along the mass-size relation should be equal to the rate at which large star-forming galaxies move out of the sample. Theoretically there are two main mechanisms by which an object can leave the pool of star-forming disk-dominated galaxies: either via merger (similar mass mergers will eventually result in a bulge-dominated galaxy), or via quenching through secular evolution (the growing mass of a central bulge may eventually be sufficient to stabilize the gas disk against fragmentation). Either way, these models clearly predict that the growth of the star-forming galaxies must be accompanied by an increasing number (toward lower redshift) of large spheroids.

Testing this requires tracking of galaxy number densities, not only as a function of size and stellar mass but also as a function of morphological type. This can be achieved by computing the bivariate (i.e., the joint probability distribution) mass-size functions for galaxy samples morphologically selected in a consistent way as a function of time. We use three catalogs developed by Galaxy Zoo: Galaxy Zoo 2 (z 0), Galaxy Zoo: Hubble (z 0.7), and Galaxy Zoo: CANDELS (z 1.5) to extract samples of disk- and bulge-dominated galaxies in various redshift regimes in order to track these number densities as a function of cosmic time.

Bias on galaxies sizes introduced by redshift-dependent surface brightness dimming, changing spatial resolution and rest-frame wavelength of images using FERENGI galaxies?

2. GALAXY ZOO 2 SAMPLE

The full Galaxy Zoo 2 catalog consists of 283,971 galaxies from SDSS including objects from Stripe 82. For our initial pass, we select only those galaxies with spectroscopic redshifts in the standard (non-Stripe 82) fields yielding a sample of 243,500 galaxies. For details on how the Galaxy Zoo team choose this sample see Willett et al. 2013. This sample is magnitude limited by design and extends to z ¡= 0.25. For our analysis, we use measured values from SDSS including half-light Petrosian radius, Petrosian magnitudes, and surface brightness. We obtain masses from the SDSS value-added MPA/JHU catalog. These masses were derived by fitting an SED from broad-band photometry.

To obtain a complete, unbiased sample we need to make careful selections from the total sample. In figure 1 we explore various characteristics of the full sample parameters including redshift, half-light Petrosian radius in the r-band, surface brightness, and r-band magnitude. In magnitude, we see a sharp cut-off around $m_r = \sim 17$ which is expected as this is the magnitude limit imposed by GZ2. There is some scatter beyond $m_r = 17$ and we place a hard cut such that all galaxies in our sample must have m_r ¿= 17.2. In addition to a cut on the dim end we also place a cut on the bright end at $m_r = 15$ to remove any remaining stars or artifacts (*Why am I doing this?! I could just go through and remove anything labelled by GZ2 to be an artificact! Dummy....Got too focused on copying Shen!*)

We can also see the distribution of the sample in redshift space and notice that the bulk of our sample falls at z¡=0.1. We exclude everything above this redshift as well as any galaxies with z ¡= 0.02 in order to circumvent the need to disentangle between a galaxy's peculiar velocity and blah blah what? This encloses a total volume of XXX (*I just want to know what it is.*)

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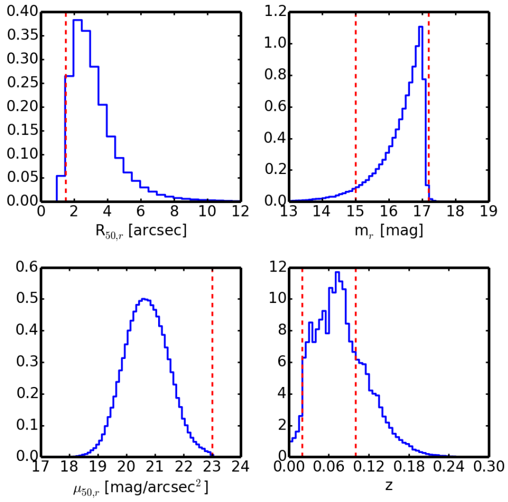

FIG. 1.— **Explore sample characteristics**

In addition to cuts in magnitude and redshift, we must also account for potential biases in size. Galaxies which have measured sizes on the order of the SDSS PSF are suspect. As these are not corrected for the PSF we exlude from the sample all galaxies with a half-light Petrosian radius larger than $1.6''$. As the SDSS PSF is $1.5''$, this is a conservative approach and removes only a small number of galaxies from our sample.

Finally, we must consider galaxy mass. In figure 2 we show the mass distribution of the full sample in two ways. In the top panel we explore mass as a function of m_r and z with color denoting mass. We see that, due to selection effects, low mass galaxies are only observed at the lowest redshifts, while massive galaxies are observed more frequently at higher redshift. The dashed black lines indicate our cuts in redshift and magnitude and demonstrate that within this sample we have massive galaxies at all redshifts. In the lower panel we show redshift against stellar mass with color as a function of (g - i) color. Again, the dashed black lines represent our selection. Here the vertical lines represent our cuts in redshift. In order to provide a complete sample, we select only those galaxies with stellar mass above log ten solar (represented by the vertical dashed line).

After these selection criteria, our sample contains 120,015 galaxies.

Still to do:
Understand completeness corrections
Understand EXACTLY how the masses were calculated and how that affects the completeness
Go back and remove the upper-limit cut on magnitude and simply remove objects classified as artifacts by GZ2?

3. MORPHOLOGICAL SELECTIONS

Once we have a complete sample we next split our sample through various morphological indicators. We want to isolate clean samples of disk- and bulge-dominated galaxies and we tackle this through cuts in concentration index (CI), color, and GZ2 visual classifications. CI and color cuts have long been known to broadly correlate with early and late type galaxies. In figure 4 we show the distribution of CI, (u-r) color and (g-r) color. The solid black lines show the cuts we apply for each indicator where samples on the right correspond to late type (disk-dominated) galaxies, whiles objects to the left correspond with early types (bulge-dominated) galaxies.

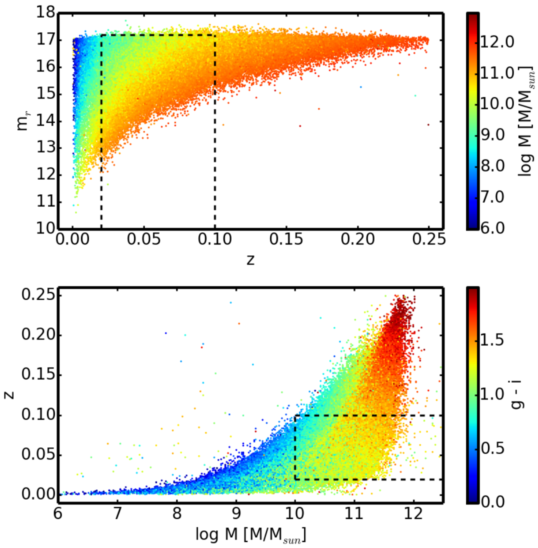

FIG. 2.— **Explore sample characteristics**

In addition, we also wish to determine how these broad morphological indicators correspond with visual morphological classifications. Galaxy Zoo 2 obtained crowd-sourced visual classifications from thousands of users through a series of increasingly complicated questions. We first focus our attention on the top level question posed: "Is the galaxy smooth with no sign of features or a disk?" to which possible responses included "Smooth", "Featured or Disk", and "Star or Artifact". *Those objects which were classifed as "Star or Artifact" have already been removed.* We look at the vote fractions for each objects and select the majority vote, i.e., galaxies with a $p_{features} > 0.5$ were considered disk-dominated while those with $p_{smooth} > 0.5$ were considered bulge-dominated. In figure **??** we show the multi-dimensional morphology space created by CI, stellar mass, and both colors. Considering first the left panel, we see, as in figure 4, that these coarse morphological indicators do a decent job of splitting the sample. In many cases, correlations exist among the various indicators (e.g., CI correlates well with both color cuts). We note that most of these indicators additionally have trends with stellar mass. In the right panel we show the same space but this time we separate on GZ2 visual morphologies. This figure serves to demonstrate that color cuts alone are not sufficient to split morphological samples cleanly as there exist blue ellipticals as well as red disks.

4. DISCUSSION AND CONCLUSIONS

5. THE FUTURE OF POLARIZATION

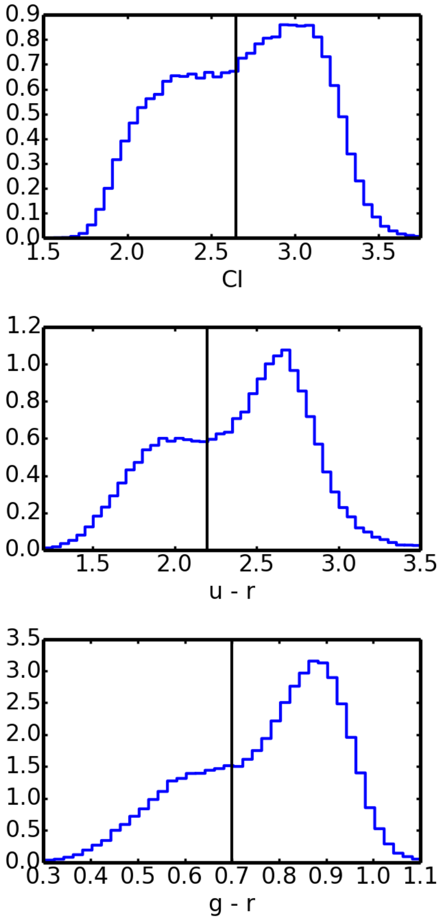

FIG. 3.— **Morphological cuts**

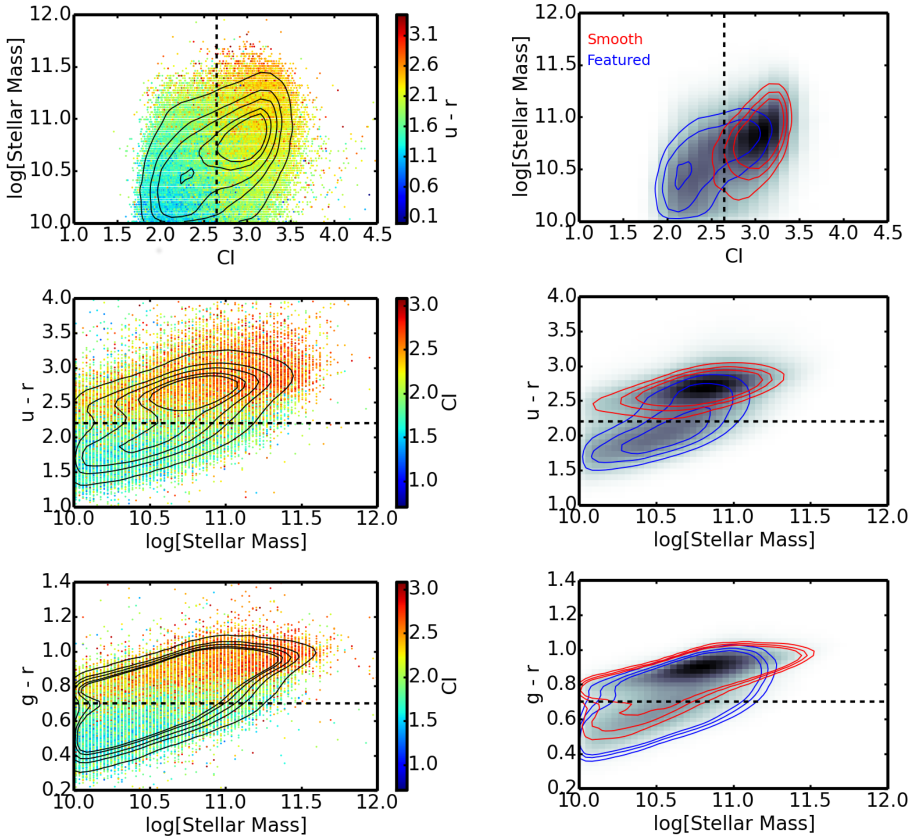

Fig. 4.— **3d Morphology space**